

# **Experimenting from a Distance RCL-experiments for teaching Physics at High-school**

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**Technical note:**

- Link to the RCL Portal: [www.remote-lab.de](http://www.remote-lab.de) as well as [rcl-physics.de](http://rcl-physics.de)
- The portal provides all the book materials for download, such as tasks with sample solutions, worksheets, drafting lessons, as well as a compilation of 335 RCLs worldwide as a result of our research.

# Preface

Physics, especially physics teaching, lives by experiment; of experiments of whatever kind. There is, in our view, no substitute for it, at most supplements like (meaningful) simulations. But what if the real experiment is not available for the next physics session?

For example, suppose you as teacher is planning for the following day an experiment, e.g. the Millikan experiment to demonstrate the quantization of charges. As you know, this experiment has its faults and you find after hours of preparation that the commissioning of the experiment simply does not succeed. What to do as a substitute:

- Only discuss the theory?
- Go through pages in the textbook, calculate tasks, perhaps use original literature?
- Discuss and use a simulation program, but which ones to take and where to find?

Exactly for such scenarios, we offer the Millikan experiment as an RCL experiment. This RCL experiment is at the University of the Bundeswehr Munich and can be operated from any computer over the Internet.

You may not want to experiment with just pushing buttons and watching the screen instead of realizing it. Maybe this is only a generation problem. In the 21st century, their students are growing up with PCs and all sorts of IT products. These students do not go into a library to look for a term they google. The handling of smartphones, iPad etc. is self-evident for this generation. They use YouTube, Facebook, buy via eBay, get information about train departures, hotels, etc. from internet providers or purchase tickets online.

This situation description is a fact. This is why, in our opinion, it is even more important to integrate this component - experimentation with RCLs - into the lessons; to learn how to deal with these media and to provide the opportunity to develop a critical attitude (keyword media competency). In the end, there is now almost no workplace that is not equipped with computers and at least requires basic knowledge and skills in dealing with it.

And what does this mean to push only buttons at the PC? Earlier, when someone wanted to use a radio, each user knew what was to be done step by step and what is behind these steps:

- Press the On key,
- Select FM / AM wave type,
- Search for station / frequency and optimize reception,
- Adjust the volume and sound quality?

What is the background to all technical processes? What skills were practiced at that time? Today, we use remote control with a rich array of buttons; we remotely control the TV or the stereo. In our experience the students use our RCL experiments quite self-evident from a distance, like everyday devices on site.

Of the approximately 300 experiments in upper secondary physics, we consider about 50 experiments to be carried out as indispensable. We have successfully implemented the following experiments as an RCL variant.

- Measurement of light velocity,
- Millikan's oil droplet experiment,
- Rutherford scattering experiment,
- Electron diffraction on graphite foil,
- Photoelectric effect,
- Radioactivity,
- Diffraction and interference,
- World pendulum for determining the location dependence of the earth attraction,
- Current-voltage characteristics of semiconductor elements,
- Wind tunnel.

These ten RCL experiments form the core of this book and are presented in chapters 3-13 according to the following scheme:

1. Introduction: What is the significance of the experiment in physics as well as in the teaching of physics and everyday life? Which technical variants are offered by the teaching industry? What are the benefits of multimedia, such as simulation programs? What are the reasons for the fact that this experiment is practically not or rarely demonstrated in the classroom?
2. The experiment and our RCL variant.
3. What is the added value of using this experiment as RCL? How good are the measured values obtained? What is the experience we gained during many years?
4. Didactic material: lesson plans, worksheets, task collection with solutions, appropriate literature as well as dissertation for possible lectures.

First, in Chapter 1, we describe the position of real experiments in physics teaching, which possibilities are available and how to evaluate them. On the basis of this, we can define clear requirements for an RCL experiment. We generally describe our idea of RCL experiments, the concept and the hoped added value. Finally, we describe how these RCL experiments are to be classified as educational (ICT in society, in professional life, in education).

Chapter 2 is more specific about the basics of RCL experiments: How have we technically implemented the requirements for an RCL experiment? How should the navigation menu of an experiment be designed? How to present the RCL portal with our 20 RCLs - necessary sufficient information, not overloaded.

We also deal with the actual state of science; which RCLs exist worldwide? How good are these? What is good?

Finally, chapter 14 contains further suggestions and details for interested parties:

- For interface technology,
- Information on the programs used,
- Collection of further topics to be realized as RCL,
- Suggestions for pupils' projects in the sense of RCL to be made by themselves,

- Proposals on how the use of RCL experiments can stimulate new forms of teaching / learning,
- Experiences from the use of external users with our RCLs in teaching courses, teaching assignments, summer camps.

The aim of the book is to point out the possibility of RCL experiments, to show their quality and potential by examples, to consider the experimenting by students with RCLs as part of basic information technology, and to embed each RCL experiment in the teaching context. The addressee is especially a physics teacher, who may save his next school lesson with the RCL experiment, if its own experiment is not working. In addition, we give suggestions for specialized work and student remarks; up to the reproduction of an RCL (see tutorial on self-construction).

**Usage:**

The book was written in 2012-2014, reflecting the state of the RCL experiments. The project promoters are doing a lot to keep the experiments, to keep them available and to develop them further. Nonetheless, it can not be ruled out that due to changes in technology, such as new operating systems, in didactics, for example, in the curricula, or in project organization, for example in financing, that experiments can be changed, switched off, or be replaced by new ones. See for yourself how the stand is: you can find the remote labs at [www.remote-lab.de](http://www.remote-lab.de)

München, August 2013

the Authors

# Preface to the English version of this book

During 1997-2002 we planned, set up and organized a very successful long distance physics course of the first year at university (FIPS Frueheinstieg in das Physikstudium, early entrance into the physics studies). In the course of the supervision of these long distance students we realized that we need experimental activities for these students. The idea of RCLs was born (remotely controlled labs).

During 2001 – 2009 we realized about 20-25 RCLs. In the years 2009-2011 we counted about 30.000 users per year using these RCLs via internet. Since then most of these RCLs are still online and functional; a great success.

From 2014 the project was taken over by other colleagues (Prof Girwidz LMU and Prof Pickl Bundeswehr Hochschule Muenchen), who manage the performance, functionality and accessibility with high enthusiasm, personal power and financial resources. But from the total number of RCLs from the beginning a few RCL labs were turned off on purpose:- a few RCLs were too simple (robot in a maze, hot wire, toll system as students projects) and two RCLs were unsafe for these host institutions (radioactivity, Rutherford scattering). But none of them were turned off because of our chosen technology, interfacing, programming or using open source software.

Now about 10-15 RCLs are online and functional, which are described in this book. It is our purpose to demonstrate by examples the advantages and the potential of RCLs. Therefore it is enough for us that a sufficient number of RCLs are online to read the book.

Recommendation at the end: When we investigated the world wide status of RCLs available, we found, that most RCLs died with the end of the producing project; i.e. 2-4 years. In our long term project (2001-2018) it happened that old partners/colleagues left university, that space for RCLs was not available anymore, that supervising personal changed etc. A pure generation problem but not because of the RCLs itself. So if a pool of RCLs may be set up in the future in a country or nation wide by a European funded project it must be guaranteed from the beginning that long term supervision is performed by long term institutions like teacher training institutions, educational industries or special research institutions at universities and will host this pool.

In the beginning of the translation of the German version of this book into English a colleague of mine – Prof. G. Torzo, Physics Department of the university of Padua was enormous helpful. Thank you Giacomo!

Munich, July 2018

H.J. Jodl

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# 1 Introduction

## 1.1 Position of the experiment in physics lessons

Physics, especially physics teaching, lives on experiment and experimentation. There has been extensive literature on this subject since 1960 [eg. 1-3]. In this technical literature, various categories of experiments are defined and repeatedly reinvented (teacher-, pupil-, demonstration-, thought experiment, low cost simple experiments, etc.), the pedagogical utility is repeatedly identified and updated by new word creations, practical objectives (abilities / skills) are differentiated, etc. It is undisputed, but also boring, to work on this topic, since every 10 years every generation change is continually reinventing new names and labels.

In all variants of curricula since the 1950s, these experiments on secondary level II are listed more or less detailed. About 300 experiments are in lists, relatively few important ones are added (e.g., experiments on chaos, quantum optics or university experiments are adapted). This demand is opposed to products from the teaching industry (Leybold, Phywe, Pasco etc.). When a sufficient amount of money was spent on education (until the early 1990s), a physics teacher could assume that practically all the necessary equipment was available for conducting experiments in the school collection - about 1000 for secondary school level I (age of 10-16) and about 300 experiments for secondary school level II (age of 17-19).

It is relatively easy to reach a consensus among those affected persons (teachers, didactics, planners of curricula, seminar- and training-teachers) that of these about 300 experiments are only about 50 essential; essential in the sense that theoretical hypotheses are proven experimentally (e.g. charge quantization with the Millikan experiment), that new measurement techniques are mediated (e.g. fast laser diodes in the measurement of the speed of light), that references to new techniques / processes / new materials in economy and in everyday life are performed (e.g. carbon fiber for sports articles and for car bodies), etc. Why, however, are these so-called essential experiments

Table 1.1: Survey of the feasibility of experiments by physics teachers (specified in %).

	Speed of light by Foucault method	Millikan experiment	Cavendish experiment	Coulomb experiment (Schürholz)
Experiment performed				
several times	40	30	60	50
as a trail	25	20	30	40
never	35	50	10	10
never performed				
because of lack of equipment	90	70	95	50
topic was not enough treated	5	10	2	10
other experiments	5	20	3	40

for the secondary level II so rarely performed? And what are the alternatives for this?

A survey of physics teachers on 83 gymnasia in Rheinland Pfalz on the feasibility of the Mainz study level (carried out in 1978, published in 1984) showed that the four essential experiments listed in Table 1.1 had never been carried out because devices were missing [4].

A recent survey conducted in 2007 [5] at gymnasium schools in Rheinland Pfalz, completed by physics chairmen, shows the following picture: At nine schools surveyed the following essential experiments are missing or are defective:

- Gravitational constant determination (4 schools),
- Compton effect (7),
- Electron diffraction (4),
- Measurement of the speed of light with light pulses (7),
- Michelson Interferometer (5),
- Rutherford scattering (6),
- Resonance absorption of the Na-D line (5),
- Spectra of  $\alpha$ ,  $\beta$  radiation (6).

Conclusion: Even if these interviews were time-spatially locally and with a small sample size, it was clear that these essential experiments could not be carried out at half of the schools.

Further reasons -why these essential (about 50) experiments are not carried out according to physics teachers participating teacher training courses - are:

- Devices are missing or defective.
- To setup the experiment is too time-consuming and too difficult for the teacher.
- The experiment does not provide a satisfactory number and quality of measured values during one school lesson.
- Commercial apparatus too expensive.
- Radioactive sources or other components (laser, filters, etc.) are not available.
- Excessive measuring times for a required series of measurements relative to one school lesson.
- Lack of student participation during the experimentation.
- Darken the room and other safety precautions.
- From the physical and mathematical point of view, the measurement data analysis and / or modeling are too demanding.

If one of these experiments fail, what remains to the physics teacher?

- simply to pass this experiment,
- only to discuss the presentation in the schoolbook,
- only to explain the theory or the model.

Since the 1970s there have been a rich variety of multimedia such as films (FWU, IWF, collection of 700 films by the University of Vienna), animations, simulations and IBEs (interactive screen experiments).

An IBE is defined as follows: In the case of a real experiment, technical parameters are systematically varied and the experiment, and in

particular, the measured values are photographed. Consider a well-known example: the polarization of light should be shown with the help of an experiment. For this purpose, the light of a light source is viewed through two angle-adjustable polarization filters (polarizer P and analyzer A). Each adjustable angle of P and A results in a digital photograph of the experiment. When the so-preserved experiment is reproduced, the user can interactively change the position of P and / or A with the mouse, and at the same time the corresponding experimental result, i.e. the intensity of the light viewed through the polarizers, is presented to him as a screen photo. IBEs can be produced by means of different techniques, allowing, for example, to switch on a device, to enlarge representation of details, quasi-continuous changes of one or more parameters, etc. The advantage of IBEs is that it is a real experiment, which can be played interactively, and no internet is needed; the disadvantage is that a once-produced set of measured values, i.e. photographs of the real experiment, is always only reproduced. In the meantime, there are a large number of IBEs for the school as well as for the standard lecture -Introduction into Physics at Universities [6-11].

Films about experiments have fallen into oblivion. In general, the equipment for demonstration is missing (16 mm, Super 8, VHS) and / or the ability to operate it. There are, however, absolutely excellent products [12-14].

Animations and simulations have been produced since the emergence of PCs (several thousands to all areas). There exist highly evaluated collections by different groups (operators of educational servers, school book publishers, training institutes). The problem for the physics teacher is to quickly find a good multimedia product as a substitute for the real experiment, where to look for and what is a good product? To our knowledge the following institution has an outstanding international collection which is evaluated and periodically updated. MPTL -Multimedia for Physics Teaching and Learning has existed since 1996 and organizes annual workshops in various locations [15]. One of the aims of the workshops is to collect, assess, provide and disseminate all multi-media to different parts of physics (mechanics, heat, optics, electrodynamics, atomic physics, quantum physics, solid state and nuclear physics) worldwide as well as to recommend excellent material. Over the years the collections of the individual areas are being modernized. The interested teacher can find everything on the website of MPTL -

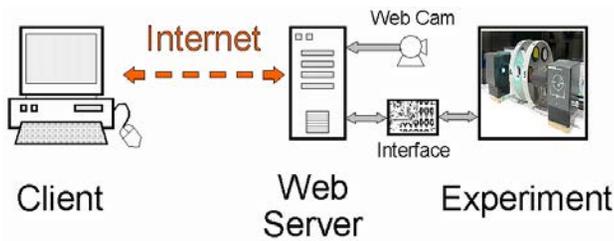


Figure 1.1: Simplified scheme of a real experiment operated on distance via the internet.

the collection of the media with links, the evaluation criteria and the recommendations [15]. Among these roughly a thousand multi-media are excellent materials. It depends on the instructor, on the real experiment to be replaced, or on the learning group whether he chooses a simulation.

Since some 15 years there have been available RCL experiments (remotely controlled labs) as a possible alternative; a real experiment at location A can be remote controlled by the user / experimenter at location B over the Internet.

## 1.2 RCL experiment

We want to present the idea, the concept, the tasks and characteristics, the collection, the added value, the experience and the evaluation of RCLs in detail. The idea of using an experiment remotely has long been known in research and technology: Such as Mars explorer, robots for the investigation of inaccessible tubes in the primary cooling circuit of nuclear power plants, space telescopes, electron microscopes etc.

About 15 years ago this application was developed by several groups for training and teaching. We speak of web-experiment, e-labs, automat-labs, RCLs. In contrast to these RCL experiments, virtual labs were also developed and successfully used; especially in the field of engineering courses. A real process or an instrument - an oscilloscope or the control panel of a nuclear power station - is photo-realistic imitated and offered for interactive experimentation (switch on/off an oscilloscope, monitoring a signal, vary x-y axis, etc.); but there are no real-time changes to real technical components but simulations.

We have designed our RCLs so that the user can not only experiment from a distance, but

- to increase and deep the use of modern communication techniques and the use of the internet for teaching / learning purposes,
- distance learning, self-studies become more interesting and more demanding; away from paper-based materials to multi-medial applications,
- that the need for real and real-time experiments is recognized with respect to simulations or digitally stored experiments, and
- that the young generation learns the possibilities of the internet in the course of the training in a playful way.

RCL experiments must be designed and offered in the internet in such a way that the following requirements are fulfilled:

- An RCL must be interactive, i.e. the experimenter should be able to vary all the essential parameters of the specific experiment; the more the better.
- An RCL must be authentic, i.e. the user must be able to track via webcam if a technical parameter is changed.
- An RCL must be intuitive to operate, i.e. the use of an RCL via the internet must be clear and self-explaining; the user should not be forced to read other manuals first.
- An RCL must be realistic, i.e. the experimenter must receive his own measured values via the internet for further analysis or further processing with his own tools.
- An RCL must be autonomous, i.e. the presentation of a special experiment must be so extensive / detailed that the user does not have to read any further texts / textbooks / special books.

- An RCL must be robust, i.e. the experiment and the internet connection must ensure continuous operation (24 hours) for months.
- An RCL must be free of charge and without hurdles, i.e. the use of the RCL must be free of charge, must be published in a common language (German, English) and must be independent of a specific operating system on the user side.
- An RCL must cover a suitable topic, i.e. not every experiment is suitable as RCL (see later).
- An RCL is all the better, the more flexible it is to serve different user levels, i.e. the RCL experiment should be useful for different target groups; which means that texts and presentations are adapted to different levels of the target group.

In addition to these tasks, RCLs must have the following characteristics; both - requirements and properties - requires rules in programming, standardization and design of the corresponding websites:

- RCLs must be easily accessible and operable via the internet using common browsers.
- RCLs should support deepened learning and allow for flexible experimentation (individual measurements as well as measurement series).
- The didactic material accompanying an RCL must meet the standards of text books, should include multi-media (appropriate matching simulation), allow for a dedicated learning path, and include tests and controls.
- The use of RCLs is intended to prepare for real lab-work, among other things.
- Experimenting with RCLs can be of irreplaceable importance to learners with disabilities.

In Chapter 2 - Basics - we will show how we have implemented these requirements and properties technically and have been developing them since 2001. In addition, the implementation of a real experiment as RCL must guarantee an added value which, of course, is above all experiment-specific:

- RCLs may appear to the user as virtual, but are actually real experiments, in contrast to simulations.
- In contrast to traditional demonstration experiments, learners can also experiment independently with RCLs.
- One can experiment with RCLs regardless of time or location.
- The RCL diffraction and interference II offers 5 different laser wavelengths.
- The RCL photoelectric effect is equipped with five frequency filters and five gray filters.
- The RCL Millikan allows to experiment in groups in order to collect and evaluate a sufficiently large number of measurements (statistics with many droplets).
- The RCL radioactivity allows safe experimentation even over long periods in time.
- The RCL Rutherford can run along with a large scattering angle (about an hour); in addition, two scattering foils (Au, Al) can be used without having to interrupt the vacuum.

Our working group in Kaiserslautern was sure to be able to build and offer such RCLs among the first groups; but we were not the only ones. Over the years, we have regularly researched activities around the world, most recently with the following results (as of 2010/11):

- We found 335 RCLs.
- 64% of these RCLs deal with technical issues such as control and electronics; 36% are assigned to physics (mechanics 25%, electrodynamics 25%, instruments 20%, other topics 30%).
- Most RCLs were worked out in projects which unfortunately disappeared with the project end.

We evaluated these 335 RCL according to certain self-created criteria, the result was disappointing. Our goal was to recognize what is a good / bad RCL? What is the standing of our RCLs in comparison to these others? What can we learn from this offer? (For details see chapter 2). If you want to take a picture by yourself, you will find the link collection in the accompanying material. What was immediately

noticed in these investigations is that not every physical subject is suitable to be realized as RCL: whether it is a simple pendulum, which is normally presented as a free-hand experiment, or a measuring device (to the Compton effect), which can only be switched on, in order subsequently to carry out an automatic measurement. That is, when selecting topics, the following should be considered:

- What is the position of this experiment in the curriculum (not just thematic)?
- What kind of learning / understanding difficulties does the student have?
- How simple / complex is the real experiment to be performed?
- Which interactions as RCL are useful to be offered?
- How fast is a data processing possible?
- How robust is the real experiment and its PC control?
- How much is the maintenance?
- Is the additional work justified to realize the experiment as an RCL?
- What kind of media can be used?

As mentioned, some pendula are found in the internet as RCL. We believe that this experiment is better demonstrated by the teacher himself. If, however, the location dependence of the earth attraction force is to be measured itself, this is only possible with great effort. This is the reason why our world pendula are offered (see chapter 10).

Of course, a new medium - here RCL experiments - opens up new forms of teaching and learning:

- Experimental homework for individuals or groups.
- Experimentation with RCLs allows the student to carry out the experiment independently of location and time, with a self-determined duration and intensity.
- A well designed RCL experiment makes it possible to design and carry out an own measuring program according to the individual questions to this experiment.

- RCL experiments enrich self-study, the distance learning, blended learning, tutorials, etc.
- RCL as an experiment in an experimental lecture by students.
- RCL as one station in an extended learning circle.
- RCL as a means of examining the physical understanding as a counter-pole to mathematical overloaded tests.

### 1.3 Educational policy aspect

Why RCLs were invented and designed at the beginning of year 2000, why not earlier (or later)? Because at that time the suited technology became practically available, as was the fast network connection for the transmission of webcam images, also at schools and in private households.

Both the student in his everyday life as well as the modern workplace, regardless of professions (academic, engineering professions, craftsmen, administration professions, etc.), is now surrounded by all forms of ICT (information communication technology)

1. Smartphones for communication including numerous apps, PlayStation for entertainment, iPods for music, iPads for books / movies, GPS systems for travel, Google and Wikipedia for information search, YouTube for videos, Facebook for social networks, etc.
2. Design tools for architects to develop 3-D house plans, programs for warehouse management of a pharmacist, interface in the vehicle factory for the function testing of cars, management of milk production of cows, transactions on the stock exchange in microseconds, etc.; actually, no profession anymore without specific PC applications.

However, the technology in the entire school sector has not been kept in the least possible way with these economically driven technical developments in everyday life and professional life. This applies not only to the technical equipment in school classes in comparison to pupils rooms at home, as well as to the readiness of all parties involved (teachers, instructors, curricula, publishers, teaching staff) to integrate ICT and respective apparatus in education; to integrate this not

only in a separate subject (computer science, informatics) but in all subjects where it makes sense. (The authors have been using PCs in education and training since 1970 and know very well the school situation, Europe-wide).

We are convinced that the use of RCLs in physics teaching can be an enormous enrichment in several respects: RCLs are not just a one-to-one replacement for real experiments. In this way the student will be presented with additional useful ICT applications as a supplement to the game mode of his own electronic devices. This provides a building block for the adequate preparation for the professional life in the 21st century with ubiquitous computer use.

This enrichment is shown for each of the RCL experiments presented in Chapters 3 to 13 with a section on didactic material and suggestions for use in the classroom. There, the interested teacher will find a variety of suggestions for using the RCLs.

In summary, we have answered the question in this introductory chapter, why RCL experiments in modern physics teaching. In the following chapter 2 - Basics - we will describe in more detail how we have implemented these general aspects (eg requirements and characteristics of RCLs) specifically, conceptually, technically, academically and organizationally.

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## 2 Basics

First, we will briefly describe what we learned from our global research on the state of RCLs for improving our own RCLs. We then explain more specifically our approach and the technical implementation of the question as to what requirements and characteristics an RCL must meet in our opinion; we describe the concept of the navigation menu of our RCLs and our RCL-Portal. Finally, we highlight the educational potential of RCLs and describe the media possibilities of RCLs.

### 2.1 What is a good RCL?

In the past 10 years we have been researching systematically several times for RCLs worldwide. The result of our research is offered as a link collection in our web portal. In addition, there are metadata for each RCL (country, author, topic, ...) as well as an evaluation of each RCL according to ten criteria such as usability at schools, presence of a standard learning environment, access and registration, technical development. With this collection we describe the actual situation and give interested parties the opportunity to quickly make their own picture.

In addition to simply capturing information on RCLs, we wanted to learn how to define "what is a good RCL?", to create assessment criteria, also to evaluate our 20 RCLs and provide recommendations on good RCLs and best practice examples. As an example, Table 2.1 shows proportionately the existence of various criteria for RCLs (for details, see Thesis by S. Gröber [1]).

For these 335 RCLs, we only found an existing website at 178 RCLs (that is, 53%). Of all RCLs, only 91 RCLs (27%) the hyperlink is working, which we found mostly only in publications. We add additional quality features such as language, unrestricted users, no booking required, no additional software like LabVIEW required by users, no registration required, status display available (i.e. display of availability of the RCL, e.g. free, busy or malfunction), only 17 RCLs remain of all 335 RCLs, which are our RCLs. This confirms the high quality of our

Table 2.1: Proportion of RCLs meeting certain quality criteria ( $N = 335$ ) [1].

Status display available										✓	✓
No registration/login									✓		✓
No additional software JRE / long charging time								✓			✓
No additional software LabVIEW							✓				✓
No booking						✓					✓
Unlimited users					✓						✓
Link quick to find				✓							✓
Laboratory site at least in English			✓								✓
Hyperlink works		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Webpage exists	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
RCLs	178	91	90	86	73	71	59	55	45	33	17
RCLs in %	53	27	27	25	22	21	18	16	13	10	5

RCLs and shows that we can count the RCLs, described in this book, in a worldwide comparison to the good RCLs.

In addition to the RCLs described here, we can recommend some 40 RCLs as best practice examples - see publication of the three working groups:

- A Spanish group offers RCLs and virtual labs for engineering education [2, 3].
- A Dutch group has several RCLs as part of a physics lab-course [4, 5].
- A Czech group has designed around 30 RCLs to replace the demonstration experiments of the beginner physics lecture [6, 7].

The corresponding literature [8-10] contains a large number of overview articles, especially in engineering sciences (controlling, robotics):

- Remote Labs in Teaching and Learning (2005).
- The development of online experiments (2004).
- Web based distance education courses (2000).
- Remote access for instrumental analysis for distance education in science (2005).
- Integrated e-learning (2009).

In conclusion, we would like a pragmatic answer to the question "What is a good RCL?":

- If the RCL is called up and experimented more than 1000 times a year, i.e. 3-10 times a day. This number is to be read as a description of the status of supply / demand in a customer-oriented manner; these numbers should be compared with other numbers; for example, a real experiment is presented in a basic or advanced course once a year only.
- An RCL is good if it meets certain evaluation criteria (see above).
- Our tracking / monitoring of user behavior (see later and chapter 14) clearly shows how a user handles the corresponding RCL; whether he just calls the RCL or whether he is experimenting systematically.

Of course, over the years, we've learned from others as well as from our RCLs, which we think must be improved in the design of additional RCLs:

- Good RCLs must be technically reliable and accessible via the Internet, practically round the clock. This requires appropriate control and maintenance. From our experience, an availability of 80-90% can be achieved with relatively little effort.
- Standardization in any direction makes easier the users use of RCLs as well as for the author the RCL development and its design. This applies to the user the interface to the content and to the laboratory, and to the author the interface between the

hardware of the experiment (actuators, etc.) and the computer control (microcontroller interface, etc.).

- Link RCLs with appropriate simulations or videos to achieve a higher level of integrated e-learning.
- The material in the web pages for the same RCL experiment must be designed in such a way that it satisfies the requirements of different target groups (primary, sec I, sec II, university), which means different levels should be offered.

## 2.2 Our concept in detail

First, we describe how we have technically implemented the requirements for an RCL and the characteristics of an RCL: An RCL should be authentic, interactive, realistic, autonomous, robust and free of charge. It is intended to implement an RCL-appropriate topic, respond flexibly to different levels, be easily accessible (independent of user-oriented computer hardware, operating system, browsers) and, if possible, build on free and / or open source software. In addition, an RCL is to allow deepened experimentation and learning, as well as provide the user with didactic material.

In chapter 1 we write in the introduction - an RCL must be authentic; i.e. if a user / experimenter change a technical parameter, he / she must be able to monitor this change and the resulting behaviour of the experiment via the webcam. For example, when measuring the speed of light, the experimenter can vary the distance between the light source and the detector. If he presses the button to reduce / enlarge the distance, he can see a car with a mirror moving via the laboratory camera. On a scale on the wall, he sees the current distance displayed in meters over the same camera. In this way, the user can select the distance to exactly one quarter of a meter. Finally, the user receives this distance as a numerical value via the web page on the computer with an accuracy required for a meaningful measurement of the speed of light. A second camera shows the screen of an oscilloscope: the reference pulse (which defines the time  $t = 0$ ) as well as the reflected propagating time pulse, which moves away from the reference pulse or towards it depending on whether the distance between light source / detector is increased or decreased. Our goal was to fully illustrate the experiment and its operation; where two webcams are enough.

None of our 20 RCLs actually needs more than two webcams to guarantee this kind of authenticity, although it is now technically possible to address several webcams and transmit their video images simultaneously in real time.

The following is a brief listing of other RCLs with two webcams and the respective parameters that can be varied by the user as well as the aspects that can be viewed via the webcam:

- Diffraction and interference II
  - Experimental setup (choice of laser etc.),
  - Intensity pattern on screen.
- Semiconductor characteristics
  - Experimental setup (choice of electronic components, multi meter display of voltage or current, etc.),
  - Oscilloscope screen.
- Radioactivity
  - Experimental setup (choice of source etc.),
  - Display of events on the counter.

In addition, a short listing of RCLs with one webcam, but several viewing angles and the respective user-controllable parameters as well as the webcam-viewable aspects:

- Photoelectric effect
  - Switch on the lamp (the light reflex is recognizable),
  - Turn the wheel with five frequency filters,
  - Turn the wheel with greyscale filters,
  - Read the multi meter.
- Rutherford scattering
  - Choice of films,
  - Selection of angle between source and detector,
  - Display of counted events on detector.
- Wind tunnel
  - Choice of one car to be bypassed from three possibilities,
  - Switch the air flow on / off (observe the thread),
  - Read the wind speed meter,
  - Read the digital multi meter (i.e. measure the force).

We were able to use this technique to close a little bit the gap between "experimenting from a distance" and "experimenting on the

spot". Numerous participants from summer camps, summer schools or trainings have confirmed this.

An RCL must be interactive, i.e. the experimenter should be able to vary all essential parameters of the experiment; the more the better. For example, in the RCL experiment radioactivity, the experimenter can first select the radioactive source ( $\alpha$ -,  $\beta$ -,  $\gamma$ - radiator, an empty tube to measure background radiation) by rotating the source wheel. Next, he can select an absorber of desired material type and thickness from approximately 150 samples by positioning the sample wheel appropriately. Furthermore, the user can adjust the distance of the detector from the previously selected source (2 cm-30 cm) as well as the angle of the detector to the beam direction (0 to +/- 45 degrees). If he wants to investigate the deflection of the rays ( $\alpha$ ,  $\beta$ ,  $\gamma$ ) by a magnetic field, he can turn on an electromagnet and select the direction of the magnetic field via the current direction. Depending on the signal strength (i.e. counting events at the detector), he selects the measuring interval (0 to 300 s). Overall, the RCL offers the experimenter six different activities and thus access to the full range of parameters of the real experiment. The experimenter sees what he is doing with two webcams.

As a further example of interactivity, the RCL diffraction and interference II will shortly be summarized:

- Select a wavelength from five laser diodes.
- Select a diffraction object of 150.
- Adjust the optical set up in the initial position, i.e. reset all movable technical components.
- Select one observation method to measure diffraction pattern (only visual observation, screenshot, reading via ruler, light sensor).
- Record many series of measurements such as light intensity as a function of the slit width, slit distance, number of slits, wavelength.
- Save the measurement result (screenshot of intensity pattern on screen, quantitative measurement with movable detector as measured data table or graph).

Here, too, all activities are reproduced as in the real experiment and made visible via webcams.

In RCL electron diffraction as another example, the experimenter can:

- Switch on the glow cathode,
- Select the acceleration voltage (less than 5 kV),
- Read the ring radii of the diffraction pattern on a scale,
- Record the measurement series and
- Save the measurement results (screenshot of the diffraction tube).

This example shows that the corresponding real experiment does not offer any more experimental possibilities.

An RCL must be intuitive to operate, i.e. the laboratory page of the RCL, via which the experimenter operates the RCL, must be easy to survey and be limited to the essentials only. As an example, the RCL measurement of the speed of light is used. Here, the experimenter selects the distance between the signal source and the mirror by means of two buttons for increasing or decreasing the distance. If he wants to adjust the amplitudes of the two signals - reference signal and propagation signal - on the oscilloscope screen, which is necessary for technical reasons, he can move two different diaphragms in or out of the light beam path. For example, in the RCL Millikan, he first selects and then activates the voltage across the capacitor; to produce oil droplets, he presses the corresponding button, which actuates a valve at the atomizer; If the experimenter has observed a falling oil droplet when looking through the microscope, he can let the oil drop rise again by about ten scale intervals by applying the voltage; when the capacitor voltage is switched off, the oil drop starts to fall again.

Each of our RCLs is technically designed in such a way that the user can experiment intuitively like in the real experiment (without the danger of breaking something!).

When experimenting with our RCLs, the experimenter gets his or her own measurement data in various ways (i.e. an RCL must be realistic): either as raw data in the form of a table, as a screenshot or graphic, for example, of an intensity distribution, or as on an instrumental display the number of counts at the detector made visible by a

webcam, etc. We think an RCL shall deliver only raw data, like when experimenting with a real experiment. On the other hand, a subsequent automatic data processing in the form of prefabricated graphics, as for example with LabVIEW, should be avoided, applied at least as carefully as possible. As in the real experiment, the experimenter, in spite of remote control, is to be as close to reality as possible and to practice the related skills; i.e. with his tools familiar to him, he will continue to analyse his raw data and present them graphically. However, as an aid, we offer in the navigation menu of each RCL a section evaluation where we present and evaluate our experimental data as an example. In this way, the experimenter can at least classify his own measurement data and results and carry out a plausibility check.

An RCL experiment should be autonomous. We have realized this in such a way that, in an experiment where the theoretical background is absolutely necessary (e.g. Rutherford scattering), we introduce a detailed theoretical chapter (the interested experimenter can follow the derivation of the Rutherford scattering formula step by step). For subjects that do not necessarily belong to the canon of physics teaching such as wind tunnel, optical computer tomography, optical Fourier Transformation, we have prepared the text as a tutorial for self-study.

An RCL must be robust. A teacher must be able to rely on the fact that the corresponding RCL is virtually (at all times) available as a replacement for his real experiment. Fig. 2.1 shows that our 20 RCLs were 80-90% technically functional and accessible via the internet over a longer period (2006-2011).

This requires a sophisticated technology for the design and technical implementation of the RCL. Furthermore, regular operator control of the RCLs by the project operator is necessary, as well as regular maintenance and care. As mentioned at the beginning, 90% of RCLs researched by us worldwide suffer exactly this: If the project of the builder of an RCL is finished, this maintenance ends. Of the remaining requirements for RCLs and properties of RCLs (see Chapter 1), we will address only two other aspects: cost-freeness to the user and independence of additional tools on the user side, such as LabVIEW. We believe that this multi medial offer of RCLs must be free, without registration / login in the sense of free education. Therefore, our technology is designed so that one can access the RCL with all common browsers. Also the reproduction of RCLs is facilitated for schools, for example, because our concept is based on open source.

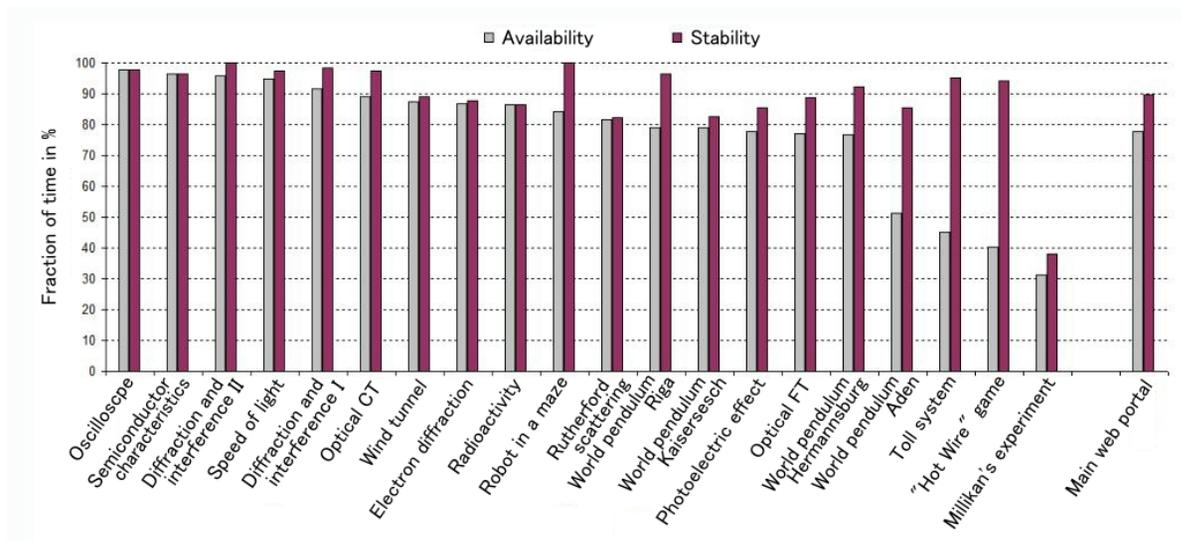


Figure 2.1: Availability and stability of our RCLs for the period 2006-2011.

A development process can be identified in the technical implementation of our concept. Figure 1.1 in Chapter 1 shows the basic structure of an RCL; in addition to the real experiment, the connection to the internet is realized via an interface and a web server. In the first generation of RCLs (2001, e.g. electron diffraction), we used commercial equipment from the teaching materials industry as well as additional commercial interface technology. Advantage: direct use of device with digital input / output. Disadvantage: much too expensive (1000 € additional costs). In the second generation of RCLs (2005) we used Fischertechnik. Advantage: Cost-effective, immediately usable. Disadvantage: the interface allowed few control parameters / functions to be addressed and was slow and of low resolution / accuracy in the data acquisition; in addition, the mechanical experimental setup was maintenance-intensive. Since 2006, we have been using a self-developed and self-programmable microcontroller-based interface in the third generation. Advantage: material costs less than 100 Euro, very flexible in control / function, depending on requirements high absolute and / or temporal resolution and accuracy. Disadvantage: After years of continuous operation, an electronic component can break down. Service / maintenance / replacement are usually only possible by a specialist. The project co-worker Dr. M. Vetter, who introduced this technique, wrote a tutorial for self-construction with a 16-year-

Table 2.2: Structure and content of the standard learning environment of the RCLs.

Website	Content
Entry	Motivation to conduct the experiment, classification of the experiment into a large context, learning contents and objectives of the experiment
Set up	Description of the setup and specification of experimental data
Theory	Physical knowledge to understand and perform the experiment
Tasks	Qualitative and quantitative tasks for experimentation with the RCL
Laboratory	Experimenting with the RCL
Evaluation	Exemplary measuring results and their analysis (usually with error discussion)
Discussion	Deepening questions and tasks concerning the contents of the websites set up, the ory.etc
Material	Information on the experimental material (device names and descriptions, companion manuals, reference sources), didactic material (teaching units, collection of tasks, media), literature and links
Support	Information about the responsibility of the RCL

old student (see RCL Portal, under the section "About the Project", a link "Self-construction"). In chapter 14, we will take a closer look at these details on interface technology.

In our worldwide research, we also found various variants with regard to interface technology:

- LabVIEW,
- Interface similar to our building block, called ISES [11],
- Local single solutions.

The websites of our RCLs follow a uniform pattern and thus offer a standard learning environment. The content and concept are developed in accordance with lab-experiments, which have proved their worth in generations of physics teaching. The navigation menu therefore reflects the structure of a lab- experiment: entry, set up, theory, tasks, laboratory, evaluation, discussion, material and support (see Table 2.2).

Depending on the subject of one of our RCL experiments, these nine points together comprise 10 - 50 pages, on average 15 pages. In particular for the support of teachers, we offer didactic material in the menu Material: starting with worksheets for the RCL experiment, a didactic analysis of the RCL (goal, content, method), teaching units, up to very elaborate task collections with worked out solutions. In some RCL



Figure 2.2: RCL portal home page.

experiments, such as the RCL optical CT or the RCL wind tunnel- topics aside the regular curriculum-, we have written tutorials in the theory section for self-study.

To the booking system (details can be found in chapter 14): In the case of teacher training, the practice-oriented question arises repeatedly, what happens when another experimenter makes use of the RCL experiment, but one would like to experiment by oneself; or, if the RCL experiment will be scheduled for a lesson (weekday, hour x). Nowadays there are lots of booking systems (e.g. hotel reservations) on the market. We have designed, tested and integrated a tailor-made reservation system - designed in the sense that it is only designed for our purposes – implemented in the RCL photoelectric effect. We want to gain experience with this and we want to connect the tracking / monitoring system; e.g. we examine in detail how a user experiments (see Chapter 14). The current use of our portal (30,000 users per year, in 2013) and of individual RCLs (some 1000 per year, i.e. 3-10 users per day) is still so low that a booking system does not appear necessary; but we are prepared.

Finally, we will describe the structure and contents of our RCL portal [12].

Using flags, the user can choose between different languages (Figure 2.2). The web pages of the RCLs are organized in a modular

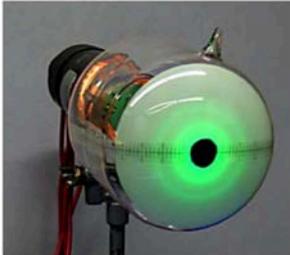
**Remotely Controlled Laboratories - RCLs**  
 experimenting from a distance

Home RCL-Project **RCLs** Technical Notes Contact Legal Notice

**RCLs**

- Electron Diffraction
- Millikan's Experiment
- Optical Computed Tomography
- Speed of Light
- World Pendulum
- Oscilloscope
- Photoelectrical Effect
- Semiconductor Characteristics
- Wind Tunnel
- Optical Fourier-Transformation
- Diffraction and Interference I
- Diffraction and Interference II

**Electron Diffraction**



Observe the diffraction of electrons on a graphite film  
 Location: [University of German armed forces Munich](#), Germany  
 Launch: 2002  
 Translation German-English: B. Eckert, [University of Technology Kaiserslautern](#)

Figure 2.3: RCL experiments with preview.

manner, allowing flexible and independent interpretation of different languages. Currently our RCLs are available in the following languages:

- German (20 RCLs),
- English (20 RCLs),
- French (3 RCLs),
- Italian (7 RCLs),
- Arabic (4 RCLs).

The portal shows the emblems of the main sponsors of our RCL project.

A menu bar contains the sub-items:

- Home,
- RCL project,
- RCLs,

- Technical notes,
- Contact.

The menu item RCL Project includes:

- Information about the project,
- Publications,
- Evaluation,
- Self-construction,
- Teaching courses,
- Partners / sponsors.

The menu item RCLs gives access to the RCL experiments. In addition, the user receives information about the access to the RCLs, the access modalities of the RCLs, the operational readiness of the RCLs and / or operational interruptions due to repair or maintenance and the language version of RCLs. If the user moves with the mouse over one of the links to the RCLs, a preview of the RCL, the location of the RCL as well as an indication since when the RCL is publicly available on the internet are displayed (Fig.2.3.)

Under the menu item *Technical Notes*, the user can find the following important informations about the necessary system requirements:

1. For some RCLs, certain ports must be enabled by the user for the web pages and for transmitting the web-cam images.
2. Information about supported browsers.

Under the menu item *Contact*, the user can find a contact person for questions about the technology, the functioning of the experiment, etc., as well as the obligatory information on contact and responsibility.

## 2.3 RCL as a multi medial medium

### 2.3.1 Practical Lab-training objectives

In the previous section, we explained how to implement the requirement - an RCL must be interactive. In some examples, we have described that there are several interactions that are specific to each RCL. In our RCLs, the respective real experiment is depicted as closely as possible by the remote variant. Each interaction is technically implemented as pressing a button of the website. Well, what are the practical goals behind the push of a button, which triggers an action on the real experiment?

- Selection and positioning of sources,
- Selection and positioning of a sample from a pool of samples,
- Variations in technical parameters such as angle, distance, time interval, number of scans, etc.,
- Measure and read the measured value,
- Choice of measurement error / accuracy,
- Reorienting an experimental set-up etc.

As can be seen, this covers a range of learning objectives that can be achieved by operating the experiment: targeted action, a theoretical and practical analysis of the experiment, clarity about the aim of the experiment and the interpretation of the results etc. By showing the experiment very authentically by means of the RCL, the stated objectives are identical with those of the real experiment in the lab. Only haptic and fine motor aspects of the activity at the experiment come too short in the RCL.

It is therefore more a question of selecting suitable RCL experiments and a complete set of RCL experiments in order to cover as far as possible all the practical learning objectives well known in literature.

Comparing the lab-page of some of our RCL experiments (chapters 3 to 13), one can easily recognize that all these interactions are very experiment specific. In our opinion, an RCL is inadequate, if there is

only one on / off button and posses fewer interactions than the real experiment. In this case, the experimenter feels intuitively that the PC takes over or even takes away the independent experimenting.

### 2.3.2 Forms of dealing with an RCL

Unlike the real experiment, where the teacher observes the student while experimenting, the user / pupil can handle the RCL: at different levels at home.

- Look briefly,  
i.e. he calls up the preview of an RCL in the portal. For example, the electron diffraction; he recognizes that one can deduce a microscopic value from the ring diameters (lattice constant or wavelength).
- Browse RCL pages,  
i.e. he calls up the RCL experiment - electron diffraction - and scrolls through the navigation menu. He recognizes no complicated theory, results are convincing, etc. Similar to scrolling in the textbook, he gets an overview.
- Playfully experimenting,  
i.e. he calls up the lab page and familiarizes himself with the possibilities offered. What happens when he presses a button (he chooses a voltage and sees how the ring diameter changes, maybe he wants to break the tube by entering 100 kV)
- Qualitative experimentation,  
i.e. he selects a small, medium and high voltage and recognizes that the ring diameter changes noticeably in the scattering pattern. But how to determine the diameter of a ring with a diffuse ring-width? He begins to be interested.
- Quantitative experimentation,  
i.e. now the student wants to know if he can succeed to detect a measurement series (voltage versus ring diameter) and how he can determine the error. The user systematically varies, according to his / her considerations, various parameters, takes measured values, and then evaluates them.

- Subsequent evaluation,

i.e. he must get involved in the theory; he must understand the scattering geometry for the evaluation; he has to think about what he really wants (question of his miniature research):if he starts with the lattice constant of graphite and determines the wavelength of the electrons or vice versa.

This scenario is one of many. It is important that this student always comes back to the RCL experiment and feels unobserved. The coronation is, however, if he motivates classmates (in his class or somewhere in the internet) to experiment with him and exchange results / insights.

The teacher will deal with an RCL experiment differently than the student. In addition, it depends on the planned teaching / learning form. In all cases, however, it is of paramount interest to how a user handles an RCL. Our monitoring system allows us to analyse user behaviour as such when accessing an RCL by logging all interactions, such as varying parameters and capturing measured values. In this way, it is possible to determine whether the user is playfully, randomly or systematically acting. Also the overall experiment duration of a user allows conclusions about the user behaviour. In Chapter 14, we revisit our findings from this monitoring. For example, the analysis of this user behaviour provides important information on the following questions:

- How good is the RCL?
- What does the author of an RCL learn for the concrete conception of an RCL (for example: what does it mean, if the majority of users leave the RCL at the same place)?
- Comparison of on-site experimentation with remote experimenting;
- Behave male / female students possibly differently? (They do it!)

### 2.3.3 Usage in class

In our opinion, there are a variety of ways to integrate RCLs into physics teaching. Since the use of an RCL depends on concrete teaching, more general considerations are allowed at this point.

- RCL experiments as homework:
  - RCL as an occasion for the formation of hypotheses (e.g. electron as a wave),
  - RCL for practicing experimental skills (e.g. dealing with the oscilloscope),
  - RCL as a continuation of the teacher's qualitative entrance experiment,
  - Cooperative measuring with RCL in groups (e.g. many measurements at RCL Millikan for statistical evaluations),
  - Presentation of the experiment or a specific method in front of the class,
  - Teacher introduces the RCL to prepare the experimental homework.
- RCL as a substitute for unavailable demonstration experiments.
- RCL as a mobile experiment in an experimental lecture by pupils.
- RCL as a mean of entering a subject area through several partial experiments on various questions (e.g. radioactivity).
- RCL as a mean to enter a topic by means of qualitative, exploratory, research-oriented experimentation (e.g. diffraction and interference).
- RCL use in blended learning scenarios.
  - Exercise theoretical methods in class and exercise experimental methods at home by experimenting from a distance.
  - Lectures on campus, RCL-Labs off campus.
- RCL as a central experiment of a teaching project.
- RCL as one station in a learning circle.

- RCL as a means of testing physical comprehension, with the experiment being in the focus. Namely, does the student know what he is doing in experimentation.
- RCL as a demonstration experiment in a student presentation.
- Self-study!
  - Support interested and talented pupils in the independent elaboration of topics outside the canon,
  - Comprehensive work (carrying out measurements with RCLs, self-assembly of an RCL or parts of it).

(This complex can be read in detail at S. Gröber [1] in conjunction with examples and with own experience reports).

### 2.3.4 Collaborative Learning (LMS)

The user / student is isolated in both types of applications - in the experimental homework as in the case of self-study / distance learning – i.e. without immediate supervision. This can be an advantage with excellent pupils, but it can also be disadvantageous, as in the case of less qualified pupils. In our opinion, this trend of isolated, not directly supervised learning is to be countered, especially since appropriate tools for LMS (Learning Management Systems) are commercially available: e-communication between learners and between learners and tutors must be planned and organized. This direction calls for a range of new technologies such as interactive whiteboard, chats, video conferencing. LMS tools allow the teacher to create and manage virtual classes. Especially in mass subjects, in engineering sciences and in universities with distance learning courses, there are already initial approaches. In chapter 2.1, we have listed a number of best practice examples of RCL in class. Some of these groups use RCLs offered in their LMS:

- Network of web-based labs for control engineering education [13],
- LMS to organize a student lab in physics [14],
- Remote experiments in engineering education by integrated e-learning [15].

This is a vision. In our opinion, in the next few years there will not be much change in real education with real pupils. Increasing, but

slowly progressing, teachers offer online support even outside of lessons.

After these introductions (chapter 1) - Why RCLs? - And basics (chapter 2) - What is a good RCL? How can it be used? - We will present approximately 10 RCL experiments in detail in the following chapters 3 to 13. Together with other good RCLs from other working groups, some 40 RCLs which we can recommend, the interested teacher has enough RCLs to use the approximately 50 essential experiments of the approximately 300 ones of the upper secondary II level in the remote version.

## 2.4 Literature

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## 3 Speed of light

In this and the following chapters, we will present nine RCLs on physics in detail according to a uniform pattern:

- Introduction (selection, justification, classification ...)
- Experiment and RCL variant,
- Evaluation and experience,
- Didactic material.

The experiments on which these RCLs are based belong to the approximately 30 most important demonstration experiments at the upper secondary level. Then we will briefly present about 2-4 RCLs for motivation, which are thematically related to Science and Technology. These can be attributed to the level of both lower secondary I (age 14-16) and upper secondary II (age 17-19) and can be worked out methodically as a project.

### 3.1 Introduction

The measurement of the speed of light is important in pure physics, in physics lessons and in everyday life.

The easiest method to determine is the time of flight method. We begin with a comparison: the sound velocity is about 330 m / s, the light velocity is about 300000000 m / s. When a thunderstorm approaches, we can see how far away the centre is: We see the lightning flash,  $t = 10$  s later it thunders, which means  $s = v \cdot t = 330 \text{ m / s} \cdot 10$  s about 3 km away. This estimate is based on the time of flight method: We produce an extremely short light pulse (duration approx. 20 ns), which we send about 10-20 m (typical classroom) and register it later with a detector. How much later?  $t = s / c = 0,1 \mu\text{s}$ . Galileo has already applied this time of flight method; since he had no short light pulses, he had to use very long propagating distances (see later didactic materials, teaching unit, Galilei Discorsi).

Table 3.1: Selected values of the speed of light from some historically important experiments [1].

Year	Experimenter / Author	Method	$c$ in km/s
Astronomical			
1676	Rømer	Motion of Jovian satellite Io	214000 +/- ?
1726	Bradley	Aberration of light from stars	301000 +/- ?
Terrestrial			
1849	Fizeau	Rotating cogwheel	315000 +/- ?
1862	Foucault	Rotating mirror	298000 +/- 500
1882	Newcomb	Rotating mirror	299810 +/- 30
1926	Michelson	Rotating prism	299796 +/- 4
1940	Hüttel	Kerr cell	299768 +/- 10
1947	Essen and Gordon-Smith	Microwave cavity resonance	299792 +/- 3
1951	Aslakson	Radar technique	299794,2 +/- 1,4
1951	Bergstrand	Modulated light	299793,1 +/- 0,4
1951	Froome	Microwave interferometer	299729,6 + 0,7
1956	Rank et al.	Optical spectroscopy	299791,9 +/- 2
1972	Evenson et al., National Bureau of Standards	Cat hair diode, He-Ne laser	299792,4562 +/- 0,011
Since 1983	Conférence Générale des Poids et Mesures	Definition of the meter	299792.458 exact

Table 3.2: Comparison of experiments for the determination of the speed of light according to the time of flight method [3].

	Year	Light source	Pulse generation	Time measurement (time)	Distance measurement (distance)	c value (measuring error)
Galilei	About 1620	Lantern	Shadowing of the light source by hand	Quality comparison (not measurable)	? (several miles)	not measurable
Rømer	1676	Sun / Jovian moon	Shielding the moon by means of Jupiter	Clock (about 22 min)	astronomical (AE of about 280,000,000 km)	214300 km/s (approx 30 %)
Fizeau	1849		Gearwheel with 720 teeth	speed of the gear wheel (about 12.5/s) (about 50 $\mu$ s)	geodetic (8,333 km)	315364 km/s (approx 5 %)
Foucault	1850		Rotating mirror	via speed of rotating mirror (about 440/s) and spot size of light (max. 5 mm) (about 100-200 ns)	Tape measure (approx. 20 m)	298000km/s (approx 0.5 %)
Light pulse		High power LED	Pulsed high power LED	via oscilloscope with reference signal (approx. 20-100 ns) tape measure (approx. 15 m)		

Table 3.3: Advantages and disadvantages of school experiments for determining the speed of light [3].

school experiment with ...	preparatory work	necessary space	measurement series	measurement of time	target group	measurement error
mechanical rotating mirror method according to Foucault [4, 5]	high (because of a lot of mechanics and time-consuming adjustment of the beam path)	high (by limited rotational speed of the rotating mirror)	no (because adjustment effort is too great and changes are too small)	indirectly (with poorly measurable deflection of the light spot to a few millimetres)	Sec II (because knowledge in mechanics is necessary)	Approx. 20%
optoelectronic measurement of phase shift of modulated light signals [6, 7]	low	low (by high modulation frequencies)	yes	indirectly	Sec II (because knowledge of wave theory is necessary)	Approx 5%
optoelectronic measurement of the propagation time of light pulses [8]	medium (because of little mechanics and simple aligning of the beam)	high (because of the width of the light pulses)	yes	direct (with well-observable signals)	Sec.I and. Sec II (because speed determination is direct)	

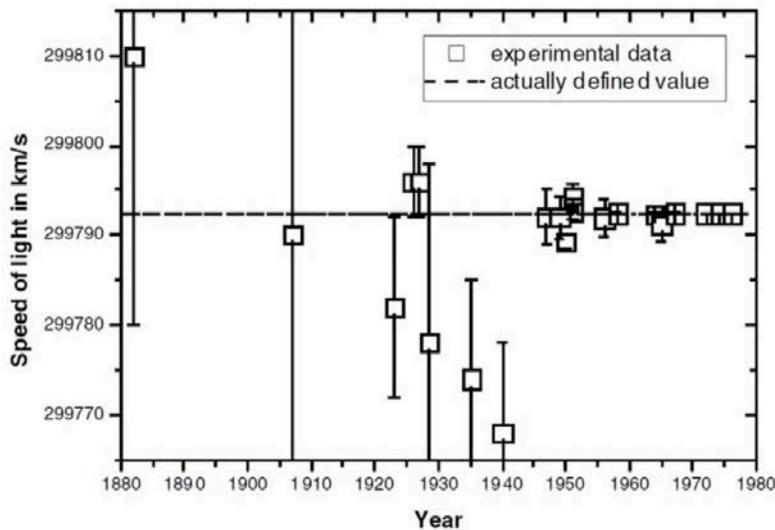


Figure 3.1: Temporal development of the measuring accuracy in the determination of the light velocity between 1880 and 1980 [2].

The finiteness of the light velocity must be taken into account when determining the position using GPS (Global Positioning System); this is based on a time of flight measurement of satellite signals

In pure physics the observation of neutrinos (2011) - sent by the CERN, registered at the Gran Sasso - which are to move with super-light speed, has caused a stir in science and in media. Post-studies in 2012 clearly demonstrated a measurement error, so that Albert Einstein's world is still in order.

Table 3.1 and 3.2 contain an overview of historically important experiments, Figure 3.1 shows the temporal development of the measurement accuracy of the light velocity between 1880-1980. Here are some facts and phenomena that highlight the importance of light velocity in physics and metrology:

- Defined value of  $c = 299792,458 \text{ km / s}$  to define the basic unit of a meter,
- Uniform propagation velocity of electromagnetic waves in vacuum,

- Limit velocity, and independent quantity with respect to motion in special relativity theory,
- Size for determining distances and positions in small (nanometers) as in the large (astronomical) scale,
- Measurement that places high demands on a time measurement; related to it the development of a frequency standard (keyword atomic clock),
- As a fundamental constant in the laws of physics.

For these two reasons (importance in everyday life and in physics), it is a must to actually carry out one of the well-known measurement methods offered for teaching physics in the classroom. (See corresponding curricula of all federal states)

Table 3.3 contains the three common methods and clearly highlights advantages and disadvantages. Because of the clear advantages, we chose the optoelectronic method as an RCL variant.

For various reasons, however, these well-known experiments by the teaching industry are hardly carried out in real education, as two surveys show:

1. Physics teachers at around 100 high schools in Rhineland-Palatinate answer the question "why they do not measure the speed of light according to Foucault": devices are missing (90%), subject too short (5%), other experiments (5%). The question "I consider this experiment to be simple, difficult, not reasonable" from the experimental point of view, was answered as follows: simple (15%), difficult (65%), not reasonable (20%) [9].
2. In 2009, we asked the following questions at the training courses for physics teachers (27 answers from 70 respondents): only 45% had at least one light-speed measurement experiment; rotating mirror method 15%, phase modulation method 15%, rotating mirror and phase modulation method 7.5%, optoelectronic time of flight method 7.5%. In addition, the rotating mirror method is described as very complex in the adjustment and with a small measurement result; the phase method entails technical effort and an opaque evaluation method [10].

If this experiment is essential in physics teaching and is practically never carried out, then this experiment is predestined as an RCL-experiment, as other media such as simulations do not make sense.

## 3.2 Experiment and RCL variant

The optoelectronic time of flight method is a pure velocity measurement: Both the propagation distance  $2s$  for a short light pulse and the propagation time difference  $t$  between the reference signal (which starts quasi clock at  $t = 0$ ) and the propagating signal are measured here.

### 3.2.1 Experimental setup and function

Figure 3.2 shows the experimental setup of the RCL on the basis of the school experiment by Leybold [8]. The operation of the experiments is as follows:

A fast high-power LED (1) emits short, approximately 20 ns light pulses with a repetition rate of 40 kHz, a wavelength of 615 nm and comparatively high light intensity. The semi-transparent mirror (3) splits each light pulse into a reference pulse and a propagating pulse. The reference pulses are reflected by themselves on a small triple mirror (4), pass through the semi-transparent mirror and reach the receiver diode (7). Propagating pulses are reflected by themselves on a second large triple mirror (6), which allows a simple adjustment of the radiation beam, and also reaches the receiver diode by reflection at the beam splitter. In order to achieve a large range for the propagating pulses, an approximately parallel light bundle is produced with the 200 mm focal length lens (5) from the propagating light pulses. Since the light paths for the divided pulses within the light-speed measuring device (2) are the same, only the propagation distance  $2s$  contributes to the difference in propagation time between the reference and propagating pulses.

The difference in the propagation time can be measured with an oscilloscope (8) in two-channel mode: on the one channel a 10 MHz signal (period duration  $T = 100$  ns) of the light speed measuring device serves as a calibrated time reference; and on the other channel the reference signal and the delayed propagating signal are displayed, so that the propagation time difference can be read directly.

The school experiment was modified as follows:

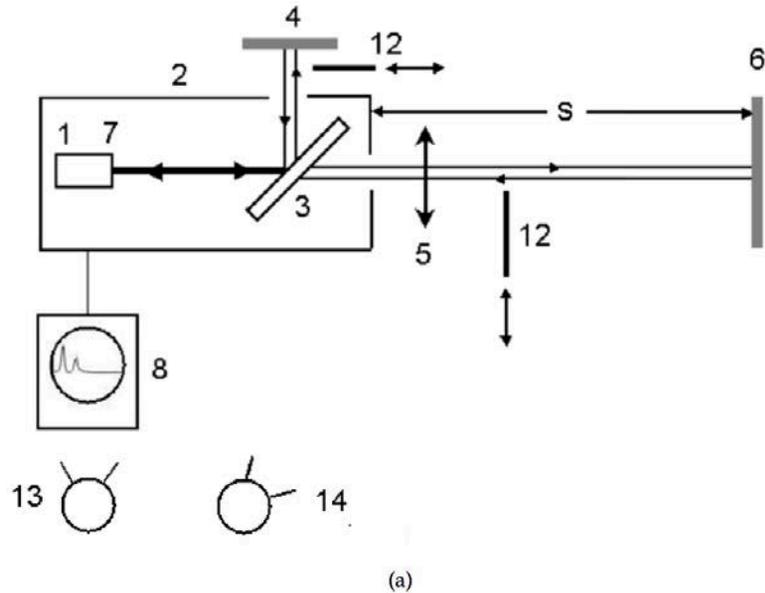


Figure 3.2: Experiment setup of the RCL as a modified school experiment.

- The large triple mirror (6) was mounted on an electrically operated toy train (9). This allows the propagating distance  $2s$  to be varied between approximately 9 m and 22 m in the premises at the RCL location. The movement of the toy train along the rails is transmitted to a spoke wheel (10) by a cord, and the distance  $s$  is measured via the relative movement of the toy train with a light barrier (11).
- For technical reasons, the propagation time difference between the reference and the propagating pulse is correct only,

if the amplitudes of both signals are the same [8]. In order to enable the user to adjust the signal heights, remote-controllable diaphragms were positioned with stepping motors in the light path of the reference and the propagating pulse (12).

- An interface is connected between the web server and the experiment. The microcontroller contained in the RCL allows a range calibration at the site, processes the data streams from the light barrier and to the stepping motors, controls the toy train and switches the oscilloscope on and off. When the lab is started, the interface automatically switches on the oscilloscope and the illumination of the experiment and, after prolonged non-use, also switches it off again.
- A webcam (13) allows the transmission of the oscilloscope screen, a second webcam (14) shows the experimental setup in total view.

### 3.2.2 Navigation menu

If you call this RCL, the navigation menu will appear on the left side, which has the same appearance for all RCLs. In the menu point *Setup*, the user / experimenter can read the experimental setup and its function again. The menu item *Theory* contains the measuring principle as well as the meaning of the measurement of the speed of light. Our philosophy in the development of RCLs was to make it self-sufficient in such a way that the user can acquire the theory without having to consult other specialist books. In the menu point *Tasks*, we usually ask questions about the theory, the experiment and the measurement (see Table 3.4). In the menu point *Lab*, the user sees webcam images in the centre as well as the control panel of the experiment on the right. Through the webcam images (position of the toy train with the reflector mirror as well as the oscilloscope), the user / experimenter sees authentically, if he / she varies a technical parameter. In addition, the technical control system must be able to be operated intuitively as operator panels of the laboratory side (and the underlying technology).

Table 3.4: Tasks.

1. Preparatory tasks for measuring the speed of light
  - a) Check that the propagating distance of the light pulses displayed in the control panel of the laboratory is approximately the same as in the video image of the whole view.
  - b) Observe and explain the change of the measured signals when moving the locomotive.
  - c) Check whether a difference in the amplitude of the reference signal and the propagating signal has an effect on the distance between the two signals. What must be considered when determining the time difference between the two signals?
2. Measurement of light velocity
3. Estimate the accuracy of the time measurement. How should you proceed to determine as exact as possible the time difference between the two signals?
4. Determine the light velocity from a pair of measured values.
5. Determine the light velocity by recording a series of measurements. How do you evaluate these measurements meaningfully? What are the advantages here compared to a single measurement?
6. The position of the reflecting mirror on the carriage can be calibrated to approx. 1 cm. Compare the error of the distance measurement with that of the time measurement

The experimenter is able to acquire his own measured values, consciously as raw data, which he is supposed to process further according to his own ideas. Of course, the experiment must always be robustly operable 24 hours a day. In the navigation menu, the menu item *Evaluation* is displayed. We do not want to take the trouble of measurement and evaluation from the user / experimenter. Rather, we offer here a few sample values, so that the experimenter can classify his own measured values. Here three distances (at 7 m, 9, 5 m as well as 14, 7 m). The user can evaluate his measured values qualitatively or quantitatively. We use the tool pixel profile to evaluate the screenshots of the oscilloscope, and to determine the propagation time. Subsequently, in a table 10 measurements at different mirror positions are listed, evaluated and displayed in a diagram - propagation distance  $2s$  versus propagation time  $t$ . A consideration of the measurement error of the time and position measurements round this sub-point evaluation.

Table 3.5: Discussion.

1. Experimental set up
  - a) Discuss the operating frequency of the oscilloscope (resolution of time measurement).
  - b) Construct the complete beam path between the transmitting diode, the receiving diode, fixed and movable mirrors.
  - c) How do transmitting and receiving diodes work?
  - d) What is the speed of a man standing on the ground of the rotating earth?
2. Theory
  - a) What is "one light year"? Consider the definition of the speed of light.
  - b) Is it possible to slow down light?
  - c) How fast does light propagate in diamond (refractive index  $n = 2,4$ ,  $c = c_0/n$  with light speed  $c_0$  in vacuum)?
  - d) Is it possible to move with a velocity larger than speed of light?
  - e) Why does it still make sense today to precisely determine the speed of light?
3. Laboratory
  - a) Why is it not possible to determine the speed of light with any smaller distances?
4. Evaluation
  - a) Compare your measurement result with the fixed value of the speed of light in vacuum.
  - b) Discuss the measurement errors (size, cause).

The following menu point *Discussion* usually contains questions on the experimental set up, the theory of the laboratory, and the evaluation (see Table 3.5). The last menu item *Material* contains both technical information about the experimental equipment (in general the manuals of the relevant equipment manufacturers) as well as didactic material such as

- Proposals for a teaching unit,
- Our publication on this RCL,

- Didactic analysis of the topic,
- Possible worksheet for pupils (see next subsection).

### 3.2.3 Operating the experiment

If the user / experimenter calls up the lab page and logs on, the experiment is automatically switched on (Fig 3.3); the user sees two webcam images. A webcam image shows the position of the toy railway with the triple mirror and along the railway line a large scale of distance (5 m - 11 m). The other webcam image shows - after switching on the oscilloscope - the oscilloscope with the 10 MHz signal as a time reference, as well as the reference signal and the propagating signal. In the upper right-hand side of the panel, the user also sees a countdown timer that informs him how much time in seconds it remains to change a technical parameter. After expiration of the countdown timer, it is assumed that the user no longer actively experiments and therefore automatically logs off from the lab page. By using the control buttons *Reflector distance s* can be *reduced* or *increased*, the experimenter can change the distance  $s$  self-explanatory. At the same time, the user can track the movement of the train in the video image, can roughly read off the distance  $s$  in the scale on the wall and can observe the changing distance between the reference and the propagating signal on the oscilloscope screen. When the experimenter presses button *stop train/measure distance s*, the toy train stops and the distance  $s$  of the triple mirror, measured across the spoked wheel and the light barrier, is displayed in the lab page. In general, the height of the propagating signal is smaller than of the reference signal (why?). In this case, the electronics of the teaching tool manufacturer used generates an error in the time interval. In order to avoid this systematic error in the determination of the speed of light, both signals must have the same amplitude (see manufacturer Leybold). As shown in the experimental set-up, one diaphragm can be moved in or out of the beam path of the reference signal or another one of the propagating signal (number 12 in FIG. 3.2.c) independently of one another. The control buttons on the right hand side of the lab page allow the experimenter to move these diaphragms in large or small increments while the experimenter can control changes in the signal amplitudes at the webcam image of the oscilloscope screen at the same time.

## Remotely Controlled Laboratories - RCLs

experimenting from a distance

**Speed of Light Laboratory**

Remaining time to perform experiment: 134 s

Decrease distance  $s$  of reflector    Increase distance  $s$  of reflector

Stop train - measure distance  $s$  of reflector

$s = \text{-- mm}$

Open ----- diaphragm for reference signal ----- Close

<<<   <<   <   >   >>   >>>

Open ----- diaphragm for measurement signal ----- Close

<<<   <<   <   >   >>   >>>

Open both diaphragms

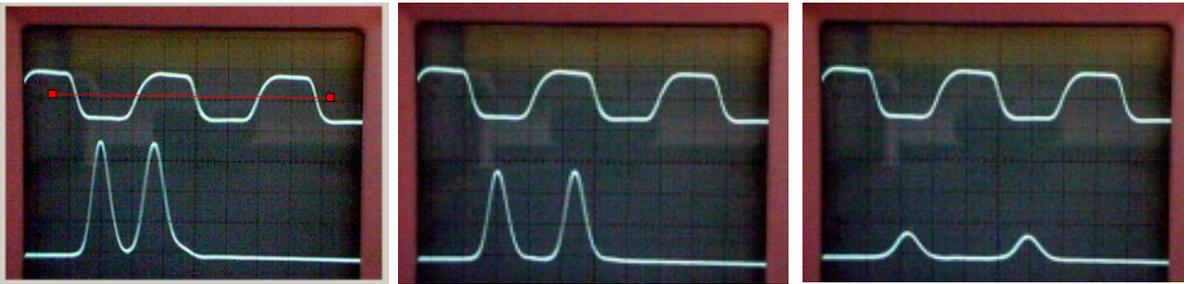
Oscilloscope and lighting of the room are starting after movement of the locomotive.  
Clock frequency of rectangular signal:  $f = 10 \text{ MHz}$ .

Oscilloscope screenshot

Figure 3.3: Laboratory page of the experiment with experiment menu (left), webcam images (center) and control panel (right).

Which experimental skills / learning goals are behind the mere push of a button? The propagating distance can be varied and measured, the propagating time is determined and the light velocity is then calculated from these data.

- Measure the size (propagation time and distance),
- Save the measured results (screen shots of the oscilloscope screen),
- Record the measurement series (propagation time),
- Position the object (triple mirror),
- Adjust the experiment (light intensity of reference and propagating beam),



(a)

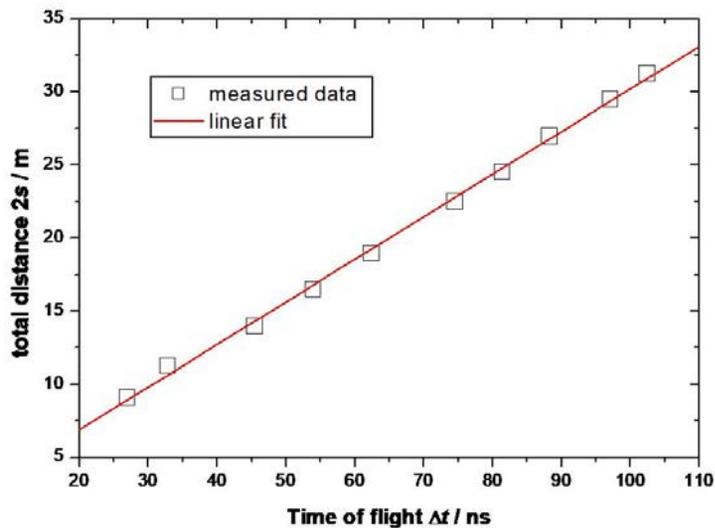


Figure 3.4: Oscilloscope images for different propagation distances  $2s$  of the propagating signals (a), calibration of time axis by means of rectangular signal and (b) result of a 10 minute lasting measurement.

- Observe correlation (propagation distance and distance in time between the two signals).

Overall, the RCL speed of light offers six interactions in experimenting and hardly meets the real-world experiment before class. From our point of view, an RCL is the more valuable the more interactions / variations of technical parameters are possible.

### 3.2.4 Measurement result

In Figure 3.4a, three screenshots of the oscilloscope screen for different propagating distances  $2s$  of the propagating signals and the same amplitude are shown. The experimenter must finally calibrate the time axis of the oscilloscope screen for evaluation. A square wave signal (frequency  $f = 10$  MHz, period duration  $T = 100$  ns) serves as a calibration signal (figure 3.4a above).

In order to evaluate quantitatively, we use an image processing program (e.g. pixel profile): 200 MHz corresponds to 241 pixels, thus 61 pixels correspond to a time difference of 50.62 ns. The associated propagation distance is 15.754 m.

To qualitatively evaluate, we can compare the known bandwidth of the signal of 20 ns with the distance reference to propagating signal; here factor 3.

Figure 3.4b shows a whole series of measurements; from the slope of the regression line we get  $c = 299791$  km / s.

The error of the regression line is - according to the evaluation program - less than 2%. The propagation distance  $2s$  can be precisely calibrated to approx. 1 cm (<1%). The readout error for the time interval of both signals is about 3 pixels, which means 2, 4 ns. The relative error  $\Delta c / c$  is mainly caused by the time measurement and varies between about 9% for the smallest and about 3% for the largest measured distances.

## 3.3 Evaluation and experience

The deviation of the measured value from the defined value in the literature is minimal (<‰); the measurement error is about 5%. For a 10-minute measurement a quite good result. The RCL has been online since 2006; it is maintained at the Department of Physics of the FHS in Heilbronn. Since then, the RCL experiment has been running stable, without repairs, around the clock.

The added value to offer this experiment as an RCL variant is, in our opinion, the following:

- The principle of the experiment is the direct determination of a velocity. The experimental setup is transparent (no knowledge of electronics is required as in the phase method)

and no special formulas need to be derived; therefore, the experiment can be used even in secondary level I.

- The user / experimenter can select different distances from a large range and further process self-measured values.
- Measurement series with different positions of the movable mirror can be recorded in a short time.
- A typical school experiment, which has hitherto been used as a demonstration experiment by the physics teacher, can thus be carried out by the student at his own pace at any time.

The acceptance and quality of an RCL is given when the RCL experiment is used as frequently and in different, specific ways. Each user leaves tracks (IP number and interactions with the experiment) when using the RCL. In the period from December 2008 to December 2009, we evaluated the experimenting behaviour of users of this RCL with the following results:

1. Number of users per day on average 3-5;
2. Actions (change of technical parameters) per minute approximately 5-10;
3. The number of actions per experimental cycle is approximately the same: less than 5 actions, 6-10 actions, 11-20 actions, more than 20 actions;
4. Proportion of users performing all types of interactions is about 60%;
5. Number of users who select only one position of the movable mirror is about 30%, up to 5 positions about 40%, more than 6 positions about 10%.

From these data, we can derive different ways of experimenting with this RCL:

- Qualitative observation and measurement, when the mirror is moving over longer distances.
- Typical single measurement at one mirror position with partial exact adjustment of both signal heights.

- Several times approach the movable mirror at the same position from different starting positions, presumably to increase accuracy.
- User performs measurements by systematically changing mirror positions.
- In extreme cases, very extensive operations up to 230 minutes of experiment duration, with up to 40 positions and 350 actions being carried out.

If the users were about 1500 per year in 2009, it was around 3800 users in 2011; i.e. an average of 11-12 users per day [10]. Is this number to be regarded as small or large? In comparison, per high-school there is offered one advanced physics course in the upper level, where this experiment is estimated to be carried out once a year; in Germany there are about 3100 high-schools in the years 2012/2013.

This means, however, that one can really experimenting with this RCL, as in real case in class, and this experimentation is experiment specific in comparison to the handling of other RCLs.

### 3.4 Didactic material

The RCL speed of light is conceivable in connection with all new teaching / learning forms:

- As an experimental homework,
- Teamwork through distributed measuring and joint data analysis,
- Multi-hour teaching unit,
- Student presentation,
- Reconstruction as project work.

The worksheet in Table 3.6 serves as a stimulus and could accompany the experimental homework in groups.

For a possible lesson in class we formulate the following learning objectives and expect the following learning requirements:

- The pupils should:

- recognize the determination of the speed of light as a measurement-related problem,
  - use the RCL to perform light velocity measurements using the time of flight method,
  - determine as accurately as possible the light velocity from distance-to-time measured value pairs and estimate the measurement error,
  - elaborate further methods of determination (Roemer, Fizeau, Foucault) and present those in the form of a lecture, using suitable materials and knowledge from geometrical optics and mechanics,
  - have an idea of the importance of light velocity in physics.
- The following learning requirements are desirable:
    - Determination of a constant velocity from distance-time measured value pairs,
    - Images or beam paths with lenses,
    - Evaluations of measured data (best fits, linear regression) with spreadsheet program or computer algebraic system
    - Assessment criteria introduced for student presentations.
  - Structure of the teaching unit (see Table 3.7):
    - Galileo's experiment to determine the speed of light,
    - Determination of the speed of light with the RCL,
    - Student's presentation to the historical experiments of this time of flight method to determine  $c$ .
    - Teacher's contribution to the importance of the speed of light.

The teaching unit is divided into a first part for the secondary level I or II and an optional second part for the second level II:

In the first part, the failure of the lantern experiment by Galileo is used to prepare the light velocity determination with the RCL. The measurement-technical problem of determining the speed of light is discussed and the time of flight method is introduced. Recording and evaluation of the measured data depends on the age, learning level and performance of the learners:

- $c$ -value from a distance-time measured value pair,

- Distance-to-time measured value series with analytical (linear regression) or graphical determination (best linear fit) of the light velocity,
- Error estimation via linear regression or with error propagation law,
- Collecting measured values of the entire course with the aid of digital media. For example a Wiki.

The optional second part of the series of courses is much more challenging than the first part. Further determination methods of the speed of light are developed and carried out independently by the pupils using materials. The following overview of experiments for determining the speed of light leads to the topic »Physical significance of the speed of light« of the concluding teacher presentation.

Table 3.8 contains a bibliography for student presentations.

Beyond this teaching unit, the following topics could also be dealt with in student lectures:

- GPS - Global Positioning System (Internet),
- Synchronization of clocks and Special Relativity Theory (specialist books),
- Recent experiments on the retardation of light (see [11-17]),
- Definition of the meter, SI units, metrology (Physical-Technical agency, PTB Braunschweig).

We also have experience with assigning RCLs to students as project work. In a first version, the RCL was set up, programmed, tested and presented to the public at the German Museum in Munich by a group of pupils in the course of a summer camp of the TU Munich within a week (Table 3.9).

Table 3.6: Worksheet

## Worksheet --- Measurement of the speed of light

## 1. Questions:

- How do these short light pulses (20 ns) be generated?
- Why can you not see the path of the propagating light?
- Why is a factor 2 in the final formula:  $c = 2s/t$ ?

2. Measure the time interval  $\Delta t$  at 3 distances, 3 times each.

6.00 m	8.00 m	10.00 m	Group 1
6.20m	8.20 m	10.20 m	Group 2
6.40m	8.40 m	10.40 m	Group 3
6.60m	8.60 m	10.60 m	Group 4
6.80m	8.80 m	10.80 m	Group 5

3. Create a plot distance  $2s$  in m versus time  $t$  in ns.4. Calculate the mean value for  $c$ , as well as the relative error.

## 5. Discussion

- Include the results of all 5 groups in one diagram, including errors.
- Refer to the literature value for  $c$ .
- How fast does light travel in diamond? (Refractive index of Diamond  $n = 2.4$  and  $c = c_0/n$ ).
- Can you slow down the speed of light?

Table 3.7: Lesson "Measurement of Light Speed" (excerpts).

Instructional unit "Determination of the speed of light" with respective RCL	
Phase	Content and working forms
1st chapter	
Introduction and learning organization	<p>Galilei's experiment (material: text from Discorsi)</p> <ul style="list-style-type: none"> <li>• Forms: Teacher tells, students read each for themselves text, student group plays discussion of Salviati, Sagredo and Simplicio.</li> <li>• Carry out the experiment (optional): At night with torches, stopwatches and mobile phone to match the beam directions, experiences with absorption of light</li> <li>• Problem of the experiment or of the light speed determination according to the time-of-flight method: Reaction time of the experimenter, either very long running distances or measurement of extremely short run times (run time for experiment with known value of <math>c</math>)</li> <li>• Pointing out known issues on the topic: questions about possibilities to measure short times, attempts to determine the speed of light, physical analogies to the term "speed of light"</li> </ul> <p>Teacher gives an overview of the learning unit:</p> <ul style="list-style-type: none"> <li>• Contents: experiments for the determination of the speed of light, meaning of the speed of light in physics</li> <li>• Learning opportunities for the students: participation in the plenum, self-instructed experimenting (homework), presentations by students /teachers</li> <li>• Evaluation and learning control: experimental homework, student assignments after certain evaluation grid, test as completion of the learning unit</li> </ul>

	<ul style="list-style-type: none"> <li>Assessment of the teachers' contribution: within the framework of a cooperation between teachers and class, the students should be given the opportunity to attend the quality of the teacher's lecture (no grades).</li> </ul>
Determination of the speed of light with RCL	<p>Introduction of the RCL and measurements with the RCL (material at website):</p> <ul style="list-style-type: none"> <li>Demonstration of laboratory of the RCL by beamer, students suggest operations in order to conduct the remote experiment</li> <li>Students work on through topics of website "Setup" and "Theory"</li> <li>For example, determine the time interval between the pulses in the webcam image with image editing software and calculate <math>c</math> from measured values. Discussion of the causes of measurement errors, estimation of the measurement error according to the fault propagation law, measuring series as homework</li> <li>For more powerful course: teacher shows RCL laboratory without further explanation. Students (groups) use the websites of the RCL to determine the speed of light as homework. Discussion of measurement errors (see above). In a second measurement run, student groups acquire successively data (filling a table in a Wiki, <i>e. g.</i>) and evaluate those data by a linear regression.</li> </ul>
	<p>Definition of the speed of light</p> <ul style="list-style-type: none"> <li>Measurement technology: Position determination with GPS, geophysical measurement of distance, definition of the meter in the framework of SI units</li> <li>Physical significance: electrodynamics (Maxwell - visible light as an electromagnetic wave), special relativity (speed of light as a universal limit)</li> </ul>

Test	Content of the tasks: <ul style="list-style-type: none"><li>• Explanation of a test setup for the determination of the speed of light</li><li>• Evaluation of a series of position-time measurement</li><li>• Derivation of a formula for the determination of speed of light</li><li>• And more</li></ul>
------	--

Table 3.8: Bibliography for students (Internet resources, except \*).

1. Leifi physics: experiments to determine the speed of light. Light velocity determination according to Galilei, Rømer, Fizeau and after the modern time of flight method.
2. Wikipedia: Speed of light. Importance of the speed of light. Determination of the speed of light after Galilei, Rømer, Fizeau and Foucault; Overview about historical measurements of speed of light between 1620 and 1983.
3. Feist, D. (2005): Measurement of light velocity. Special learning performance to determine the speed of light (school project) according to Foucault, according to modern time-of-flight method and according to phase shift of a modulated light signal.
4. Leybold Didactics: Determination of the light velocity according to the rotating mirror method. Operating instructions for the determination of the speed of light by the rotating mirror method after Fizeau and Michelson.
- 5.\* Fraunberger, F. & Teichmann, J. (1984): The Experiment in Physics (in German). Vieweg and Teubner, Braunschweig.  
In chapter "The determination of the speed of light"(p. 189 – 193) the gear wheel method of Fizeau is described in the historical context.
6. Wikipedia: Ole Rømer. Life of Ole Rømer and determination of the speed of light by Rømer.
7. Practical lab-experiment of the University of Stuttgart: Measurement of the speed of light according to Foucault and Michelson. (Exemplary for many similar manuals.)

Table 3. 9: Poster of the summer camp »Speed of Light« 2005.

## Summercamp 2005

### Lichtgeschwindigkeit



Christiane Schneider



Katharina Sewart



Christopher Beck



Max Göllrich

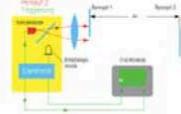
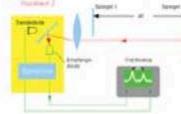
### Mit Spiegel und Zug zur Lichtgeschwindigkeit

300.000  
km/s

Als Lichtgeschwindigkeit „c“ wird die Ausbreitungsgeschwindigkeit des Lichts bezeichnet. Nach genauen Messungen wurde ihr exakter Wert 1983 per Definition auf 299.792.458 m/s festgelegt.

Durch diese Festlegung erhielt der „Meter“ seine heutige Definition: „1 Meter ist die Entfernung, die das Licht in 1/299.792.458 s zurücklegt“

### VERSUCHSAUFBAU

Eine Leuchtdiode sendet sehr kurze Lichtimpulse (40.000 pro Sekunde) aus, sie werden durch einen Strahlenteiler gespalten. Ein Teil wird vom kleinen Tripelspiegel auf eine Empfangsdiode reflektiert; der andere Teil legt den Weg bis zum großen Tripelspiegel zurück, wird dort reflektiert und trifft dann ebenfalls auf die Empfangsdiode.

Bei jedem empfangenen Lichtimpuls sendet die Empfangsdiode ein elektrisches Signal an das Oszilloskop, auf dessen Bildschirm das Signal sichtbar gemacht wird.

Nun kann abgelesen werden, wie lange das Licht für die Strecke zum Zug und zurück braucht.

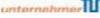
Da der Abstand Messgerät-Zug bekannt ist, kann die Lichtgeschwindigkeit mit Hilfe der Formel „Geschwindigkeit = Weg / Zeit“ ermittelt werden.



Eberhard  
von  
Kaiserheim  
Stiftung



Technische Universität  
München



Management  
Mare

### 3.5 Literature

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# 4 Millikan experiment to determine the charge of an oil droplet

## 4.1 Introduction

The determination of the elementary charge is of great importance in physics as well as in physics teaching. It plays no role in everyday life. Students learn for the first time discrete quantities and their meaning (charge  $Q = n \cdot e$ ;  $n$  - number,  $e$  - elementary charge). One can illustrate the concept - discrete or quantized quantities - in many areas of physics; But this is only important in quantum physics.

There are different variants of the experiment from different teaching aid companies; the measuring principle and, to a certain extent, the experiment itself is based on the classical experimental setup by R. A. Millikan (1909). As early as 1747, Franklin assumed the atomic character of charge  $Q$ . M. Faraday found in the investigation of the electrolysis a regular relationship between the amount of chemically monovalent substance deposited per one mole and the number of particles:  $F = N_A e$  with  $F$  - Faraday constant in C/mol,  $N_A$  - Avogadro constant (Loschmidt Number)  $6 \times 10^{23}$  particles/mole and  $e$  as a hypothetical elementary charge. R.A. Wilson (1903) and J. J. Thomsen (1899) actually invented the measuring principle; however, they used ionized water droplets whereas Millikan had his breakthrough with oil droplets. He determined the elementary charge  $e$  to  $1,6 \times 10^{-19}$  C and discovered the charge quantization.

In the 1980s and 1990s, when the quark model was developed to build mesons and baryons from 2 and 3 quarks respectively, the classic Millikan experiment has once again gained ground in two respects:

1. Have there been indications at Millikan's studies on one-third or two-thirds of the elementary charge?
2. Could the Millikan experiment be improved to observe quarks directly?

The original data from Millikan did not give an indication of a possible partial charge of oil droplets [1], nor were free quarks observed so far. However, what could be observed were, for example, electron-based quasi-particle excitations in a solid state under special conditions with a calculated one third of the elementary charge [2].

If Millikan's experiment is so essential, why is it so rarely done in real lessons? In the context of a master thesis for teachers (about 1978), which we published partly in a different context [3], we asked the physics teachers at about 100 high schools in Rhineland-Palatinate, among other things: "This experiment by Millikan was not carried out by me ., , "

- Since devices are missing (70%),
- This topic has not been dealt with in detail (10%),
- Because other experiments are more important (20%).

"I consider this is an experiment. , , "

- easy (20%),
- difficult (40%),
- can not be reasonably realized (30%).

Although this survey is relatively old, we believe that nothing has changed drastically. However, there are some very nice simulation programs exactly for this (see later).

Reasons why the real experiment is so seldom performed are due both to experimental set up, to implementation as well as to theory. Usually, the Millikan experiment in the classroom produces a series of problems

... to the teacher:

- To set up the experiment in an attractive manner to students with camera and monitor takes a lot of time.
- Although suitable oil is found, one does not know its density. Or the capacitor, especially the inlet opening for droplets, is glued.
- There is no suitable camera to transfer the image of the microscope to the screen for the class.

- The number of measurements that can be carried out in the classroom is too few to make a clear statement about the quantization of the electrical charge.
- Long series of measurements are not possible in some experimental setups because the oil atomizer is easily glued with oil and / or the light source heats up the capacitor chamber and convection currents are produced between the capacitor plates.
- Quality of measurement results is often unsatisfactory; the measurement error is of the order of measured magnitude.
- Only the observer is actively involved in the measuring process.

,,, to the student:

- Calculation of Stokes frictional force (without derivation) is problematic.
- The need for the corrected viscosity  $\eta_{\text{corr}}(r)$  - according to Cunningham - is not immediately apparent.
- First confrontation with the fact of the smallest size and the concept of quantization of physical values in school teaching.

Actually, the measuring principle is simple: if charged oil droplets are placed between two capacitor plates, an electric field is applied, the droplets undergo different forces. Instead of directly determining forces, one measures velocities, respectively times for rising and falling. Since the radius of the observed droplet is not known, it is necessary to measure twice, with and without applied voltage.

## 4.2 Experiment and RCL variant

### 4.2.1 Experimental setup and function

Figure 4.1 shows the simplified principle of the Millikan experiment: Sample chamber between two capacitor plates, oil is atomized and the oil droplets are sprayed into the sample chamber. Illumination from the right, observation of the movement state of the oil droplets with

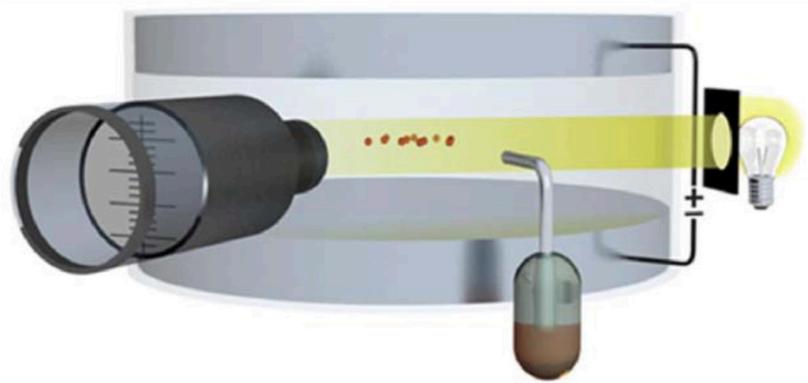


Figure 4.1: Schematic set up of the Millikan experiment [4].

microscope from the left. From a technical point of view, we have modified a commercially available apparatus of Leybold Didactic [5].

The Millikan chamber (1) consisting of a plate capacitor is a central component of the experimental setup (Fig. 4.2 and Fig.4.3) Oil droplets with diameters in the  $\mu\text{m}$  range are generated with the aid of an oil atomizer (2), thereby also being charged indirectly and blown into the Millikan chamber. The necessary air pressure is generated by an air-brush compressor (not shown) and a controllable solenoid valve (installed in 3). In order to not only fall down oil droplets in the Millikan chamber, but also to rise them against the force of gravity, a high-voltage source (in 3) supplies a controllable capacitor voltage between 300 V and 700 V and thus a controllable homogeneous electric field.

To monitor the rising or falling oil droplets, the oil droplets are illuminated laterally by a light source (4). The oil droplets can then be observed by a microscope (5) as bright spots against the dark background at the rear of the Millikan chamber (a kind of dark field illumination). The experimenter can observe the oil droplets shown enlarged in the microscope using a special webcam (6). Individual oil droplets can be focused via a first servomotor (7), and the microscope can also be pivoted laterally via a second servomotor (8).

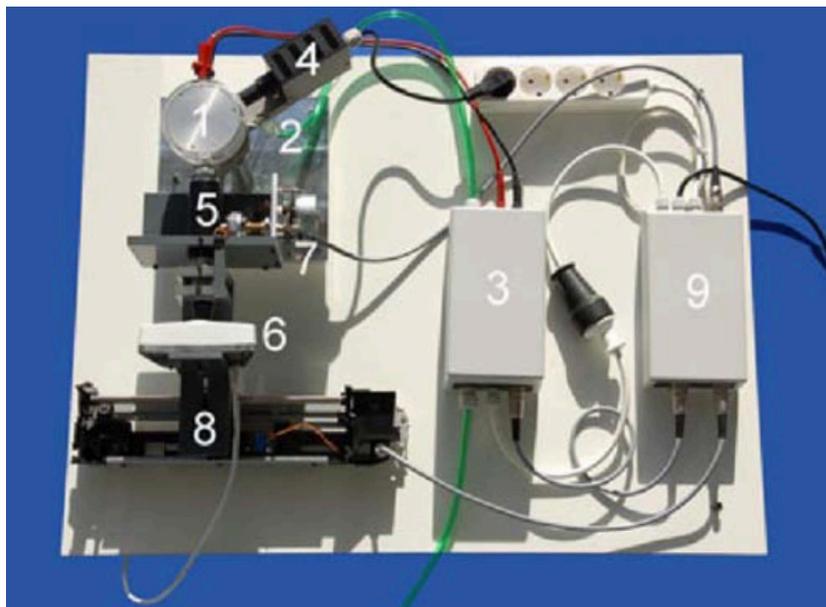


Figure 4.2: Overall view of the experiment setup.

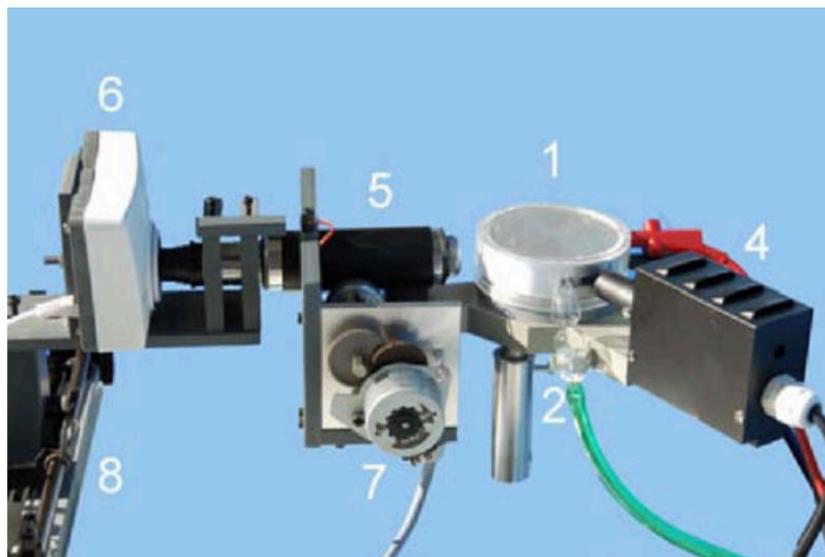


Figure 4.3: Generation and observation of oil droplets.

## 4.2.2 Navigation menu

If one calls this RCL, the navigation menu appears on the left side, which has the same appearance for all RCLs. In the menu point *Set up*, the user / experimenter can read the experiment setup and its function again. In the menu point *Theory*, the user can follow the derivation of the final formula for the charge  $Q$  of an oil droplet step by step (an RCL must be offered in such a way that the user does not have to consult x text books, i.e. it must be autonomous)

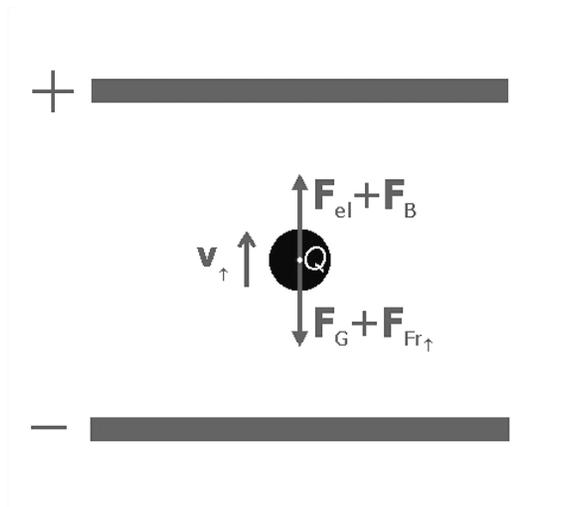
$$Q = \frac{6\pi d}{U} \sqrt{\frac{9\eta_{Air}^3}{2g(\rho_{Oil} - \rho_{Air})}} (v_{fall} + v_{rise}) \sqrt{v_{fall}}$$

(with:  $d$  - distance of the capacitor plates,  $U$  - capacitor voltage,  $\eta$  - viscosity of the air,  $g$  - acceleration due to gravity,  $\rho$  oil density,  $\rho$  density of the air,  $v_{Fall}$  falling velocity without electric field,  $v_{Rise}$  - rising velocity with electrical field). For both cases of a negatively charged droplet - rising and falling - the relevant forces are drawn in Fig. 4.4.

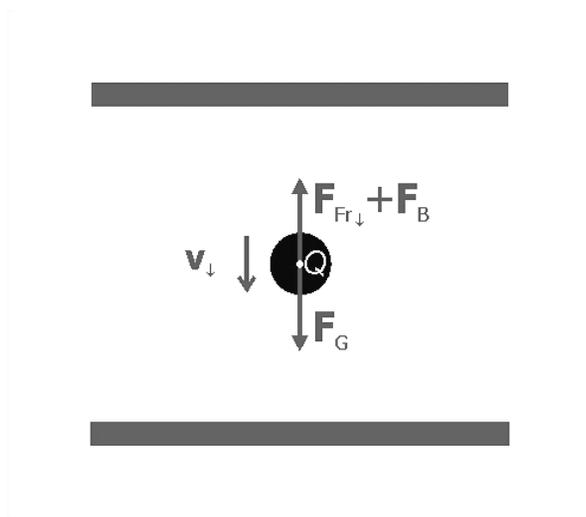
- Weight force  $F_G = m_{oil} \cdot g$ ,
- Buoyancy force  $F_A = \rho_{Air} \cdot V_{oil} \cdot g$ ,
- Electrical force  $F_E = Q \cdot E$ ,
- Stokes frictional force  $F_R = 6\pi\eta r v$ .

The derivation of the velocity-dependent frictional force in the teaching is problematic.

In the didactic material section (see later and also in the navigation menu for the RCL Millikan), we offer a video showing how a glass ball is falling in oil; measured data can be analyzed by means of video analysis and thus the Stokes frictional force can be confirmed as a formula at least.



(a) Forces on the oil droplet during the rising movement.



(b) Forces on the oil droplet during the falling movement.

Figure 4.4: Forces on the oil droplet during the rising and falling movements.

In the final formula for the charge  $Q$ , the viscosity of the air is  $\eta_{\text{Air}}$ . Since the radius of the oil droplets  $r$  is of the order of magnitude of the free wavelength  $\lambda$  of the air molecules, the viscosity  $\eta_{\text{Air}}$  is not a constant quantity but depends on the radius of the oil droplets - Correction according to Cunningham:

$$\eta_{\text{corr}} = \frac{\eta_{\text{Air}}}{1 + \frac{A\lambda}{r}}$$

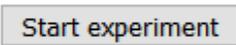
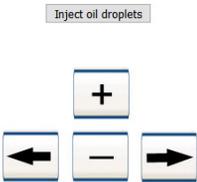
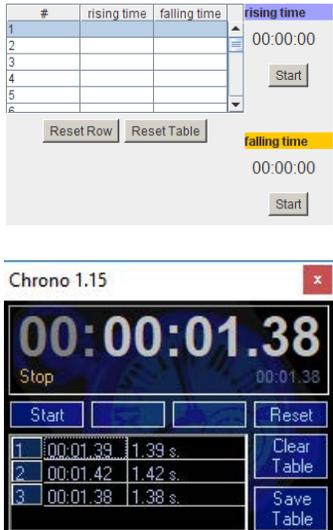
with  $A = 0,864$  an empirical constant for this flow-oil in air;  $\lambda = 9 \cdot 10^{-8}$  m as mean free path length of air molecules under normal conditions. According to our experience, the learner usually has no difficulty with this correction; it makes the evaluation somewhat more complex.

In the next point of the navigation menu *Tasks* we have stored measurement instructions (Table 4.1). For the inexperienced user / experimenter, it is not easy to complete all operating functions in the correct sequence for a quantitative measurement of the rising and falling times of a selected oil droplet. We recommend partnering: one student generates droplets and switches the selected voltage on / off; another student measures and records the rising times, another the falling times.

In the navigation menu *Laboratory*, the user sees the webcam image of the microscope with a scale division and, on the right, the control panel of the experiment. The RCL Millikan is authentic (the user sees oil droplets rising and falling through the microscope), is intuitively operable (select voltage, enter oil droplet, operate microscope, voltage on / off) and provides own measured values.

In the menu point *Evaluation*, all necessary information such as density, viscosity and geometry are given. About 10 oil droplets are observed several times during rising and falling and the corresponding times are measured. Subsequently, all variables such as droplet radius, Cunningham correction, charge of the respective droplet are calculated, inserted in a table and presented in a graph charge / number of the oil droplets.

Table 4.1: Measurement instructions for RCL Millikan's Experiment.

	<p style="text-align: center;"><b>Start experiment</b></p> <ul style="list-style-type: none"> <li>Press the "Start Experiment" button on the lab page.</li> </ul>
	<p style="text-align: center;"><b>Observation of falling oil droplets</b></p> <ul style="list-style-type: none"> <li>To blow in oil droplets into the condenser, press the button "Blow oil droplets" once or several times, wait a few seconds until slow moving droplets gain visibility.</li> <li>Press the "Plus" and "Minus" buttons to focus on certain oil droplets and the "Arrow left" and "Arrow right" buttons to move the microscope in order to observe an oil droplet in front of the micrometer scale.</li> </ul>
	<p style="text-align: center;"><b>Selection of a suitable oil droplet</b></p> <ul style="list-style-type: none"> <li>Check by pressing the "U on / off" button, if the adjusted voltage is sufficient to bring an oil droplet to rise. If not, increase the voltage by selecting a higher value from the drop-down box and by pressing the "Set Voltage U" button. If not successful, choose another oil droplet.</li> <li>For a more accurate time measurement, slowly rising oil droplets are more suitable.</li> </ul> <p style="text-align: center;"><b>Up and down movement of an oil droplet</b></p> <ul style="list-style-type: none"> <li>Move an oil droplet between two markers of the micrometer scale by pressing the "U on / off" button.</li> </ul>
	<p style="text-align: center;"><b>Measurement of time for upward and downward motion with stopwatch</b></p> <ul style="list-style-type: none"> <li>Choose a sufficiently large measuring path in the centre of the image, For example, 5 scale parts.</li> <li>When counting the time, count the number of scale parts too. It does not matter if you start the measurement of rising time or falling time. To do this, press the "<b>Start</b>" button under "rising / falling time" as soon as the oil droplet enters the measuring range and the corresponding "<b>Stop</b>" button as soon as it exits. Outside the measuring range, press the button "<b>U on / off</b>" to bring the oil droplet to the ascending / descending position.</li> <li>Carry out several measurements with the same oil droplet at the same voltage and the same number of scale parts.</li> <li>The measured values can be copied (Ctrl-C) after marking with the mouse and copied into an Excel table (same cell number) (Ctrl-V).</li> <li>Note the set voltage and the number of scale parts.</li> </ul> <p style="text-align: center;"><b>Measurement of climbing and falling time with mobile phone stopwatch</b></p> <ul style="list-style-type: none"> <li>If a mobile phone stopwatch with memory function is used, larger measuring distances than before can be selected, since the mobile phone can be operated with one hand and the button "U on / off" with the other.</li> <li>If a memory function is missing, the measurements can be performed in pairs.</li> </ul>
	<p style="text-align: center;"><b>Initial state</b></p> <ul style="list-style-type: none"> <li>If no oil droplets are visible after the injection, the microscope can be moved to a standard position with the button "Reorient optics".</li> </ul>

The following menu point *Discussion* will contain questions about the experimental set up, the theory and the laboratory (Table 4.2). The last menu point *Materials* contains technical notes on the experimental device (here from Leybold didactics) as well as didactic material such as

- Suggestions for a teaching unit,
- Our publication of these RCLs,
- Didactic analysis,
- Task collection,
- Possible worksheet for students

(See next subsection).

Table 4.2: Discussion.

### 1. Experimental Setup

- a) What changes have to be made in the experimental setup to determine the amount of charge of positively charged oil droplets?
- b) In Millikan's original experiment set-up, a transparent water tank was found between an arc lamp as a light source and the capacitor plates. What should prevent this water tank?
- c) How can an ocular scale be calibrated?
- d) Why do water droplets evaporate faster than oil droplets?
- e) How can the density of a liquid be determined?

### 2. Theory

- a) Why can not the friction force  $F_{\text{friction}}$  be calculated according to the Stokes approach when the particle size is of the order of the mean free path  $\eta_{\text{air}}$  of the molecules of the surrounding medium ( $F_{\text{friction}}(v) \sim \eta_{\text{air}}$ )?
- b) How does viscosity and average free path length in a gas coalesce?
- c) Estimate the duration of the acceleration phase before the force equilibrium is set during the fall or ascending movement.
- d) What is the cause of the quantization of the electric charge? Is this question to be posed at all?

### 3. Laboratory

- a) The oil droplets sometimes cause a lateral drift movement. Where does it come from? Drift movement? Does it have any influence on the measurement result?
- b) Why do you see the oil droplets as bright dots?
- c) Do big drops carry a large charge?
- d) Do fast drops carry a large charge?
- e) How are positively charged oil droplets recognizable?

### 4.2.3 Operating the experiment

If the user / experimenter calls up the menu point *Laboratory*, he sees in the centre the web-cam image of the microscope. If he has registered and the experiment is free to access, the experimenter sees the control panel, clearly structured and intuitive to use (Fig. 4.5).

The first line above shows how many seconds remain until the first technical parameter should be varied: Select and set the voltage; Infiltrate oil droplets; adjust the focus + /- at the microscope, and move it laterally; Voltage on / off; as well as newly align optics. In order to measure the rising / falling times of a selected oil droplet, one can use the stopwatch under the web cam image or use a smart phone with a built-in time measurement function.

The user should first familiarize itself with the control panel, then read the measuring instructions (Table 4.1) thoroughly; as well as organize the group work. It is advisable to select a voltage that is not too low (600 - 700 volts) in order to detect the drift of the droplets immediately. The button *Inject oil droplets* should be pressed 5-10 times; about 10 seconds break in between. At the latest, one should see droplets, otherwise something is wrong (contact with the supervisor). As a rule due to our experience, we do not need to adjust the microscope more precisely; the microscope has a sufficiently large opening angle as well as sufficient depth of sharpness, so that one can usually recognize a whole cloud (5-10 droplets). If you want to adjust the microscope nevertheless, the focus adjustment + /- corresponds to a displacement of the lens by 2-3 mm. You can press the arrows for lateral movement, ← or →, 10 times each, which means a swinging around 3 - 4 degrees (see Fig. 4.2).

When the user / experimenter performs the experiment, i.e. pressing buttons, what are interactivity or experimental learning objectives?

- Oil density, capacitor plate spacing, air viscosity, air density, scale spacing are given.
- Controllable are capacitor voltage, microscope direction, microscope focus, oil droplet production.
- Rising time and falling time are measured.

The screenshot displays the RCL - Remotely Controlled Laboratories portal. The top navigation bar includes links for Home, About RCLs, Labs, Partner, Contact, and Technical Notes. The main content area is titled 'Millikan's experiment' and features a sidebar with navigation options: Introduction, Setup, Theory, Tasks, Lab (selected), Analysis, Discussion, Material, and Support. The central video feed shows the experimental setup. To the right, the 'RCL - Millikan Laboratory' control panel includes a timer showing '87' seconds remaining, a voltage selector set to '500V', an 'apply voltage' button, an 'inject oil droplets' button, and a stopwatch for measuring 'rising time' and 'falling time'. A 'U on / off' button with a high voltage warning symbol is also visible.

Figure 4. 5: Millikan experiment on RCL portal.

- The rising and falling velocity as well as the elementary charge can be determined.

The following actions are performed:

- Turn the system on / off (compressor for injecting the oil).
- Measure dimensions (rising / falling distance, and rising / falling time).
- Save data (rising / falling times with stopwatch tool).
- Set the instrument (the direction and focus of the microscope).
- Record measurement series (several droplets and determine per droplet the rising / falling velocity several times).
- Select the parameter (rising voltage).

- Observe correlation (oil droplet radius and its charge to rising / falling velocity).

As you can see, the RCL offers a whole range of interactions, quite comparable to those in the real experiment in class; i.e. an overall reasonable RCL experiment.

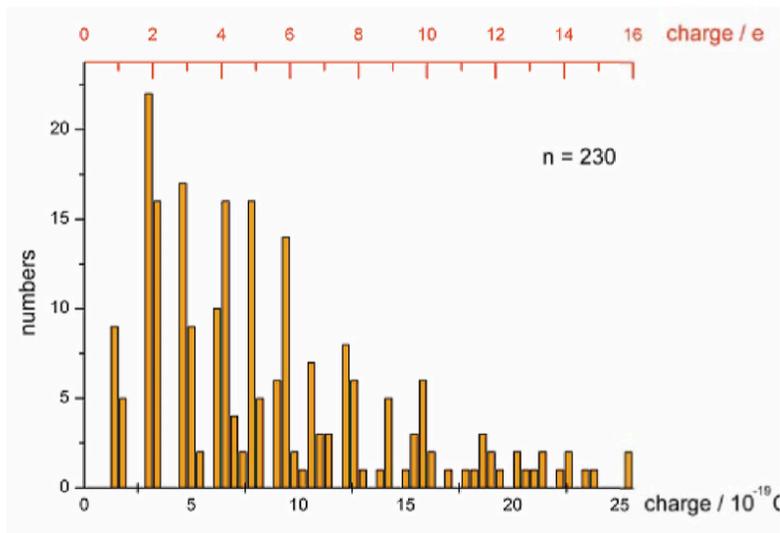
#### 4.2.4 Measurement result

Figure 4.6 contains two long-term measurements ( $n = 230$  and  $n = 90$  droplets). We obtain for the elementary charge  $e = 1,58 \times 10^{-19}$  C; the statistical error  $< \pm 5\%$ ; Literature value  $e = 1,602 \times 10^{-19}$  C). The relative error  $\Delta Q/Q$  is about 11 % and takes into account all predefined parameters as well as measured values. The discretization (quantization) of electrical charges up to  $n = 3 - 4$  can clearly be seen in both measurements.

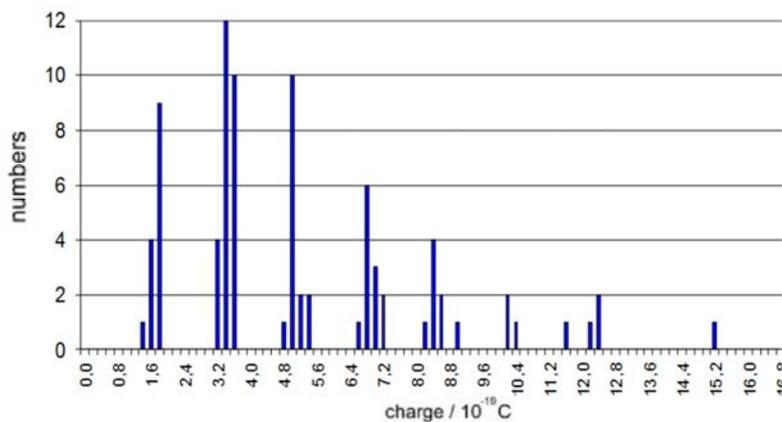
### 4.3 Evaluation and experience

The deviation of our measured value from the literature value  $e$  is approximately 1 %; the measurement error of around 10% is tolerable in such a complex experiment. If the quantization of charges is taken as a measurement target, then about 100 evaluated data sets (more or less droplets) are needed to recognize the discretization. It takes about 1 minute for one droplet and about 10 rising/falling times; for 10 droplets, therefore 10 minutes (trained user). A class of 10 groups provides this result in a tolerable measuring time. The added value offered by Millikan as an RCL consists of the following:

- The user can measure several droplets and each droplet several times to increase the statistical accuracy for falling and rising times.
- The experimenter can perform the RCL experiment in the same way as the on-site experiment in class.
- Several users can enter their individual measurement results (elementary charge  $e$ , as well as  $Q = n \cdot e$ ) into a common table that grows.



(a)



(b)

Figure 4.6: Measurement results. (a) Measurement result carried out with  $n = 230$  oil droplets. Charge  $Q$  in units of elementary charge  $e$  (upper scale) and in units of  $10^{-19}$  Coulomb (lower scale). (b) Mean values of many individual measurements with  $n = 90$  oil droplets.

- Under *Material*, we have stored 10 measurement videos in case the RCL does not work or is occupied by another visitor.

An RCL experiment is then good / effective / helpful when it is used frequently and experiment specific. In 2011, we registered 18-19 visitors per day, with the average visit duration of about 3-4 minutes.

## 4.4 Didactic material

The following worksheet (Table 4.3) could accompany the experimentally posed homework, which is idealistically completed in group work.

For the following teaching unit, we formulate these learning objectives and learning requirements:

The pupils should ...

- explain qualitatively the friction-infected movement of the oil droplets in air.
- recognize the determination of the charge as the target of the Millikan experiment.
- as far as possible, derive the formula of a measuring method for determining the oil droplet charge.
- collect experimental data and present those in diagrams, individually or in groups with the RCL Millikan experimental data.
- formulate the charge quantization as a hypothesis and confirm it by means of its own measurement results and determine the elementary charge.

The following learning preconditions are necessary or desirable:

- Dynamic force balance with friction and buoyancy,
- Forces on charges in the electric field,
- Knowledge of recording measured values with a video analysis program,
- Knowledge of the analysis of measured data with a table calculation program,

- Experiences of the pupils with the cooperation in small groups.

The structure of the teaching unit (Table 4.4) can be outlined as follows:

- Preliminary experiment for the Stokes frictional force,
- Qualitative examination of the experiment as an RCL,
- Development of the theory to this experiment,
- Collaborative measuring and joint analysis of the experimental data.

The Millikan experiment and its physical background are among the difficult experiments in upper secondary education for pupils and teachers. The causes are manifold:

- **Experimental statistics:** For a clear statement about the charge quantization time-consuming measurements with many charge determinations are necessary.
- **Student participation:** Only a few pupils can carry out measurements during lessons.
- **Stokes frictional force:** A deductive derivation at school level is not possible. An inductive access is too time-consuming compared to the one-time use of the Millikan experiment. For learners, the existence of relevant limits of validity in laws is unfamiliar (Cunningham correction, only small velocities).
- **Charge quantization:** For the first time a discrete physical quantity occurs in the upper secondary level.
- **Experimental theory:** For students, the comprehensive experimental theory (contents from mechanics and electrostatics) is unusual.
- **Experiment methodology:** Determining the radius of a droplet, necessary for the determination of the charge in the same experiment by means of a second measurement of a different droplet movement, represents a new quality of an experimental approach for the students.

Due to these difficulties, the teaching unit (Table 4.4) aims at a more independent learning of the pupils. For student presentations, topics are summarized in Table 4.5.

In addition, we have compiled the most comprehensive task collection with model solutions: about 10 tasks for theory, 5 tasks for experimental setup, 2 tasks for measuring and evaluation; i.e. 17 tasks consisting of 54 individual tasks. These are suitable for the school (21), school / university (20), only for the university (13). Table 4.6 shows an overview - task topic / learning content / teaching unit. Subsequently, some tasks with model solutions (Tables 4.7 and 4.8).

Finally some multimedia to this Millikan experiment: Under the menu point *Material* we have 10 videos filed. The viewer observes, as it were, through the microscope and sees various oil droplets rising and falling at 525 V and 575 V. If the RCL does not work or should be occupied by other users for a long time, these measurement videos are a meaningful substitute.

We have found a video (665 kB) showing a glass ball falling in oil; thus the formula for the Stokes frictional force can be confirmed. Both in the context of the above teaching unit and in the corresponding task collection (task 1 in Table 4.7), this video with video analysis of the falling movement has a meaningful use.

A student (C. Groß) has written a simulation program [6] as part of his master thesis for teachers. This applet provides several measurement methods; it is not a substitute for the real experiment or RCL experiment, but the user can familiarize himself with the measurement procedure (see Fig. 4.7).

Table 4.3: Worksheet.

Worksheet --- Millikan oil droplet experiment

1. Questions:

- Oil droplets are charged. Why? What process?
- One must measure both the time of fall and the climbing time. Why both? (Consider the final formula for  $Q$ )
- What is the distance between two lines in the eyepiece?

2. For a selected voltage measure these times several times:

Number of the drop	Rise (s) Fall (s)				
1					
2					
3					
4					
5					

In case the webcam image is not good enough, use videos under Material

Video 1 (525V)	Video 6 (575V)	Group 1
Video 2 (525V)	Video 7 (575V)	Group 2
Video 3 (525V)	Video 8 (575V)	Group 3
Video 4 (525V)	Video 9 (575V)	Group 4
Video 5 (525V)	Video 10 (575V)	Group 5

3. Create the following table for data analysis:

4. Discussion:

- for all measurement data of all groups, apply charge  $Q$  against the number of droplets.
- Expected result is  $Q = n e$  (with  $n = 1, 2, 3, 4, 5 \dots\dots$ )
- How big is the elementary charge  $e$ ? Compare with literature value.

Table 4.4: Instructional unit Determination of elementary charge with RCL Millikan experiment.

Phase	Content and working forms
Preliminary test for the Millikan experiment	<p>Introduction of Stokes's friction force with a glass ball sinking in oil (material: video to the Stokes's friction force)</p> <ul style="list-style-type: none"> <li>• Experimental forms: Either carry out the experiment as a teacher demonstration experiment and record with digital camera (scientific and interesting for students) or video to show the Stokes's friction. Alternatively, with a longer oil-filled tube, the falling time with stopwatch and the falling distance with ruler can be measured. The acceleration phase of the ball, which is no longer measurable, is disadvantageous.</li> <li>• Qualitative predictions and explanation of the movement: Before carrying out the experiment, students can predict the movement and explain the effect (friction, buoyancy, weight), the relationship between force and movement.</li> <li>• Measurement of movement: Recording of distance-to-time measured value pairs with a video analysis program by the pupils, determination of the descent rate, explanations of the existence of an acceleration phase and the dynamic balance of forces.</li> <li>• Comparison of calculated and measured falling speed of the ball: First calculation with known Newtonian friction force and optionally with / without lift results in a difference which can not be explained by measurement errors. Teaching force introduces Stokes's friction (formula, viscosity, validity limits). Second calculation with Stokes's coefficient of friction gives a satisfactory agreement. Calculation of the value of all acting forces for comparison with the Millikan experiment.</li> </ul>
Objective and method of the Millikan experiment	<p>Purpose and mode of operation of the experiment (Material: RCL-Portal under Labs / Millikan- experiment / Setup / Laboratory):</p> <ul style="list-style-type: none"> <li>• Presentation of the experiment: Teacher provides the main test components on the website for experiment setup without further explanation. Then, on the laboratory side of the RCL, let the oil droplets rise and fall (if necessary, only fall for stepwise procedure)</li> <li>• Thoughts of the students to this experiment: As a student discussion in small groups with short presentation and discussion of the results. Key questions are: Why do you see light points in the microscope? Why do they rise or fall? Analogies to the preliminary test? Which forces work? Which variables could be determined from the falling or falling and climbing? Which must be given or known? What sizes are constant, which vary?</li> <li>• Results / findings of the student discussion and supporting experiments: it must have the same friction as before (no accelerated movement) Buoyancy force in air can be neglected compared to the weight force (weight force factor 1000 greater) Oil droplets must be charged (otherwise no upward movement) electrical force causes oil droplets to rise Microscope reverses direction of motion, ... Explanation of light points with demonstration experiment (water atomizer, light source, black background): radius of the oil droplets can not be measured directly (possibly inform the radius of the atomized water), oil instead of water (hardly evaporation), functional principle dark field illumination, teacher supports if necessary.</li> </ul>

	<p>Purpose and mode of operation of the experiment (Material: RCL-Portal under Labs / Millikan- Test / Setup / Laboratory):</p> <ul style="list-style-type: none"> <li>Objective "Charge Determination": Lessons: Why could charge determination be interesting at all (e.g. elementary charge or charge quantization), small oil droplets can carry only a small amount of charge, macroscopic appearance of charge is continuous (e. g. charging a capacitor), developing the equation for determining the elementary charge, discussing quantities: viscosity and density of oil and air, gravitational acceleration, distance of capacitor plates, students develop equation by their own, teacher supports if necessary.</li> </ul>
Statistical errors of charge determination	<p>Necessity and execution of many measurements to determine the charge (material see RCL portal and then RCLs → Millikan's Experiment → Laboratory, as well as → Material):</p> <ul style="list-style-type: none"> <li>Introductory sample measurement and evaluation: Measure the rising and falling time of an oil droplet several times and allow students to calculate the charge. Students (groups) determine the charge of an oil droplet as homework.</li> <li>Discussion of results: There are both near and far apart values of measured charges. Discussion with students about the causes and how to proceed further. If the hypothesis of charge quantization, which has not been discussed so far, comes from the pupils, this is enormous.</li> <li>Collecting measurements in small groups: Teaching staff provides the gathering of measured values by different persons by means of spreadsheet and with the help of a Wiki tool Dividing the course into small groups. As a home assignment for 2 - 3 days, each student group should carry out at least 40 measurements and store them in their spreadsheet. Optional for more interested students: graphical representation of the measured charge values.</li> </ul>
Detection of charge quantization and determination of elementary charge	<p>Evaluation of the measurement data (material: spreadsheet for experiment evaluation)</p> <ul style="list-style-type: none"> <li>Representation of the values in the two forms: charge as a function of number of measurement and as a distribution with charge divided in classes</li> <li>Successive summation of the measurements from the groups, for clear proof of charge quantization</li> <li>Determination of the elementary charge by mean values of the first or most precisely accumulations</li> </ul>
Sources on the Millikan experiment	<p>Possibilities for the final deepening of the Millikan experiment (→ Material: Task Collection on the RCL "Millikan experiment" and literature given in the additional information)</p> <ul style="list-style-type: none"> <li>Tasks for the Millikan experiment: Select tasks from Tasks Collection. Small groups work on different tasks and present results to the course</li> <li>Short presentations about the person "Millikan" and the historical context of the experiment: Using the Millikan experiment as an example, a discussion on the scientific standards of the handling and the publication of measurement data can be found</li> <li>Final test on learning outcomes</li> </ul>

Table 4.5: Material for student remarks

*Information about the school experiment*

- Kuhn - Manual of Experimental Physics: Sec. II, Volume 8 (atoms and quanta)  
Section 2.3.1 The Millikan Experiment for the Determination of Elementary Charge, page 60-72: Information on the determination of the elementary charge with DC and AC voltage and devices of various teaching materials manufacturers and evidence that a correction to Cunningham has to be carried out for oil droplets with smaller radii
- Vogel - The evaluation of the Millikan experiment  
Article in Physics at School 34 (1996), 3, pages 110-113: Description of an evaluation method for the Millikan experiment and its implementation with a computer program
- Stautberg et al. - Using the Atwood machine to study Stokes' law  
Article in American Journal Physics 54 (1986), 10, page 904-906: The proportionality between the frictional force and the velocity of the ball at a constant radius of the ball is shown experimentally (good excitation for a specialist work for the experimental investigation of Stokes friction coefficient).

*On the history of the experiment*

- Millikan - On the elementary electrical charge and the Avogadro constant  
Article in Physical Review 2 (1913), 2, pages 109-143: Original article on the Millikan experiment with experimental assumptions, experimental requirements, description of measuring method, experimental setup and experiment evaluation
- Millikan - The Electron: Its Isolation and Measurement and the Determination of Some Properties. Book, The University of Chicago Press; 7th impression (January 1, 1930): Detailed information from Millikan on his experiment
- Koch - Robert A. Millikan: The purpose justifies the means.... Article in Physics at School 30 (1992), 6, pp. 235-236: Report on the Confrontation between Ehrenhaft and Millikan on the Experimental Proof of Charge Quantization.
- Heering - questionable in the Millikan experiment  
Article in physics in our time 37 (2006), 5, page 227: Report on the analysis of the laboratory books by Millikan, according to which he has only published the measured values favorable for the desired result.
- Fäßler & Jönsson - The Top Ten of the Most Beautiful Physical Experiments  
Book with information on the Millikan experiment in the Chapter Determining the charge of an electron - Millikan's oil droplet experiment, page 118-135: The text about the professional career of Millikan, the description of the Millikan experiment in the historical context and the experimental work of Millikan is also for learners suitable.

Table 4.6: Overview - Task topic / Learning content / Teaching unit.

N.	task topic	learning content	educational use
I.1	Stokes frictional force	<ul style="list-style-type: none"> <li>• Uniform motion under the influence of Stokes friction</li> </ul>	<ul style="list-style-type: none"> <li>• Preparation of a more independent work with the Millikan experiment</li> <li>• Introduction of Stokes friction</li> <li>• Repeat on movement with friction</li> <li>• Formulating and reviewing hypotheses</li> </ul>
I.2	Quantization	<ul style="list-style-type: none"> <li>• Distinguishing between quantized and continuous quantities</li> </ul>	<ul style="list-style-type: none"> <li>• Introduction of the term "quantization"</li> <li>• Preparation of a more independent working with the Millikan experiment</li> </ul>
I.3	Preparatory work for the Millikan experiment	<ul style="list-style-type: none"> <li>• Problem of the existence and detection of the elementary charge</li> <li>• Time location of the Millikan experiment</li> </ul>	<ul style="list-style-type: none"> <li>• Student's presentations or teacher's lectures</li> <li>• Learning circle</li> </ul>
I.4	Variable calculations in the Millikan experiment	<ul style="list-style-type: none"> <li>• Mathematical-physical interrelationships between the variables in the Millikan experiment</li> <li>• Calculation of microscopic sizes</li> </ul>	<ul style="list-style-type: none"> <li>• Exercise following the theory</li> <li>• Part of learning circle</li> </ul>
I.5	Model experiment for the Millikan experiment	<ul style="list-style-type: none"> <li>• Form analogies between two experiments</li> <li>• Limits of analogies</li> </ul>	<ul style="list-style-type: none"> <li>• Review the qualitative understanding of the Millikan experiment</li> </ul>
I.6	Experimental variants of the Millikan experiment	<ul style="list-style-type: none"> <li>• Dealing with the system of equations in the physical context</li> <li>• Mathematical transformations</li> </ul>	<ul style="list-style-type: none"> <li>• Differentiation of the group of students according to mathematical skills</li> <li>• Calculus competition between two groups of the course</li> </ul>
I.7	Oil droplets of choice	<ul style="list-style-type: none"> <li>• Dependence of the measurement results on the selected oil droplets</li> <li>• Distinction between statistical and analytical contexts</li> <li>• Analysis of the Millikan data under a new point of view</li> </ul>	<ul style="list-style-type: none"> <li>• Teacher-guided lesson on theory building in physics</li> </ul>
I.8	Acceleration phase of oil droplets	<ul style="list-style-type: none"> <li>• Estimation of acceleration at non-constant forces</li> <li>• Exact calculation with differential equation</li> </ul>	<ul style="list-style-type: none"> <li>• Task to apply learned content in a new context</li> </ul>
I.9	Cunningham correction	<ul style="list-style-type: none"> <li>• Mean free path and viscosity of gases</li> <li>• Validation of Cunningham correction</li> <li>• Limit of a mathematical function</li> </ul>	<ul style="list-style-type: none"> <li>• Independent acquisition of new learning content with appropriate student-oriented learning materials</li> </ul>
I.10	R. A. Millikan	<ul style="list-style-type: none"> <li>• Millikan as a scientist, lecturer and private individual</li> </ul>	<ul style="list-style-type: none"> <li>• Student's presentation or teacher's lectures</li> <li>• Part of learning circle</li> </ul>

Table 4.7: Tasks and model solutions to the theory of Millikan's experiment.

## Task for Friction.

**1. Stokes frictional force**

The video (download from RCL-website, Material, 2.) is showing a falling glass sphere ( $\rho_{\text{glass}} = 2.23 \text{ g/cm}^3$ ,  $r = 2 \text{ mm}$ ) in oil (density  $\rho_{\text{oil}} = 0.922 \text{ g/cm}^3$ , viscosity  $\eta_{\text{oil}} = 0.09 \text{ Ns/m}^2$  of oil made out of sun flowers).

- a) Plot a qualitatively correct stroboscope picture of the motion of the glass sphere and assign all forces acting on that sphere:
  - Which type of all forces are constant or variable starting with the free fall?
  - Explain, why the glass sphere is falling down with constant velocity shortly after letting off.
- b) Study the trajectory of the moving glass sphere by means of video analysis. Show that the motion of the glass sphere happens under the action of the Stokes frictional force ( $F_s = 6\pi\eta_{\text{oil}}rv$ ) and determine all acting forces.
- c) How one may modify the experiment to demonstrate  $F_s \sim v$ ?
- d) How one may modify the experiment to demonstrate  $F_s \sim r$ ?

## IV. Solutions to problems I

### 1. Stokes frictional force

a) See Fig.11.

- The only changing term along this distance is the Stokes frictional force  $F_s$ .
- At the time when the glass sphere is released its velocity is  $v = 0$ . The sphere starts falling, because the gravitational force  $F_g$  is larger than the force due to buoyancy  $F_b$ . The sphere will be accelerated till the increasing Stokes frictional force – increasing with increasing velocity during falling – is reaching a dynamical balance of forces. The resulting total force  $F$  on sphere is now zero and the ball is falling with constant velocity.

b) If the formula for the Stokes frictional force is correct, then the experimentally determined velocity during falling  $v_{\text{exp}}$  is like the theoretically determined velocity during falling  $v_{\text{theo}}$ : With  $\Delta s = 10 \text{ cm}$  and  $\Delta t = 0.833 \text{ s}$  from the video we get  $v_{\text{exp}} = 12 \text{ cm/s}$ . For  $v_{\text{theo}}$  we get

$$F_g = F_s + F_b \Rightarrow v_{\text{theo}} = \frac{2r^2 g (\rho_{\text{glass}} - \rho_{\text{oil}})}{9\eta_{\text{oil}}} = 12.6 \frac{\text{cm}}{\text{s}}.$$

Inserting all technical parameters we get for the forces  $F_s = 0.4 \text{ mN}$ ,  $F_g = 0.733 \text{ mN}$  and  $F_b = 0.33 \text{ mN}$ .

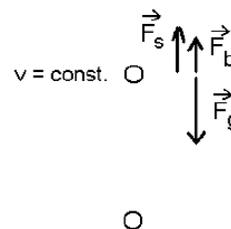
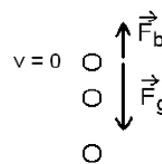


Fig. 11: Stroboscopic view of a falling sphere of glass.

c) One must use a set of balls with identical radius  $r$  but different density  $\rho$  of ball material (different mass  $m$  of ball). We measure the radius  $r$  and the constant velocity  $v_{\text{exp}}$  during falling. We can determine the frictional force  $F_s$  from the dynamical balance of forces (for  $v_{\text{exp}} = \text{constant}$ ) according to

$$F_s = mg - m_{\text{oil}}g = (m - m_{\text{oil}})g = \frac{4}{3} \pi r^3 g (\rho - \rho_{\text{oil}})$$

Alternatively one can use different kinds of oils with different oil densities. This is problematic, because each kind of oil with different density possesses also different viscosity. Unless one is looking for oils with different density but the same viscosity.

d) To show  $F_s \sim r$  one has to vary the sphere radius  $r$  and keep the velocity constant. But increasing  $r$   $k$ -times at constant density  $\rho$  of balls will increase velocity  $v$  quadratically.

$$v = k^2 \cdot \frac{2r^2 g (\rho - \rho_{\text{oil}})}{9\eta_{\text{oil}}}$$

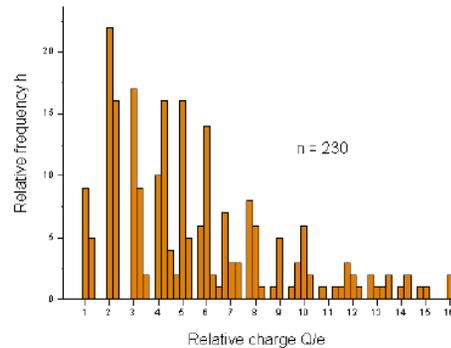
So to keep  $v = \text{constant}$  the difference in densities must be put  $k^2$  smaller if the radius is increasing by a factor of  $k$ .

## Task for oil droplet selection

**7. Selection of oil droplets**

The histogram (Fig. 2) shows the distribution of relative charges  $k = Q/e$  of about  $n = 230$  oil droplets of the Millikan experiment.

- For small values of  $k$  the distribution shows discrete values: why is this discrete pattern smeared out for larger values of  $k$ ?
- Search for a relation between charge and velocity of oil droplets looking up data material in the RCL-website, Analysis, 1. respective theoretical considerations or using the data material itself.
- What is the proper recommendation for the performance of Millikan's experiment according to the results and experiences of problem a) and b).



**Fig. 2: Histogram for absolute frequency  $h$  of measured oil droplets versus relative charge  $Q/e$ .**

## 7. Selection of oil droplets

a) Oil droplets with larger charges are moving much faster. Therefore, the error in determining the velocity and therefore in charge  $Q$  is increasing.

b) The charging of oil droplets by friction is a statistical process similar to the process of charge separations of particles in clouds. Therefore, there is no deterministic condition given for that process. Due to empirical data oil droplets, which are closer together than  $0.45 \mu\text{m}$ , will be charged negatively: in addition one supposes empirically that the amount of charge  $Q$  is increasing with increasing radius of oil droplets. This hypothesis is confirmed by the fact that the capacity

$$C_{\text{sphere}} = 4\pi\epsilon_0 r$$

is increasing with radius  $r$ .

Using Fig. 14 we can model in a simple linear model the negative charge of an oil droplet (for  $r > 0.45 \mu\text{m}$ ):

$$Q(r) = 1.823 \cdot 10^{-12} \frac{\text{C}}{\text{m}} (r - 0.45 \mu\text{m}).$$

No.	Radius $r$ in $10^{-7} \text{ m}$	Velocity $v_{\text{fall}}$ in $10^{-5} \text{ m/s}$	Velocity $v_{\text{rise}}$ in $10^{-5} \text{ m/s}$	Charge $Q$ in $10^{-19} \text{ C}$
1	7.86	7.66	5.30	3.05
2	5.34	3.53	7.16	1.60
3	8.44	8.83	3.50	3.14
4	8.51	8.97	3.26	3.15
5	10.6	13.9	20.1	11.19
6	7.47	6.92	7.83	3.28
7	7.23	6.47	8.12	3.12
8	6.26	4.86	12.8	3.19
9	9.68	11.6	20.1	9.42
10	6.99	6.06	9.07	3.11

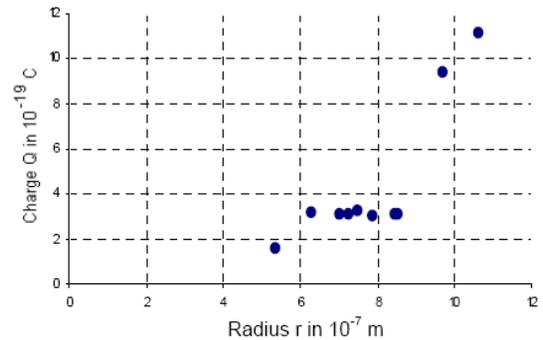


Fig. 14: Measured charge  $Q$  of oil droplets versus radius  $r$  of oil droplet.

We have to distinguish between raising and falling of an oil droplet. The velocity of falling  $v_{\text{fall}}$  depends on the radius  $r$  only.

$$\frac{4}{3} \pi r^3 \rho_{\text{oil}} g = 6 \pi \eta_{\text{air}} r v_{\text{fall}} \Leftrightarrow v_{\text{fall}} = \frac{2 \rho_{\text{oil}} g}{9 \eta_{\text{air}}} r^2$$

An oil droplet with double radius is falling four times as fast. In general, larger oil droplets possess on average also larger charge  $Q$ , therefore, all those quickly falling droplets possess larger charge.

According to empirical data (Fig. 15) the charge  $Q$  depends also on the velocity of raising  $v_{\text{rise}}$ . What do we expect for  $v_{\text{rise}}(Q, r)$  in such a simple linear model?

$$\frac{4}{3} \pi r^3 \rho_{\text{oil}} g = Q \frac{U_{\text{rise}}}{d} - 6 \pi \eta_{\text{air}} r v_{\text{rise}} \Leftrightarrow v_{\text{rise}} = \frac{Q \frac{U_{\text{rise}}}{d} - \frac{4}{3} \pi r^3 \rho_{\text{oil}} g}{6 \pi \eta_{\text{air}} r}$$

and

$$Q(r) = 1.823 \cdot 10^{-12} \frac{\text{C}}{\text{m}} (r - 0.45 \mu\text{m}) \Leftrightarrow r(Q) = 5.485 \cdot 10^{11} \frac{\text{m}}{\text{C}} \cdot Q + 0.45 \mu\text{m}.$$

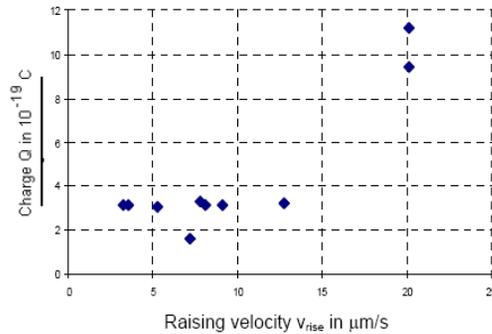


Fig. 15: Measured charge  $Q$  of oil droplets versus raising velocity  $v_{\text{rise}}$ .

If we insert both dependencies  $v_{\text{rise}}(Q, r)$  and  $r(Q)$  into the definition equation of the raising velocity  $v_{\text{rise}}$  we get as graphical dependence  $v_{\text{rise}}(r)$  in Fig. 16 and  $v_{\text{rise}}(Q)$  in Fig. 17:

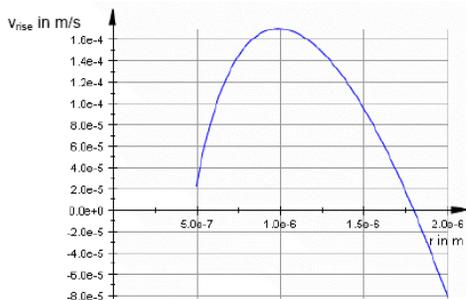


Fig. 16: Raising velocity  $v_{\text{rise}}$  versus radius  $r$  of oil droplet.

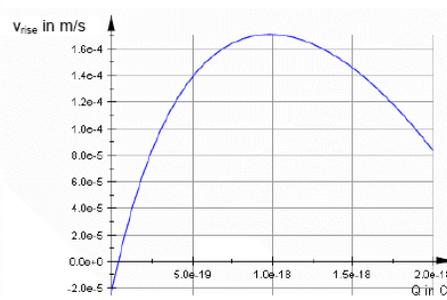


Fig. 17: Raising velocity  $v_{\text{rise}}$  versus charge  $Q$  of oil droplet.

Because the gravitational force  $F_g$  is increasing with radius  $r$  larger than the electric force  $F_e$  with  $Q$  the raising velocity  $v_{\text{rise}}$  is decreasing again for oil droplets with radius  $r > 1 \mu\text{m}$  or  $Q \sim 6e$ .

- c) Since only a few oil droplets in the Millikan experiment are larger than  $r > 1 \mu\text{m}$  or possess a charge  $Q \geq 6e$  it is suggested to select only smaller oil droplets to guarantee a possibly accurate determination of charges.

## Task for the acceleration phase of the oil droplets

**8. Acceleration phase of oil droplets**

Under the action of gravitational and electric forces (buoyancy will be neglected here) oil droplets will be accelerated in air to a final constant velocity  $v_{\text{fall}}$  (during falling without an electric field) or velocity  $v_{\text{rise}}$  (during raising with an electric field):

- Explain the existence of such final stationary velocities.
- Estimate the time interval during acceleration of an oil droplet ( $\rho_{\text{oil}} = 1.03 \text{ g/cm}^3$ ,  $r \approx 0.8 \text{ }\mu\text{m}$ ,  $Q = 3e$ ) till it reaches the final constant velocity during falling and raising motion ( $U = 600 \text{ V}$ ,  $d = 6 \text{ mm}$ ,  $\eta_{\text{air}} = 1.81 \cdot 10^{-5} \text{ Ns/m}^2$ ).  
Hint: suppose a constant force in Newton's axiom acting on the oil droplet.
- The velocity of a spherical body (radius  $r$ , density  $\rho$ ) during falling in a medium (viscosity  $\eta$ ) with initial velocity  $v_0 = 0$  is given by

$$v(t) = \frac{g}{k}(1 - e^{-kt}) \quad k = \frac{9\eta}{2r^2\rho} :$$

- Show that  $v(t)$  is a solution of the differential equation  $m\dot{v}(t) = mg - 6\pi\eta rv$  (balance of forces).
  - Display a graph of  $v(t)$  with the given values in b), determine the time interval for acceleration and explain the difference to result found in b).
- Do we have to consider this acceleration time interval for the determination of  $Q$ ?

## Acceleration phase of oil droplets (solutions)

**8. Acceleration phase of oil droplets**

a) See I.1a.

b) In the very beginning of the falling process the resultant acceleration is  $a(t = 0) = g$ . The velocity of falling is

$$\frac{4}{3} \pi r^3 \rho_{\text{oil}} g = 6 \pi \eta_{\text{air}} r v_{\text{fall}} \Leftrightarrow v_{\text{fall}} = \frac{2 \rho_{\text{oil}} g}{9 \eta_{\text{air}}} r^2 = 0.8 \frac{\mu\text{m}}{\text{s}}.$$

The time interval of the acceleration phase is

$$\Delta t_{\text{fall}} = \frac{v_{\text{fall}}}{g} = 8 \mu\text{s}.$$

c)

- The evolution of the falling velocity  $v(t)$  is

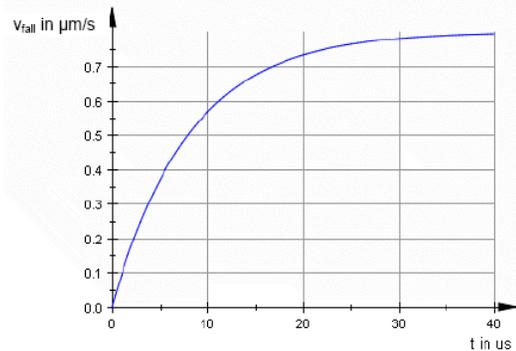
$$m \dot{v}(t) = mg - 6 \pi \eta r v \Leftrightarrow \dot{v}(t) = g - \frac{6 \pi \eta r v}{\rho_K \frac{4}{3} \pi r^3} = g - \frac{9 \eta v}{2 r^2 \rho_K} = g - kv$$

$$-\frac{g}{k} (-k) e^{-kt} = g - k \frac{g}{k} (1 - e^{-kt})$$

- Using all measured values we get for  $k = 1.23 \cdot 10^5 \text{ s}^{-1}$ . The time interval  $\Delta t_{\text{fall}}$ , till the falling velocity is constant, is  $\approx 40 \mu\text{s}$  (Fig. 18). The time interval, till the falling velocity is about 63 % of the final velocity  $v_{\infty} = v_{\text{fall}}$ , is about  $1/k = 8 \mu\text{s}$  considering

$$\left(1 - \frac{1}{e}\right) \cdot \frac{g}{k} = 0.63 \cdot v_{\infty}.$$

Comparing both results  $\Delta t_{\text{fall}} \sim 8 \mu\text{s}$ ,  $\Delta t_{\text{fall}} \sim 40 \mu\text{s}$  from b) the time interval for acceleration is too large in c) than in b), because in c) we used a too high constant gravitational force during the whole phase of acceleration.

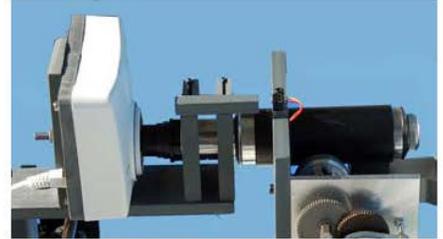
Fig. 18: Falling velocity  $v_{\text{fall}}$  versus time  $t$ .

- d) Therefore the acceleration times in the falling and raising phases can be neglected with respect to the reaction times of the user, if an oil droplet changes its direction under the action of an applied voltage.

Table 4.8: Tasks with sample solutions for experimental setup

**2. Observation of oil droplets**

- a) What is the difference between bright field and dark field illumination? Which one is used in the RCL?
- b) If light is scattered by oil droplets which kind of scattering exists in the RCL - Rayleigh or Mie scattering? Give a typical example for both kinds of scattering.
- c) The webcam has a teleobjective with 13.5 cm focal length, the focal length of the microscope objective is 5 cm, the focal length of the ocular is 2.5 cm (Fig. 5): Make a sketch of the optical rays between oil droplets and the CCD chip of the camera.
- d) How can one measure distances in the  $\mu\text{m}$ -range with a microscope?
- e) In the RCL a bulb of the illumination unit was replaced by a white LED. At the real Millikan experiment a glass container with copper chloride water solution was positioned between arc lamp and capacitor: What do one want to avoid in both cases? Without both improvements one would expect perturbing influences on the determination of charge  $Q$ . Which kind of perturbations?
- f) How many pictures can be transmitted by ISDN (8 kB/s) or by DSL 1000 (128 kB/s) using a compression factor of 20 in JPEG format with a resolution of  $320 \times 240$  pixels and 24 bit colour depth?



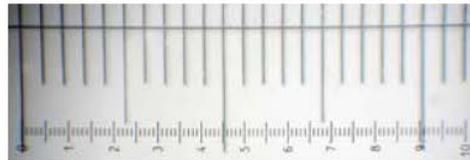
**Fig. 5: Webcam and microscope to observe the oil droplets in the RCL.**

## Observation of oil droplets (solutions)

### 2. Observation of oil droplets

- a) In bright field illumination light transmitted through an object is collected by the microscope objective. In dark field illumination only the light scattered by an object is collected by the microscope objective.
- b) We are speaking of Rayleigh scattering, if the dimension  $d$  of a scattering object is smaller than the wavelength  $\lambda$  of scattered light (e.g. light scattering by gas molecules, this fact is explaining the blue colour of sky, the red colour of sun rise and sun dawn). We are speaking of Mie scattering if the dimension  $d$  of an object is of the same order or larger than the wavelength  $\lambda$  (e.g. scattering by aerosols, by fog (0.01 mm – 0.1 mm) or by rain drops (0.1 mm – 5 mm)). In the Millikan experiment the diameter of oil droplets ( $0.1 \mu\text{m} < 2r < 1 \mu\text{m}$ ) is of the same order as the wavelength ( $0.4 \mu\text{m} < \lambda < 0.8 \mu\text{m}$ ) which means this scattering is between the one of Rayleigh or of Mie.
- c) Optical ray diagram of a microscope and of a telescope (functions).

- d) We use an ocular micrometer to measure distances in the microscope, which we calibrate by an objective micrometer in the following way (Fig. 20):



**Fig. 20: Ocular micrometer.**

Fig. 19) at the focal plane of objective respective at the object plane of the ocular: focussing by means of the ocular lens.

- Put object micrometer (scale division of 1 mm for 100 parts i.e. 1 part =  $1 \mu\text{m}$ , upper part of Fig. 20) on object carrier of microscope, focussing by rough and fine drive, than rotate ocular micrometer till it is parallel to objective micrometer.
- Count scale units of both objective and ocular micrometer over a maximum wide coinciding distance  $s$ . In Fig. 19  $m = 20$  scale units of the object micrometer represents  $n = 90$  scale units of the ocular micrometer.
- Length  $x$  of one scale unit of ocular micrometer:

$$s = 20 \text{ Skt} \cdot \frac{10 \mu\text{m}}{\text{scale unit}} = 90 \text{ Skt} \cdot x \Leftrightarrow x = \frac{20}{9} \frac{\mu\text{m}}{\text{scale unit}} = 2,222 \frac{\mu\text{m}}{\text{scale unit}}$$

- e) The heat transfer from the light source by heat radiation to the air in the capacitor will be prevented by the absorption of the heat radiation by copper chloride. Consequence of this heat transfer is convection in the air inside capacitor, which may cause a side drift motion of oil droplets and therefore additional vertical forces on the oil droplets. This side drift motion is influencing the vertical motion of the oil droplet. In that case for a motion with friction the principle of independency is not valid any more.

But there is not influence of this side drift motion on the measurement of falling – and raising velocity, because one is measuring only the vertical (i.e. projected) distance of the motion of a droplet in the ocular micrometer.

- f) Transport of data:

$$x \cdot 320 \cdot 240 \cdot 3 \text{ B} \cdot \frac{1}{20} = y \text{ B/s}$$

For  $y = 8000$  we get  $\alpha = 0.7$  pictures/s, for  $y = 128\,000$  we get  $x = 11.1$ .

## Task for the production of oil droplets

**3. Generation of oil droplets**

An airbrush compressor is used to blow a pulsed stream of air to the atomizer (Fig. 6), controlled by mouse click to open a magnetic valve.

- a) Quote and describe an experiment which demonstrates, that the static pressure in flow of liquid or gas is as smaller as the large becomes the velocity of the flowing liquid or gas.
- b) Explain qualitatively how one can succeed in atomizing the oil into small droplets.
- c) Which velocity of air  $v_{\text{air}}$  ( $\rho_{\text{air}} = 1.3 \text{ kg/m}^3$ ) must be produced by the airbrush compressor at the glass nozzle (2 cm as distance to the inlet for oil droplets of the capacitor) to atomize the oil ( $\rho_{\text{oil}} = 1.03 \text{ g/cm}^3$ ).
- d) Why one uses oil of high vacuum pumping systems in the Millikan experiment for the oil droplet?



**Fig. 6: Atomizer in the RCL.**

## Production of oil droplets (solutions)

**3. Generation of oil droplets**

- a) The vertical tubes are measuring the static pressure  $p$  of the liquid ( $p = \rho gh$ ,  $h$  height). At the reduced part (cross section) of the horizontal flow tube the static pressure is smaller than elsewhere: since the total pressure  $p_0$  is constant everywhere the dynamical pressure  $p = \rho v^2/2$  is larger at that position.

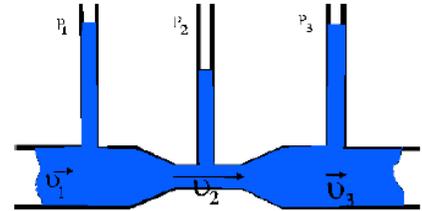


Fig. 21: Static and dynamic pressure in tubes.

- b) The principle of an atomizer is based on two mechanisms:
- According to Bernoulli equation rapidly moving air at the narrow nozzle will produce a lower pressure at the bottom of the vertical tube with respect to atmospheric pressure  $p_0$ . The atmospheric pressure, therefore, will press the liquid into the vertical tube.
  - Liquid will be strongly perturbed by the turbulent flow of air, such that the liquid will decay into small droplets.

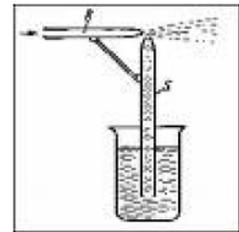


Fig. 22: Atomizer.

- c) The minimum velocity will be determined for the case that oil has  $v_{oil} = 0$  at the upper end of the vertical tube:

$$p_0 - p = \rho_{oil} gh$$

The air-brush compressor will accelerate the air at rest to a velocity  $v_{air}$  at the upper end of the vertical tube. Following Bernoulli

$$p_0 = p + \frac{\rho_{air}}{2} v_{air}^2$$

consequently

$$\frac{\rho_{air}}{2} v_{air}^2 = \rho_{oil} gh \Leftrightarrow v_{air} = \sqrt{\frac{2\rho_{oil} gh}{\rho_{air}}} = 17.6 \frac{m}{s}.$$

- d) The saturation vapour pressure of high vacuum oil at  $T = 20^\circ C$  is  $10^{-4}$  kPa much smaller than the one from water (2.34 kPa). Therefore, the mass of oil droplets will be constant during measurements.

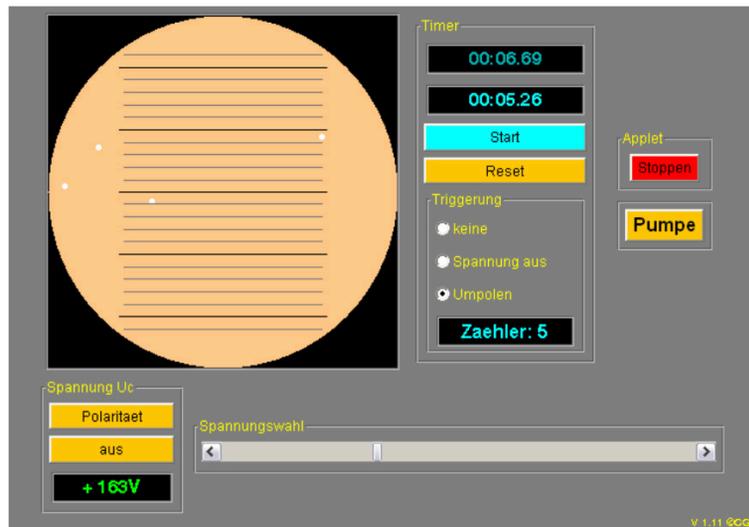


Figure 4.7: Simulation for the Millikan experiment (only in German language) [6]

## 4.5 Literature

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- [4] Eckert, B., Gröber, S., Vetter, M. and Jodl, H.-J. "Millikan's oil-drop experiment as a remotely controlled laboratory." In: Eur. J. Phys. 33.5 (2012), p. 1227.
- [5] LD Didactic GmbH. Millikan device No. 559411.
- [6] Groß, C. Simulation for the Millikan experiment (applet). URL: <http://ne.lo-net2.de/selbstlernmaterial/p/e/mi/miindex.html>

# 5 Rutherford scattering experiment

## 5.1 Introduction

This experiment can be used to decide the validity of historical atomic models (Dalton 1803, Thomson 1903, Rutherford 1911); therefore this experiment is only of importance for physics and chemistry; in pure physics only important as a historical, classical experiment; in everyday life it does not matter. In addition, the experiment represents the prototype experiment for the class of the scattering experiments, namely deduce indirectly from the angular distribution of scattered particles on the scattering object.

Characteristics of the Dalton atomic model are:

- Atoms of an element are equal, indivisible, indestructable and structureless balls,
- Does not explain the permeability of the metal foil for almost all alpha particles,
- Improved model with smaller spheres provides a uniform distribution over the scatter angle in contradiction to the measurement.

Characteristics of the Thomson atomic model are:

- Positive charge of the atom is evenly distributed over the atomic volume,
- Electrons with equal total charge are embedded in a homogeneously positively charged sphere,
- Structure of the atom is determined by electrical Coulomb force,
- Estimation of the maximum scattering angle when deflected by an atom (single scattering) yields max.  $\vartheta_{\max} = 0,05$  degree and does not explain large deflection angles,

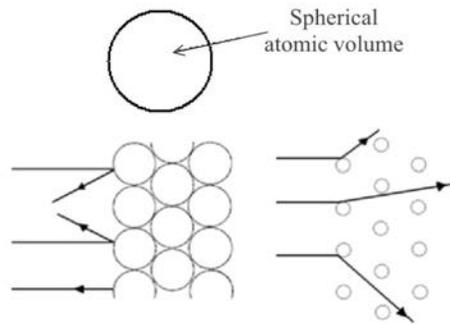


Figure 5.1: Atomic structure and particle scattering in Dalton's atomic model (schematic).

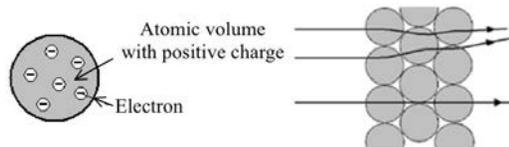


Figure 5.2: Atomic structure and particle scattering in Thomson's atomic model (schematic).

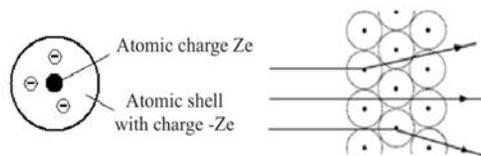


Figure 5.3: Atomic structure and particle scattering in Rutherford atomic model (schematic).

- Improved model with scattered  $\alpha$ -particles by several atoms (multiple scattering) delivers in contrasts with measurement for small angles too many and for large angles less scattered particles.

Characteristics of the Rutherford atomic model are:

- Total positive charge and almost the entire mass of the atom are concentrated in the nucleus.
- The nuclear diameter is a few femto meters (fm) about a factor of 10,000 smaller than the atomic diameter.
- Electrons form the atomic shell.

- Concentration of the positive charge from the atomic volume ( $r_{A, Au} = 144 \text{ pm}$ ) to the much smaller nuclear volume ( $r_{K, Au} = 7,56 \text{ fm}$ ) yields a Coulomb force greater by a factor of  $10^8$ . This explains the large deflection angles and the small probability with which they occur.
- Backward scattering of the  $\alpha$ -particles can only be explained by a positively charged nucleus (repulsion of the same charges).
- Small decrease of the velocity of the  $\alpha$ -particles can be explained by elastic collision of the  $\alpha$ -particles with the heavier atomic nuclei and by inelastic collisions with shell electrons.
- The influence of the shell electrons on the motion of the  $\alpha$ -particles can be neglected (maximum velocity loss / electron collision is approx. 0.05%, maximum deflection angle  $< 0,008$  degree).
- Model with deflection of  $\alpha$ -particles by scattering on an atom (single scattering) in the field of a point-like charge agrees very well with the measurement.

The standard experiment for the Rutherford scattering experiment in physics / chemistry is the classical experimental set up according to Rutherford:  $\alpha$  particles -i.e.,  $\text{He}^{2+}$  nuclei- are scattered in vacuum by a very thin gold foil. From the angle distribution of scattered  $\alpha$  particles, one can conclude details (shell and nucleus) of the gold atom.

The following observations can be made with the apparatus:

- The number of the  $\alpha$ -particles registered in a fixed time interval is the largest in the direction of incidence ( $\vartheta = 0$ ) and becomes smaller as the scattering angle  $\vartheta$  increases.
- Almost all  $\alpha$ -particles traverse the metal foil without a major change in direction (about 90% between 0 and  $\pm 10$  degrees).
- For larger scattering angles and a sufficiently long measuring period,  $\alpha$  particles are recorded behind the metal foil, but also in front of the metal foil in case of back-scattering (only about 50 of  $10^9$   $\alpha$ - particles).

- The same number of  $\alpha$ -particles is registered by the statistical mean for equal scattering angles on the left and right of the direction of incidence of  $\alpha$ -particles.
- These qualitative results are independent of the velocity or the kinetic energy of the  $\alpha$ -particles, of the foil material and its thickness.

For our RCL variant, we chose the experimental set up according to Leybold [1, 2]; other teaching firms (Phywe, Pasco) offer similar experimental arrangements. The Rutherford scattering formula is based only on the Coulomb interaction of two point-like charges, including laws of mechanics. Since the beginning of simulation programs for physics and chemistry lessons, this classical experiment has been programmed again and again (Powersim, Coach 6 [3]).

There are a number of reasons why the real experiment of the teaching aid industry is rarely demonstrated:

- The experimental setup is not available everywhere due to the price of the purchase (about 1500 €, without vacuum pump) and the rare use once a year.
- The  $\alpha$ -beam source (Am-241, 340 kBecquerel) is not always available; as well as a rotary vacuum-pump.
- The measuring time to obtain the dependence of the scattering angle and the scattering rate is too long to be carried out during the lesson (longer than 30 minutes); especially the measurement at interesting larger scattering angles requires hours.
- The student has few possibilities to actively intervene in the measurement process; typically for a demonstration experiment conducted by the teacher.
- The measurements are not exciting, because the number of scattered  $\alpha$ -particles is read off at the counter for time intervals.

Even the most common simulation programs are not a substitute; only the real experiment or the RCL variant provides statistically distributed, meaningful data sets.

The RCL Rutherford scattering experiment has the following advantages over the traditional experiment:

## 1. Experimental setup

- The RCL replaces the frequently unavailable experimental equipment.
- The experiment is already set up. The teacher has only to test the experiment on the website.
- Handling with radioactive sources and vacuum pump is omitted.
- The accuracy of the motorized angle setting, of less than half a degree, is above that of the traditional experiment.
- Changing the scattering material (Au, Al) is possible without venting the vacuum chamber.

## 2. Performing the experiment

- The experimenting time is shortened by the motorized adjustment of scattering angle and of scattering material.
- The feasibility of the experiment over the Internet allows measurements out of schools and the collection of scattering data for different scattering angles in groups of students (co-operative measurement). The learner can observe the statistically fluctuating and decreasing counting rates with increasing scattering angle during measurements. From this experimental experience, interest can develop in an interpretation of the experimental results and in a subsequent mathematical treatment.
- The feasibility of the experiment as a student experiment places the planning of measuring series (for example, a series of measurements with minimum experimentation time) in the hands of the learners.

In teacher training courses about the use of RCLs, physics teachers have answered as to whether the RCL variant can replace the real experiment; they judged the usefulness of the RCL as very good; similar to the RCL speed of light.

## 5.2 Experiment and RCL variant

### 5.2.1 Experimental setup and function

The RCL variant essentially follows the real experimental setup, with Leybold [1, 2, 4, 5] recreating the "classic" setup by Rutherford.

Since  $\alpha$ -particles (nuclei of helium) have only a range of a few centimetres in air, the experiment is in a vacuum chamber (1) made of plexiglas (see Fig. 5.4). This chamber is continuously evacuated via a hose (2) with a rotary vacuum pump (not shown).

The apparatus consists of an Am-241 radiation source (3) for the generation of  $\alpha$ -particles, a slit diaphragm (4) for masking the  $\alpha$ -particle beam, metal foils (5) of gold and aluminium as scattering materials, a semiconductor detector (6) with slit diaphragm to register scattered  $\alpha$ -particles, a discriminator preamplifier (8) for amplifying and pulse-shaping the signals of the semiconductor detector, and a counter (9) for displaying the number of registered  $\alpha$ -particles.

Controlled by the interface (10), the experimenter can choose between a slit diaphragm, mounted on a sample wheel (11) without a foil and between metal foils including slit diaphragms via a first motor. A second motor makes it possible to set the angle at which  $\alpha$ -particles are registered between  $-50^\circ$  and  $+50^\circ$ , and read off an angle scale (12). The settings can be monitored via a webcam (13).

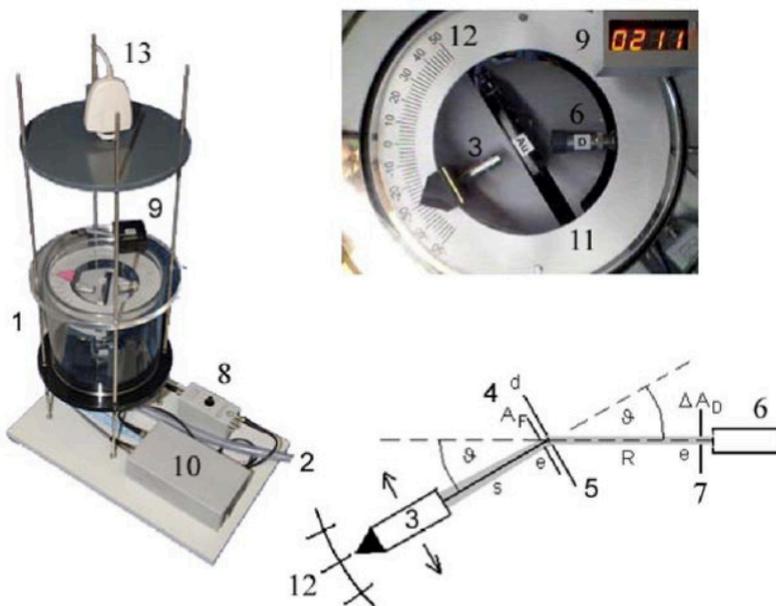


Figure 5.4: Total view of the experiment (left), webcam image (right top) and experimental sketch (bottom right): Vacuum chamber (1), rotary vacuum pump (2), a radiation source (3), metal foils (5), semiconductor detector (6), slit diaphragm (7), discriminator-preamplifier (8), counter (9), interface (10), sample wheel (11), angle scale (12) and webcam (13).

A large number of technical data is necessary to evaluate the raw data (angle-dependent scattering rates) with the final formula according to Rutherford: the activity and geometry of the radiation source, the geometry and the properties of the two metal foils, the overall scattering geometry including the diaphragms and the detector area. All this can be found in the menu point *Set up*. It was our philosophy in the design of RCLs to deliver measured data as raw data - as in the laboratory -; we deliberately omitted any form of automatic analysis, data modelling, or graphical representation; all this is the responsibility of the experimenter / user.

## 5.2.2 Navigation menu

The menu point *Introduction* and *Experimental set up* is followed by the point *Theory*. We present the theory with all of our RCLs so that the experimenter / user need not to consult further books, schoolbooks (RCLs must be self-sufficient, offered autonomously). The theory of Rutherford scattering is somewhat complex; therefore a separate section in the following. The *Theory* contains an explanation of the experimental results in the three atomic models. The Rutherford scattering formula is discussed and the structure of the formula, i.e. essential dependencies, is made conscious for a deeper understanding. The validity limits of the Rutherford scattering formulas are emphasized in order to explain the deviation of the experimental values from the theoretically expected distribution of the measured values. For the numerical evaluation by the experimenter two further aids are offered: How is the scattering geometry including the position and areas of the diaphragms as well as the detector geometry to be taken into account? How can we conclude from the raw measured data the ratio of the nuclear charge numbers  $Z_{\text{Au}} / Z_{\text{Al}}$  of the two metal foils?

Finally, the absorption of the  $\alpha$ -radiation in the cover of the radioactive source by the metal foil and the residual air in the vacuum chamber is described in detail; because the kinetic energy of the  $\alpha$ -particles is contained in the Rutherford scattering formula; so we do not insert the value  $E_{\text{kin}, \alpha}$  when exiting the source, but we must appropriately reduce it.

The student has primarily difficulties in understanding the Rutherford scattering in the derivation, its structure to be recognized, as well as to evaluate the measured data and given technical data. Schoolbooks and university textbooks do not always contain a step by step, comprehensible derivation. For this reason, we offer a detailed derivation of the final formula in the menu point *Theory*: model assumptions, scattering geometry and metrologic parameters, trajectory, Coulomb force for the interaction, angular momentum conservation law and Newton axiom for the description of the trajectory, correlation of scattering angle and impact parameters, theory of scattering of many particles by atomic nuclei of metal foils, connection of space angle and detector area, final formula. This derivation is commented at each step.

The next menu item contains tasks (Table 5.1).

Table 5.1: Tasks

1. Effect of the slit diaphragm without metal foil
  - a) What is the angular distribution of the counting rate in the slit diaphragm without metal foil? Check your guess, and explain the experimental result. What are the measures to achieve an ideal experimental result?
2. Angle dependence of the scattered  $\alpha$ -particles with gold foil
  - b) Gain an overview of the scattering of the  $\alpha$ -particles by means of probabilities.
  - c) Consider in which angular range and with which step widths a measurement of the angular dependence of the scattering rates of the  $\alpha$ -particles according to the prediction of the Rutherford grades is useful. Observe the required total measuring time.
  - d) Measure  $\Delta N_D(\vartheta)$  for the gold foil and check if  $\Delta N_D \propto \sin^4(\vartheta/2)$ .
  - e) Consider the findings of a measurement of the scattering rates at larger scatter angles. For this purpose, measure the measured values on the gold foil for large angles (see menu item Material).
3. Angle dependence of the scattered  $\alpha$ -particles with aluminium foil
  - f) Give reasons for whether the aluminium foil is larger or smaller in size of scattering rates than the gold foil.
  - g) Measure  $\Delta N_D(\vartheta)$  for the aluminium foil and represent the pairs of measured values in a suitable coordinate system. Which problems arise for the evaluation? How do you make sense?
4. Determination of nuclear charge numbers
  - h) Determine the nuclear charge number of gold ( $e = 1.6 \times 10^{-19} \text{ C}$ ,  $\epsilon_0 = 8,854 \times 10^{-12} \text{ As / Vm}$ ). Discuss the causes of the deviation from the literature value and make a worst case estimate of the error.
  - i) Determine by which factor the nuclear charge numbers of gold and aluminium differ.

In the menu point *Laboratory*, the experimenter / user sees in the centre the web cam image of the scattering chamber with source S, metal foil Au, detector D, as well as counter display. On the right the control panel: selection of the scattering object, choice of the scattering angle, time interval for measurement. If the user chooses to start experimenting, he can see authentically through the web cam what he is doing. The control panel can be operated intuitively and takes into account all interactions.

In the menu point *Evaluation*, the scattering distributions for the slit diaphragm, for the gold foil and aluminium foil, are shown. Laboratory inadequacies (e.g. displacement of a scattering distribution against scattering angle  $\vartheta = 0$ ) as well as measurement errors are discussed. The measured values for the gold foil are used in the Rutherford scattering formula and are shown graphically. Finally, the relative ratio of the nuclear charge numbers Z for both metal foils is determined and the deviation from the expected value is commented.

The next menu item *Discussion* (Table 5.2) contains in-depth questions on the experimental set up, theory, measurement and analysis.

The last sub-item *Materials* contains, of course, details about experimental set up materials, as well as a list of further literature (possible topics for student presentations). The didactic material - see the following subsection - contains:

- Our publication of this RCL [6],
- A teaching unit,
- Task collection with model solutions,
- A didactic analysis of the experiment,
- A worksheet for students for independent measuring.

### 5.2.3 Theoretical basics

In the measurement of the speed of light, only the definition of velocity was important; in the Millikan experiment, the final formula for the charge could also be derived simply from the force balance on an oil droplet during the rising / falling. Here is something different.

Table 5.2: Discussion

1. Experimental setup
  - a) Which influence on the angular dependence of the number  $\Delta N_D(\vartheta)$  of scattered  $\alpha$ - particles has an enlargement of the detector surface  $\Delta A_D$  or an enlargement of the scattering surface of the metal foil  $A_F$ ?
  - b) How does a semiconductor detector work?
  - c) What is the essential advantage of the study of the scattering of  $\alpha$ -particles by the experimental arrangement of J. Chadwick, as opposed to that of Rutherford? Perform a search (e.g. on the Internet).
2. Theory
  - a) Why can the electrons in the metal foil be neglected in the first approximation when  $\alpha$ -particles are scattered?
  - b) Does not the gravitation play a part in the scattering of the  $\alpha$ -particles at the mass-rich nuclei?
  - c) What basic model assumptions are made in the derivation of the Rutherford scattering formula?
  - d) Why is it not useful to investigate the scattering of gases of the elements  $H_2$ , He, Li,  $N_2$  or  $O_2$  instead of metal foils using the Rutherford method?
  - e) Compare the de Broglie wavelength of  $\alpha$ -particles and electrons of the same energy: When are  $\alpha$  particles more suitable for scattering experiments, when electrons?
  - f) By what mechanisms can  $\alpha$  particles lose kinetic energy in matter? For which questions of the experiment is this important?
3. Laboratory
  - a) How long would the measurement time have to be when using the gold foil in the experiment in order to measure the number of backscattered particles at the angle  $\vartheta = 180$  at 10%?
  - b) How could one determine from which angle of scattering the Rutherford scattering formula applies?
  - c) Assess the quality of the beam preparation (setup between alpha-ray source and metal foil) in the experiment.
4. Evaluation
  - a) What causes a displacement of the measured values in a  $\Delta N_D(\vartheta)$  diagram along the  $\vartheta$  axis and along the  $\Delta N_D$  axis?

When  $\alpha$  particles (total number  $N$ , kinetic energy  $E_{\text{kin}}$ ) hit a metal foil (atomic nuclear density  $n$ , nuclear charge number  $Z$ , thickness  $d$ ), then the number  $\Delta N_D$  is the number of scattered alpha particles registered under the scattering angle by the semiconductor detector (semiconductor detector area  $\Delta A_D$ , distance  $R$  of metal foil scattering area) according to Rutherford.

$$\Delta N_D = N \frac{nd}{R^2} \left( \frac{Ze^2}{8\pi\epsilon_0 E_{\text{kin}}} \right)^2 \frac{1}{\sin^4\left(\frac{\theta}{2}\right)} \Delta A_D$$

Such complex formula can be better memorized and understood if the structure is worked out (Table 5.3).

As for the Rutherford atomic model, the angular distribution of scattered  $\alpha$ -particles can also be modelled for Dalton's and Thomson's atomic models. In Figure 5.5, theory and experiment are compared and the Rutherford atomic model is presented as suitable, which correctly describes the measured values.

For scattering angles larger than a critical scattering angle  $\theta_K$  approx.  $90^\circ$  (see Fig. 5.6), the experimentally measured values are lower than the theoretically calculated curve according to the Rutherford scattering formula: Large scattering angles occur for small impact parameters  $b$ . In the vicinity of the nucleus, however, besides the Coulomb force, which is taken into account only in the Rutherford scattering, the short-range-attracting nuclear force also acts on the  $\alpha$ -particle. Two further reasons are mentioned in the corresponding literature: the field of the electrons in the atomic shell of the gold atom, as well as scattering by several gold nuclei; in this case, the gold nucleus is no longer to be regarded as a point. The quality of the measured data is so good that it is possible to distinguish between the gold atoms ( $Z = 79$ ) and aluminium atoms ( $Z = 13$ ) (see evaluation). It is advisable to determine  $Z$  from the Rutherford scatter formula.

$$Z = \frac{8\pi\epsilon_0 E_{\text{kin}}}{e^2} \sqrt{\frac{\Delta N_D R^2 \sin^4\left(\frac{\theta}{2}\right)}{\Delta A_D N n d}}$$

and to form the ratio

$$\frac{Z_{\text{Au}}}{Z_{\text{Al}}} = \frac{E_{\text{kin,Au}}}{E_{\text{kin,Al}}} \sqrt{\frac{\Delta N_{D,\text{Au}} d_{\text{Al}} n_{\text{Al}}}{\Delta N_{D,\text{Al}} d_{\text{Au}} n_{\text{Au}}}}$$

Table 5. 3: Qualitative explanation of the Rutherford scattering formula.

Dependence	Qualitative explanation
$\Delta N_D \propto N$	In the case of $n$ -times the number of $\alpha$ -particles on the metal foil, $n$ times as many are scattered in each direction.
$\Delta N_D \propto 1/[\sin^4(\vartheta/2)]$	$(\vartheta/2)$ larger $\rightarrow \sin^4(\vartheta/2)$ greater $\rightarrow 1/\sin^4(\vartheta/2)$ smaller $\rightarrow$ decrease of scattered particles $\Delta N_D$ with increasing scattering angle $\vartheta$ . Straight power distribution $\Delta N_D$ symmetrical to $\vartheta = 0$ since exponent of sin function is an even integer. 4th power causes rapid decrease of $\Delta N_D$ with $\vartheta$ .
$\Delta N_D \propto Z^2$	The $Z$ -dependence of $\Delta N_D$ is due to the $Z$ -dependency of the Coulomb force. Since collision parameter $b$ is proportional to $Z$ and the same holds for $\Delta b$ and $Z$ , the surface area of $\alpha$ -particles with collision parameter $b$ is that $\Delta A_D = 2\pi d \Delta b \approx Z^2$ .
$\Delta N_D \propto d$	A multiplication of the thickness of the metal foil $d$ multiplies $\Delta N_D$ because the number of atomic nuclei is multiplied.
$\Delta N_D \propto n$	A multiplication of the atomic nucleus density $n$ multiplies $\Delta N_D$ because the number of atomic nuclei is also multiplied.
$\Delta N_D \propto 1/E_{kin}^2$	At higher kinetic energy, the stream of $\alpha$ -particles, which runs along an atomic nucleus, is closer to the atomic nucleus. As a result of the increasing Coulomb interaction near the nucleus, this particle stream is fanned more and the $\alpha$ -particles are more distributed.
$\Delta N_D \propto \Delta A_D$	With $n$ -fold detector area $\Delta A_D$ , $n$ times as many $\alpha$ -particles are detected (with constant scattering rates and if the detector area is not enlarged a lot). $\Delta N_D$ is averaged by the detector over a larger angular range.
$\Delta N_D \propto 1/R^2$	At $n$ -fold film-detector-distance $R$ , the scattered $\alpha$ -particles are distributed to the $n^2$ -times larger sphere surface and $\Delta N_D$ becomes $n^2$ times smaller.

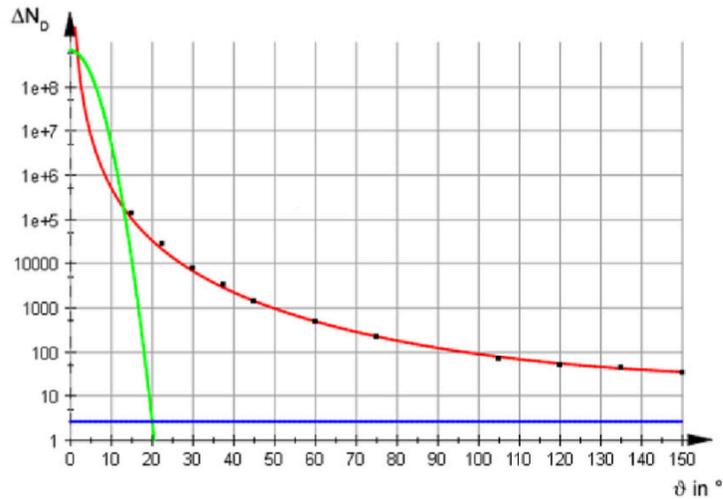


Figure 5.5: Number  $\Delta N_D$  of the  $\alpha$ - particles scattered at the same time intervals in a logarithmic representation over the scattering angle  $\vartheta$  for  $d = 2 \mu\text{m}$  thick gold foil with  $Z = 79$ ,  $N = 6,5 \times 10^8$   $\alpha$ - particles with kinetic energy  $E_{kin} = 5,45 \text{ MeV}$  and detector area  $\Delta A_D = 3,8 \text{ mm}^2$ . Theoretical graphs for Dalton atomic model (spherical radius  $r_K = 2 \text{ pm}$ , blue), Thomson atomic model (atomic radius  $r_A = 144 \text{ pm}$ , 8000 atomic layers, green) and Rutherford (red). Experimental measured values according to Rutherford (black)

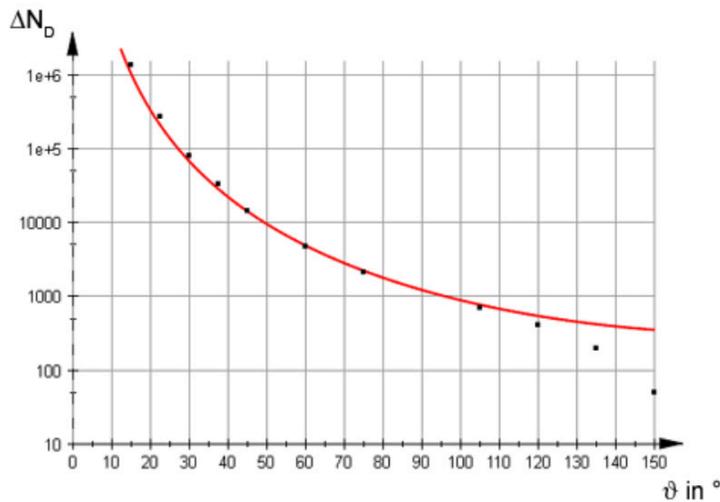
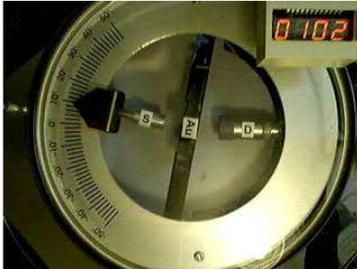


Figure 5.6: Deviations from the Rutherford scattering formula for large scattering angles: Theoretical progression according to Rutherford (red), measurements (black).

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### Rutherford's Scattering Experiment

- Introduction
- Setup
- Theory
- Tasks
- Laboratory
- Analysis
- Discussion
- Material
- Support



Display of digital counter:

1. Countdown of chosen time interval
2. Number of registered alpha particles

### Rutherford's Scattering Experiment Laboratory

Remaining time to perform experiment:  s.

Scattering object:  Adjust

Scattering angle (-50° - +50°):  ° Adjust

Time interval (0 - 300 s):  s Start

Realign experiment

Restart (RESET):  
In case the experiment does not react on input you can restart the RCL. This will take approximately 2 minutes. After that please call the RCL again using the menu item "RCL" at the RCL homepage. MS Windows sometimes causes a problem when communicating through the RS232 interface on the server.

RCL RESET

Figure 5.7: Laboratory page of the experiment with experimental menu (left), webcam image (centre) and control panel (right).

### 5.2.4 Operating the experiment

If the experimenter / user calls the menu point *Laboratory*, he / she can log on and start the experiment as long as no other user is active. In the middle of the screen, he can see the webcam image of the experimental setup from above (Figure 5.7). On the right the control panel. In the upper right corner the remaining time is presented until the user changes a technical parameter. First, the experimenter should select the scattering object (gold foil Au, aluminium foil Al, slit opening) and press the button to adjust the scatter object. On the web cam he can follow this. Next, he can select a *scattering angle* from a range +50 to -50 degree; if he presses the corresponding button to set the scatter angle, the detector moves to the position using a stepping motor; In the webcam image, the triangular arrow shows the approximate position on the angle scale (internally the angle accuracy is  $<0.5$  degree). Thirdly, he has to consider the measurement time interval (range 0-300 sec) and start the measurement with the button *Start measurement*. In the webcam image, the experimenter sees the counter display in the upper right; the system counts from 9, 8, 7, 6, , 0 and then displays the counting rate; i.e. the number of scattered  $\alpha$ -particles at the selected scattering angle in the set time interval.

What are the interactions behind pushing these buttons?

- The experimenter can choose one from two metal foil types with the nuclear charge numbers  $Z_{\text{Au}}$  and  $Z_{\text{Al}}$  and determine the ratio of the two nuclear charge numbers from his own measured values.
- He must consider the proper measurement time intervals for the different scattering angles, than set these time intervals.
- He measures the scattering processes and determines the scattering rate.
- The scattering angle can be selected and measured.

In terms of general lab-objectives: The user selects objects (metal foils), takes a series of measurements (angle of scattering against scattering rate), sets technical parameters (nuclear charge number, measuring time) and can realign the experiment again (metal foil wheel, scattering angle). That is, several interactions, which are experiment specific in addition.

### 5.2.5 Measurement result

Figure 5.8a shows the scattering angle distribution for the 2 metal foils as well as the slit diaphragm. It is immediately apparent that the distribution for the gold foil is symmetrical to the scatter angle  $\vartheta = 0$ , as is expected with a perfect adjustment. Both other are slightly displaced from the zero position of the angle (Fig. 5.8b); we could have done more effort to adjust these two scattering objects better; but this result also has a convincing laboratory component. This offset scattering angle  $\vartheta_0$  can be read off in the case of aluminium ( $\vartheta_0=8$  degree) and slit opening ( $\vartheta_0=2$  degree) and taken into account in this graph fit function.

The distribution of the measured data points in the case of the mere slit opening is not rectangular as one would expect; the radioactive source has an active area of about  $5 \text{ mm}^2$ , the irradiated area at the location of the metal foils is about  $4 \text{ mm}^2$  and the detector area is about  $4 \text{ mm}^2$ , thus not at all point like. Therefore, the measured scattering angle distribution in the case of the gold / aluminium foil for small scattering angles is essentially determined by the finite extent of the mentioned objects. Remember that the Rutherford scattering formula diverges for scattering angle  $\vartheta_0=0$  degree.

The area below the scattering angle distributions for the slit opening and for the gold foil is almost the same size; consequently, only a few alpha particles are absorbed by the gold foil. The area under the curve for aluminium is only about 0.6 of the other two; this has two reasons: the aluminium foil is slightly thicker ( $d_{Al}: d_{Au} = 4: 1$ ); the energy losses of the  $\alpha$  particles in a metal foil are greater when the nuclear charge number  $Z$  is smaller.

The angular distributions for the two metal foils are somehow broader than for the slit opening, since the  $\alpha$  particles are scattered in the direction of greater scattering angles.

Finally, the quantitative evaluation of the measured values with respect to the  $\sin^{-4}(\vartheta/2)$  and the  $Z$  dependence in the Rutherford scattering formula will be discussed. If all technical parameters for the radioactive source, the scattering geometry and the measured scattering angle distribution are inserted into the formula, we obtain for Gold the result shown in Figure 5.9a.

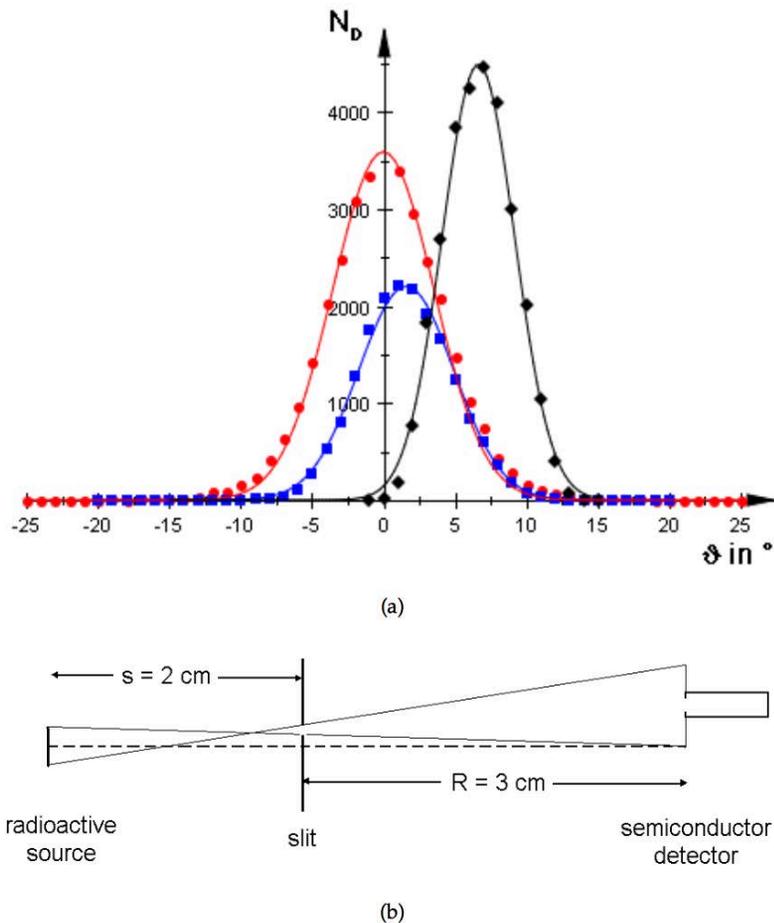


Figure 5.8: (a) Number  $N_D$  of the registered  $\alpha$ -particles as a function of the scattering angle  $\vartheta$  for the slit opening (black squares), for the gold foil (red circles) and for the aluminium foil (blue diamonds). The measured values can be modelled approximately by a Gaussian curve (line). (b) Geometric arrangement - seen from above - for the radioactive source, scattering foil and slit, and detector [6].

In the case of the gold foil (Fig. 5.9a), the theoretically expected straight line for the scattering formula  $N_D(\vartheta) \propto \sin^{-4}(\vartheta/2)$  deviates significantly from the measured values for angles  $\vartheta < \pm 7$  degree (see: Influence of scattering geometry). For larger scattering angles, we see

no deviation from the theoretically expected progression (see the arguments to Figure 5.6)

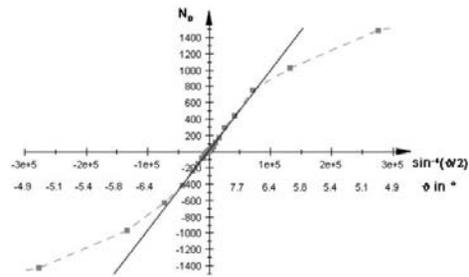
A short estimate to show how near an alpha particle approaches the gold nucleus in principle; more or less a question about the influence of nuclear forces: From the energy conservation ( $E_{\text{kin}} = E_{\text{Cb}}$ ) in the case of a central collision, we can determine the smallest distance between the alpha particle and the scattering gold nucleus. In case of  $E_{\text{kin}} = 4,5 \text{ MeV}$  we get  $r_{\text{Au,min}} = 51 \text{ fm}$  ( $r_{\text{Al,min}} = 8 \text{ fm}$ ) in comparison to the nuclear radius  $r_{\text{Au}} \approx 7 \text{ fm}$  ( $r_{\text{Al}} \approx 3.6 \text{ fm}$ ), which makes it possible to rule out the influence of short-range nuclear forces in this experiment.

From the slope of the straight lines in Fig. 5.9b and 5.9c as well as the corresponding formulas for the nuclear charge number (see earlier), we can determine the nuclear charge numbers  $Z_{\text{Au}} \approx 116$  (in reality 79) and  $Z_{\text{Al}} \approx 18$  (13). The deviation has in our opinion at least two reasons:

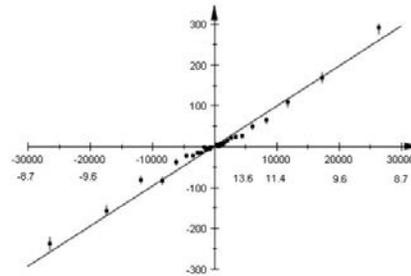
1. The nuclear charge number  $Z$  is determined by several parameters ( $d, A_d, R, N$ ) which themselves have an inaccuracy of about 10%.
2. The energy losses of the  $\alpha$ -particles in the cover of the radioactive source as well as in the metal foils are considerable ( $\Delta E_{\text{kin, Au}} \approx 0.4 \text{ MeV}$ ,  $\Delta E_{\text{kin, Al}} \approx 0.5 \text{ MeV}$ ). Thus, we can correct the nuclear charge number,  $Z_{\text{Au}} \approx 86$  and  $Z_{\text{Al}} \approx 12$  with an error of 10%. A very satisfactory result with this simple experimental set up.

### 5.3 Evaluation and experience

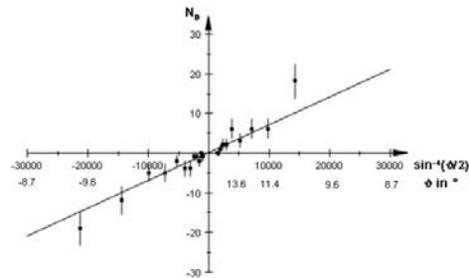
The self-obtained measured values are so good that it is possible to clearly distinguish between the three atomic models. The Rutherford scattering formula can be convincingly confirmed experimentally ( $\sin^4(\vartheta/2)$ ,  $Z$ -dependence, scattering geometry, properties of scattered objects) in a scattering angle range  $8 < \vartheta < 25$ . The deviation between experiment and theory for small angles is clearly measurable and can be explained by our experimental set up.



(a)



(b)



(c)

Figure 5.9: (a) Number  $N_D$  of the registered  $\alpha$ -particles as a function of  $\sin^4(\vartheta/2)$  for the gold foil and scattering angles  $\vartheta < 25$  degree (grey squares and dashed line). For the sake of clarity the measured values  $N_D$  are shown negatively for scattering angles  $\vartheta < 0$ . The solid line corresponds to the theoretically expected curve  $N_D(\vartheta)$  for scattering angles  $\vartheta > 6$  degree. The scattering angle distribution for gold foil (b) and aluminium foil (c) is shown in comparison to scattering angles  $8 < \vartheta < 25$  (squares).

The measuring time for one scattering angle is short (<1 min), for a series of measurements with several angles medium (10 -20 min); if one wants to measure accurately, especially at large scatter angles, it requires hours. But as experimental homework for about 10 groups of 2 students, sufficient data can be obtained in a tolerable time for each group. The RCL Rutherford runs since 2007 in continuous operation without problems (vacuum pump, radioactive source) and necessary care.

In Section 1 (Introduction), the shortcomings of the traditional real experiments as well as the advantages of the RCL variant were listed. The added value of the Rutherford scatter experiment as RCL is the following and offers the teacher opportunities to enrich the teaching by new teaching / learning forms:

- Schools that are missing the real experiment are available free of charge on the RCL portal.
- Students can independently plan their own measurements at home (e.g. to arrive at meaningful experimental results with as few measurements as possible), carry out and evaluate them.
- The teacher has not only the opportunity to distribute experimental home work, but also to organize students work in groups and to collect extensive data material in electronic form.
- Students can hold experimental lectures with this RCL, which would otherwise only be possible in a restricted form.
- It is also conceivable for projects in which a group of pupils prepares themselves as independently as possible with the help of an experiment for a larger presentation (e.g. open day at school).
- The learning environment of the RCL provides teachers with a wide range of teaching materials and students with all the necessary information to understand the experiment.

The RCL has been visited in the past years about four times a day, whether for experimenting or to reading the websites.

What is missing is an investigation as how the experimenter operates with it:

- How long is a user logged in? Where does he quit this website?
- Qualitative or quantitative measuring?
- Unsystematic (permanent change of scattering objects) or systematic (measurement series with several scattering angles) measuring?
- Meaningful measuring series with suitably selected parameters (select a longer measuring interval at large scatter angle)

## 5.4 Didactic material

The point *Material* in the navigation menu contains both necessary information on the technical details of the teaching material manufacturer (radioactive source, scattering chamber, counting unit) as well as suggestions for the teacher.

If the teacher wants to introduce the prototype of scattering experiments in his class, here is a suggestion: How can one deduce from the measured angular distribution of scattered particles on the (geometric) properties of the scattering object? Imagine a covered cube (about 50 cm in length). In it an object (disk, sphere, cone, ...) is invisible. If you shoot with an air gun on the cube you can see the entrance / exit positions of the projectiles. If this gun is systematically moved horizontally with respect to the cube (impact parameter), the angular distribution of the scattered balls can be observed and the shape of the object can be concluded indirectly.

The obvious use of this RCL is an experimental homework organized in groups. For this purpose, here is a possible worksheet for motivation (Table 5.4).

For the subsequent lesson we formulate the following learning objectives:

The pupils should

- Use knowledge from mechanics, electrostatics and radioactivity to explain the scattering of  $\alpha$ -particles,
- Experimentally investigate the scattering of  $\alpha$ -particles with the RCL "Rutherford scatter experiment"

- Compare the predictions for the scattering of  $\alpha$ -particles according to the Daltonian, Thomsonian, and Rutherford model with the measurement results.
- Present experimental results appropriately.

The following didactic considerations form the basis of this teaching unit: The Rutherford scattering experiment is one of the central experiments of physics. Historically, the Rutherford atomic model, derived from it, forms the transition from earlier atomic conceptions (ancient atomic model and Thomson's atomic model) to our present atomic concept, according to which an atom consists of a positively charged nucleus and a negatively charged shell. The Rutherford scattering experiment also provides the physical basis for today's standard method of the element-specific analysis of solid samples by means of Rutherford backscattering spectroscopy (RBS). Thus, this experiment is relevant both in general education for students at school and university, as well as in specific education for students of physics and chemistry.

Table 5.5 contains a proposal for a teaching unit as a flow chart with detailed information on the individual steps:

For this RCL experiment, we have also prepared a very complex collection of tasks with model solutions: about 8 tasks for theory, 3 tasks for experimental setup, 5 tasks for measuring and evaluation; i.e. 16 tasks consisting of 57 individual tasks. These are suitable for school (20), for school / university (16), only for university (21). Table 5.6 shows an overview - task / learning content / teaching use - to help the teacher to find more quickly his own selection.

At the beginning of all tasks, all experimental data used in the experiment or required for the solutions of the tasks are presented: to the metal foils, to the properties of the  $\alpha$ - particles, to the scattering geometry, and some fundamental constants.

Then we present some tasks with model solutions in Table 5.7.

Finally, a note about a multi-hour measurement series on the gold foil for large scattering angles - see navigation menu / material / measurement data. Only in the rarest cases will an experimenter make the effort to generate his own measurement data, because this experiment will last hours; but for further analysis, however, these raw data in form of a table are very well suited.

Table 5.4: Worksheet - Rutherford scattering.

## Worksheet --- Rutherford scattering

## 1. Questions:

- a) Is there a difference in the scattering rate at the scattering angles + and -?
- b) Source, metal foil and detector. Which component is fixed, which can be rotated?
- c) For scattering angles greater than  $10^\circ$ , longer time intervals should be selected for the measurement of the scattering rates. Why?

## 2. Measure the scattering rates at several angles as well as at one angle several times.

$0^\circ$	$5^\circ$	$10^\circ$	$15^\circ$	Group 1
$1^\circ$	$6^\circ$	$11^\circ$	$16^\circ$	Group 2
$2^\circ$	$7^\circ$	$12^\circ$	$17^\circ$	Group 3
$3^\circ$	$8^\circ$	$13^\circ$	$18^\circ$	Group 4
$4^\circ$	$9^\circ$	$14^\circ$	$19^\circ$	Group 5
Measurement 1	Measurement 2	Measurement 3	Measurement 4	

3. Create a graph: number of scattered  $\alpha$ -particles against scattering angles; including error bars.

## 4. Discussion:

- Create a table for all 20 scattering angles.
- Calculate the expression  $\sin^{-4}(\theta/2)$  according to theory
- Plot  $N_D$  (for  $\Delta t = 100$  s) against  $\sin^{-4}(\theta/2)$
- Discuss the size of the error bars as well as the quality of the result.
- Can you see a deviation from the expected theory curve for  $\approx 100^\circ$ ? Explain!

Table 5.5: Instructional use - Rutherford scattering.

Instructional use of the RCL Rutherford scattering experiment
<p>1. Idea</p> <p>The contents of the radioactivity necessary for the understanding of the experiment - especially the decay statistics - are mediated before the experiment and then applied directly to the RCL. This allows a physically correct test to determine whether the Rutherford scattering formula correctly describes the angular dependence of the scattered alpha particles.</p> <p>The students are experimentally and theoretically investigating in parallel, according to the respective atomic model (Dalton, Thomson, Rutherford), the question, which atomic model describes the scattering of the alpha particles best. This is the only way to allow the critical discussion of different atomic models and the reasoned rejection of some models</p>
<b>2. Flow diagram of the teaching unit</b>
<p><b>Introduction to atomic physics (1)</b></p> <p>Oil drop experiment</p> <p>Atomic models (antique, Dalton, Thomson)</p>
↓
<p><b>Basics Rutherford scattering (2)</b></p> <p>Types of radiation</p> <p>Detection of <math>\alpha</math>-particles with semiconductor detector</p> <p>Absorption of alpha radiation</p> <p>Decay statistics</p>
↓
<p><b>Initial experiment and hypothesis formation (3)</b></p> <p>Qualitative detection of the scattering of <math>\alpha</math>-particles</p> <p>Hypotheses about the relevant forces</p> <p>Multi-particle scattering, single and multiple scattering</p> <p>Structure of metal foil</p> <p>Experimental setup for quantitative analysis with RCL</p>
↓
<p><b>Model and Experiment (4)</b></p> <p><b>RCL "Rutherford scattering experiment"</b></p> <p>Angle distribution of the scattered <math>\alpha</math>-particles</p> <p>Offset correction</p> <p>Fit the measuring points with different functions</p> <p>Application of decay statistics</p>
↓

	<b>Team "Dalton's Model"</b>	<b>Team "Thomson Model"</b>	<b>Team "Rutherford Model"</b>
Particle scattering	Calculation and comparison of the scattering function with quantitative model experiment (deflection of a sphere or reflection of a laser beam on a cylinder)	Modelling Calculation of the scattering angle	Modelling Mathematical discussion of the given scattering function Qualitative model experiment (Deflection of a suspended charged ball by another charged ball)
Many-body scattering	Construction of a model experiment (Galton board made of nails) Investigations on the scattering and the single and multiple scatter with the model experiment.	Comparison of the measuring results with a given scattering formula Lenard's experiment with electrons and thin aluminium foil (so-called Lenard's window)	Comparison of the results with Rutherford scattering formula Qualitative explanation of the dependencies in the Rutherford scattering formula
↓			
	<b>Presentation of the results (5)</b> Comparison of models with respect to scattering function and experimental results Limits of the Rutherford model		
↓			
	<b>Deepening and final test (6)</b> Practicing of problem solving with problem from the collection Experiment: determination of nuclear charge number, lower boundary of validity of Rutherford's scattering formula Test		

### 3. Details and tips on the steps

#### **Introduction Atomic Physics (1)**

Traditional introduction to atomic physics with the aim of developing qualitative concepts of the atomic models up to Thomson's.

Can be performed as a learning circle with the stations Oil Spot Experiment, Antique Atom Models, Dalton's Atom Model and Thomson's Atom Model. This has the advantage that students can carry out the oil spot experiment by themselves and the reading and processing of texts is promoted.

#### **Basics Rutherford Scattering Experiment (2)**

The aim is to lay the foundations for understanding the experimental set-up and the measurement results of the Rutherford scattering experiment

Use RCL radioactivity for decay statistics, types of radiation, alpha radiation and alpha radiation absorption.

Use exercises II.2, II.3 and III.2 from the task collection.

#### **Initial experiment and hypothesis formation (3)**

Investigation of the scattering of alpha radiation in air and through a metal foil in air. This leads to questions of the experimental design of the RCL (minimizing absorption, suitable radiators, jet preparation) and hypotheses of the causes of the scattering and the scattering mechanisms.

The absorption of radioactive radiation is an obvious assumption and causes little problems for students. However, it is astonishing that in addition to absorption, there is a scattering of the alpha radiation as it passes through matter.

Discuss the further procedure for the investigation of the scattering (model and experiment).

#### **Model and experiment (4)**

The aim is to explain the angular distribution of the  $\alpha$ -particles measured by the RCL with the atomic models of Dalton, Thomson and Rutherford.

Use tasks I.1, I.2, I.5, I.6, I.7 and II.1 of the task collection and own teaching materials as a working basis for the groups.

Example measurement with RCL in class. Further measurements with the RCL take place in the teams from home, which also brings a gain in class time.

### **Presentation of the results (5)**

Teams present their results in limited time.

Subsequent contents: Key points of Rutherford's atomic model, possibly original publications by Rutherford-Geiger-Marsden, limits of Rutherford's Atomic Model

### **Deepening and test (6)**

Modelling is deepened by extending the model for the scattering of one  $\alpha$ -particle to prove the validity of the law of conservation of energy or to investigate the influence of nuclear forces on particle motion (see Exercises I.1d and I.4d).

Measurement errors of integer quantities such as the atomic number  $Z$  are particularly obvious. Perform worst case estimates for error estimation (no error propagation).

Test contents: Setup and operating the Rutherford scattering experiment, evaluation of measurement series, simpler arithmetic tasks for the scattering of alpha particles, fitting of model and experiment.

Table 5.6: Overview of the task collection.

	<b>task topic</b>	<b>learning content</b>	<b>educational use</b>
I.1	Single particle scattering in Rutherford's atomic model	<ul style="list-style-type: none"> <li>• Relevant forces in the scattering</li> <li>• Discussion and application of the scattering function</li> <li>• Simulation of the trajectories of scattered alpha particles with a modelling program</li> </ul>	<ul style="list-style-type: none"> <li>• Teaching project with experimental group (deflection of a charged TT ball), mathematics group (discussion of the scattering function with computer algebra system) and model formation group (modelling of the two-dimensional Coulomb scattering)</li> </ul>
I.2	Many particle scattering in Rutherford's atomic model	<ul style="list-style-type: none"> <li>• Qualitative explanation of dependencies in Rutherford's formula</li> <li>• Correlations between the distribution of alpha particles and Rutherford's scattering formula</li> <li>• Application of the scattering formula to the RCL and the backward scattering</li> <li>• Determine the sum function for the angular distribution of the alpha particles</li> </ul>	<ul style="list-style-type: none"> <li>• Content for theory input by teachers after measuring the angle dependence with RCL</li> <li>• Apply the formula to students with the data of the RCL on their own</li> <li>• Task e) for students or talented students</li> </ul>
I.3	Model assumptions for the derivation of the Rutherford scattering formula	<ul style="list-style-type: none"> <li>• Name and substantiate model assumptions for the derivation of the Rutherford scattering formula</li> <li>• Experimental verification of single scattering</li> <li>• Energy loss of alpha particles by collision</li> </ul>	<ul style="list-style-type: none"> <li>• Content for teacher-guided lessons with more independent work phases of the pupils</li> <li>• Physical application of the curve discourse a broken-rational function</li> </ul>

I.4	Estimation of the radius of the atomic nucleus	<ul style="list-style-type: none"> <li>• Calculation of the smallest distance between alpha particles and nucleus</li> <li>• Explanation of the deviation of measurement results from the Rutherford scattering formula</li> <li>• Estimation of the gold atomic nucleus radius</li> <li>• Potential of nucleus and atomic shell</li> <li>• Influence of the nucleus potential on the scattering</li> </ul>	<ul style="list-style-type: none"> <li>• Application of knowledge in mechanics and electrostatics</li> <li>• Discussion on different methods of determination of nuclear radius</li> <li>• For students: Examining the influence of the nuclear potential on scattering by means a modelling program</li> </ul>
I.5	Particle scattering in Dalton's atomic model	<ul style="list-style-type: none"> <li>• Derivation and discussion of the scattering function</li> <li>• Derivation of a Dalton scattering formula in analogy to the Rutherford scattering formula</li> </ul>	<ul style="list-style-type: none"> <li>• Derivation of the scattering function in small groups (application of mathematical knowledge)</li> <li>• Possibility of experimental confirmation of the scattering function with reflection of laser beam by cylinder</li> <li>• Possibility of experimental confirmation of the Dalton scattering formula with self-built model experiment</li> <li>• For students: derivation of Dalton's scattering formula</li> </ul>

I.6	Particle scattering in Thomson's atomic model	<ul style="list-style-type: none"> <li>• Conclusions from Lenard's experiments with electrons</li> <li>• Estimation of the scattering angle for single particle scattering</li> <li>• Scattering rates in terms of Thomson's and Rutherford's atomic models</li> </ul>	<ul style="list-style-type: none"> <li>• Content for teacher-guided lessons with more autonomous student work phases</li> <li>• For students: Mathematical comparison of the scattering in Thomson's and Rutherford's atomic models</li> </ul>
I.7	Structure of metal foils	<ul style="list-style-type: none"> <li>• Calculation of element cell sizes from macroscopic data</li> </ul>	<ul style="list-style-type: none"> <li>• Exercise after appropriate preparation by the teacher</li> </ul>
I.8	Circular motion of electrons in Rutherford's atomic model	<ul style="list-style-type: none"> <li>• Acceptance of a circular movement</li> <li>• Calculation of orbit, time for one orbit, kinetic and potential energy of an electron</li> <li>• Problem of the radiation of accelerated charges</li> </ul>	<ul style="list-style-type: none"> <li>• Application of knowledge of mechanics</li> <li>• Understanding the sign and the course of energies in the atom</li> </ul>

II.1	Experimental setup RCL "Rutherford Scattering Experiment"	<ul style="list-style-type: none"> <li>Name and function of experimental components</li> </ul>	<ul style="list-style-type: none"> <li>Task to the first use of the RCL</li> </ul>
II.2	Radiation source for Rutherford's scattering experiment	<ul style="list-style-type: none"> <li>Reasonable choice of a radiation source for Rutherford's scattering exp.</li> <li>Influence of conversion electrons</li> <li>Handling of radioactive radiators</li> </ul>	<ul style="list-style-type: none"> <li>Teacher lecture or student presentation to prepare for the experiment</li> </ul>
II.3	Detection of alpha particles with a semiconductor detector	<ul style="list-style-type: none"> <li>Functional principle of a semiconductor detector</li> </ul> <p>Advantages of a semiconductor detector over an ionization chamber</p>	<ul style="list-style-type: none"> <li>Teacher lecture or student presentation to prepare for the experiment</li> </ul>
III.1	Problem of the Rutherford scattering as a school experiment	<ul style="list-style-type: none"> <li>Planning of measured value recording</li> <li>Statistical measurement error</li> <li>Measures to increase the scattering rate</li> </ul>	<ul style="list-style-type: none"> <li>Deepening of the Rutherford scattering experiment</li> </ul>

III.2	Absorption of alpha radiation	<ul style="list-style-type: none"> <li>• Dependence of absorption of alpha particles of different sizes</li> <li>• Concept of area weight</li> <li>• Estimation of the energy loss of the alpha particles in the radioactive source</li> <li>• Determining energy values for the Rutherford scattering formula</li> <li>• Estimation of the absorption by the residual air in the vacuum chamber</li> </ul>	<ul style="list-style-type: none"> <li>• Teacher lecture or student presentation to prepare for the experiment</li> </ul>
III.3	Influence of the detector area on the measurement of the scattering rate	<ul style="list-style-type: none"> <li>• Qualitative explanation and calculation of influence</li> <li>• Use to measure low rates of scattering</li> </ul>	<ul style="list-style-type: none"> <li>• For students or talented students: use of integral calculus in metrology</li> </ul>
III.4	Evaluation of the scattering angle distribution of gold	<ul style="list-style-type: none"> <li>• Presentation and interpretation of measured values</li> <li>• Possibilities to examine a series of measurements for a functional connection</li> <li>• Calculation of the measuring time to a given statistical error</li> <li>• Validity limit of the Rutherford scattering formula</li> </ul>	<ul style="list-style-type: none"> <li>• Practice and application of knowledge for the representation and evaluation of measurement series</li> <li>• Example that physical laws have only limited scope</li> </ul>
III.5	Investigation of further dependencies of the scattering rate	<ul style="list-style-type: none"> <li>• Dependency of the scattering rate on the metal foil thickness, the atomic number of the metal foil material and the energy of the alpha particles</li> </ul>	<ul style="list-style-type: none"> <li>• In-depth discussion of Rutherford's Scattering formula</li> <li>• Exercise to investigate functional relationships of measurement series</li> </ul>

Table 5.7: Tasks with solutions

**To the theory: Tasks to estimate the radius of the nucleus**

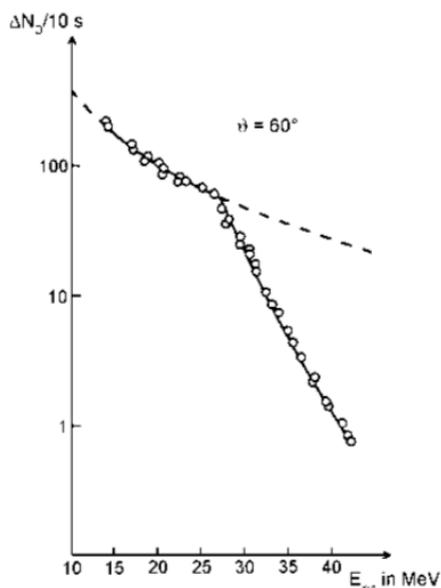
- In which case does the distance to the atomic nucleus become minimal during the scattering of an alpha particle? Derive a formula for the smallest center-to-center distance  $r_{\min}$  between an alpha particle and the atomic nucleus. How big is this for gold? Can this be used to make a statement about the size of the gold atomic nucleus?
- Which functional relationship is represented by the dashed curve in Fig. 3? How is the deviation of the measuring points from the Rutherford scattering formula explained in the figure? Is the deviation in the right direction? In which direction should the value for the kinetic energy -from which the deviation occurs- shift, if the scattering angle is increased?
- For the minimum distance of an alpha particle from the atomic nucleus applies

$$r_{\min} = \frac{b}{\sqrt{1 - \frac{E_{\text{pot}}(r_{\min})}{E_{\text{kin},P}}}}$$

Check the correctness of the formula for the special case from a). Use the information from Fig. 3 under b) to estimate the radius of the gold atom nucleus.

- The nuclear potential of atomic nuclei is described by  $V_0 = 50 \text{ MeV}$ ,  $a = 0.5 \text{ fm}$  and  $r_K = 1.4 \text{ fm}$  ( $A$ )<sup>1/3</sup>, in a good approximation with the Saxon-Woods potential:

$$V(r) = -\frac{V_0}{1 + e^{\frac{r-r_K}{a}}}$$



What is the meaning of the parameters  $V_0$ ,  $r_K$  and  $a$ ? Graph the overall potential of an alpha particle for the gold atom. Use a modelling program to study the influence of nuclear power on the number of alpha particles scattered at the scattering angle.

Fig 3. Theoretical (broken curve) and measured scattering rate (circles) for gold and scattering angle  $60^\circ$ .

### Solutions: Estimation of the radius of the atomic nucleus

- a) The alpha particle has a smallest distance to the atomic nucleus for each impact parameter  $b$  during the movement. Only when the alpha particle is centred on the atomic nucleus ( $b = 0$ ) does it have the smallest possible distance from the nucleus, because once during the motion the velocity or kinetic energy becomes zero and the potential energy becomes maximal and the distance becomes minimal. The application of the law of conservation of energy yields:

$$E_{\text{kin,P}} = E_{\text{pot}} = \frac{zZe^2}{4\pi\epsilon_0 r_{\text{min}}} \Leftrightarrow r_{\text{min}} = \frac{zZe^2}{4\pi\epsilon_0 E_{\text{kin,P}}}$$

Insertion of the values gives for gold  $r_{\text{min}} = 50.5$  fm. The nuclear radius can not be estimated with this calculation, since it is unknown whether the alpha particle has reached the range of short-range nuclear forces or not.

- b) According to the Rutherford scattering formula, Fig. 3 shows the relationship

$$\Delta N_D \sim \frac{1}{E_{\text{kin}}^2}$$

High-energy alpha particles come closest to the atomic nucleus and enter the area of influence of the short-range, attractive nuclear forces. As a result, the resulting deflecting force on the alpha particle becomes smaller and less alpha particles are registered under the fixed scattering angle of  $60^\circ$  than when the Coulomb force alone is present. Increasing the scattering angle means that alpha particles with a smaller collision parameter  $b$  are considered. These get closer to the core, so that the deviation begins even at smaller particle energies.

- c) For  $b = 0$  it follows since  $r_{\text{min}} \neq 0$  that  $E_{\text{pot}}(r_{\text{min}}) = E_{\text{kin,P}}$ . With  $E_{\text{kin,K}} = 28$  MeV, all calculations can still be done in the Coulomb field because the reading is on the Rutherford curve. The collision parameter  $b$  is calculated from the scattering function (see RCL website, Theory, 1.3)

$$b(\vartheta) = \frac{zZ_{\text{Au}}e^2}{8\pi\epsilon_0 E_{\text{kin,K}}} \cot\left(\frac{\vartheta}{2}\right)$$

to  $b(60^\circ) = 7.027$  fm. The potential energy in the Coulomb field is given by

$$E_{\text{pot}}(r) = \frac{zZe^2}{4\pi\epsilon_0 r} = \frac{k}{r}$$

- c) The calculation of  $r_{\min}$  leads to the solution of a quadratic equation:

$$r_{\min} = \frac{b}{\sqrt{1 - \frac{E_{\text{pot}}(r_{\min})}{E_{\text{kin,K}}}}} \Leftrightarrow r_{\min} \sqrt{1 - \frac{k}{r_{\min} E_{\text{kin,K}}}} = b \Leftrightarrow$$

$$\sqrt{r_{\min}^2 - \frac{k r_{\min}}{E_{\text{kin,K}}}} = b \Leftrightarrow r_{\min}^2 - \frac{k}{E_{\text{kin,K}}} r_{\min} - b^2 = 0$$

$$r_{\min} = \frac{k}{2E_{\text{kin,K}}} \pm \sqrt{\left(\frac{k}{2E_{\text{kin,K}}}\right)^2 + b^2}$$

The minus sign provides a negative gold nuclear radius. For the plus sign you get  $r_{\min} = 12.17$  fm. After deducting the nuclear radius of the alpha particle of 2.2 fm, we obtain  $r_{\text{Au}} \leq 10$  fm (literature value  $r_{\text{Au}} = 8.14$  fm).

- d)  $V_0$  determines the minimum of the potential well,  $r_K$  the width of the potential well and  $a$  the steepness of the transition between the bottom and the edge of the potential well (Fig. 18, red curve). The total potential is obtained by adding the Saxon-Woods potential and the Coulomb potential, setting a lower limit for the Coulomb potential (Figure 18, blue curve).

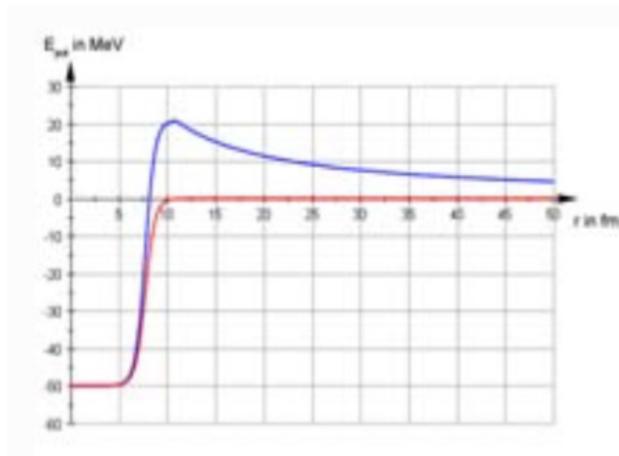


Fig. 18: Graph of the nuclear potential (red) and the total potential (blue) of a gold atomic nucleus as a function of radius.

**The experimental setup:****Tasks for the radiation source for the Rutherford scattering experiment**

For the Rutherford scattering experiment two radioactive sources are available:

Nuclid	Am - 241	Ra - 226
Activity A	340 kBq	3.3 kBq
Beam source diameter	2.5 mm	3 mm
Cover	2 $\mu\text{m}$ rare metal foil	2 $\mu\text{m}$ rare metal foil
Radiation	<p>Energy level diagram for <math>^{241}_{95}\text{Am}</math> decaying to <math>^{237}_{93}\text{Np}</math>. The diagram shows energy levels in MeV (0, 0.0032, 0.0095, 0.0050, 0.01585) and alpha particle energies in MeV (5.48, 5.513, 5.480, 5.440, 5.489). Transitions are labeled with <math>\alpha_1</math> through <math>\alpha_5</math> and <math>\gamma_1</math> through <math>\gamma_4</math>.</p>	<p>Decay scheme for <math>^{226}_{88}\text{Ra}</math> (1600 a) decaying to <math>^{222}_{86}\text{Rn}</math> (3.82 d) and <math>^{214}_{84}\text{Po}</math>. The diagram shows alpha particle energies of 4.59 MeV (5.7%) and 4.78 MeV (94.3%), and a gamma energy of 0.186 MeV. The text indicates "Zerfallsreihe zum <math>^{210}\text{Pb}</math>".</p>

- Give a reasoned statement as to which of the radiation sources is suitable for Rutherford's scattering experiment.
- The decay of Am-241 also produces conversion electrons: by which processes are these generated and how do they differ from the  $\beta$ -radiation? Do the conversion electrons influence the results of the Rutherford scattering experiment?
- Does the decrease in the activity of the Am-241 source during experimenting play a role?
- What are the most important rules for experimenting with radioactive sources?
- At what speed do the alpha particles hit the film in an ideal vacuum? Which acceleration voltage  $U_B$  would they have had to pass to reach this velocity?

**Solutions:****Radiation source for the Rutherford scattering experiment**

- a) More suitable is the nuclide Am-241, because
- the activity for sufficiently scattering rates at large scattering angles is 100 times greater than that of the Ra-226
  - Ra-226 is a mixed emitter that also emits beta radiation besides alpha and gamma radiation in the decay series of the lead. The gamma radiation is not registered by the semiconductor detector. The beta radiation can penetrate the thin metal foils and is registered by the semiconductor detector and thus falsifies the measurements.
  - The daughter nuclide Np-237 from Am-241 is virtually stable and thus the activity of further derived products is negligibly small. Since the gamma radiation is not registered by the semiconductor detector, Am-241 is in the experiment to a first approximation a pure  $\alpha$ -emitter. The emission of alpha particles of different energies (the 5 most frequent ones with energies between 5.389 MeV and 5.545 MeV with  $\Delta E = 156$  keV) play no role in the experiment, since  $\Delta E / E \approx 3\%$  and the single peaks of the energies in passing the metal are broadened and smeared into a single widened peak.
  - Ra-226 is closer to a mono energetic emitter than Am-241, but can not be used because of beta radiation.
- b) Conversion electrons are formed when an excited nucleus gives its energy to the shell electrons (internal conversion). These electrons are mono energetic in contrast to the beta radiation. They produce a noticeable zero effect at large scattering angles, in particular in the backscatter together with "strayed" alpha particles. In the RCL the effect does not matter, because  $|\theta| < 50^\circ$  is.
- c) Because of the relatively large half-life  $t_H = 433$  years or the small decay constant  $\lambda = \ln 2 / t_H$ , the Am-241 decays only slowly. According to the decay law we get for the time  $t$  until the activity has decreased by 1%

$$A(t) = A_0 e^{-\frac{\ln 2}{t_H} t} = 0,99 A_0 \Leftrightarrow t = -\frac{\ln 0,99}{\ln 2} t_H = 6,27 \text{ a}$$

- d) Rules to minimize the exposure to radioactive radiation are:
- Keep as far away as possible from the radiator.
  - Always keep the radiation source away from the body.
  - Always design work processes in such a way that as little as possible has to be handled with the radiator.
  - Keep the duration time of the exposure small.
- e) With  $E_{kin, \alpha} = 4.5$  MeV we get:

$$v_0 = \sqrt{\frac{2E_{kin, \alpha}}{m_\alpha}} = 1,47 \cdot 10^7 \frac{\text{m}}{\text{s}} \quad E_{kin, \alpha} = qU_B = 2eU_B \Leftrightarrow U_B = \frac{E_{kin, \alpha}}{2e} = 2,25 \text{ MV}$$

### For experiment procedure and its evaluation

#### Tasks about the influence of the detector area on the measurement of the scattering rate

- a) Which angular range does the detector detect when measuring at the scattering angle  $\vartheta$ ? Consider how large the detector is by measuring the size of the  $\Delta N_D(\vartheta)$ , and whether the number  $\Delta N_D$  of scattered alpha particles is too large or too small. Check the assumption for a scattering angle with gold and 300 s measurement time.

Note: 
$$\int \sin^{-4}\left(\frac{x}{2}\right) dx = -\frac{2}{3} \cot\left(\frac{x}{2}\right) \cdot \left[2 + \sin^{-2}\left(\frac{x}{2}\right)\right]$$

- b) Compare in a coordinate system the number  $\Delta N_D(\vartheta)$  calculated according to the Rutherford scattering formula for gold and 300 s measurement time with the number of alpha particles registered by the detector. Determine the course of the relative error  $f(\vartheta)$  on the basis of the detector area and discuss the result.
- c) How can the result from b) be used to better cope with the small  $\Delta N_D$  values at large scattering angles?

### Solutions:

#### Influence of the detector area on the measurement of the scattering rate

- a) The detector covers the following angular range:

$$\Delta\vartheta = \frac{e}{R} \cdot \frac{180^\circ}{\pi} = 1,91^\circ \approx 2^\circ$$

The mean value  $\langle \Delta N_D \rangle$  of  $\Delta N_D$  is measured over the interval  $[\vartheta - (\Delta\vartheta)/2, \vartheta + (\Delta\vartheta)/2]$ :

$$\overline{\Delta N_D}(\vartheta) = \frac{\int_{\vartheta - \Delta\vartheta/2}^{\vartheta + \Delta\vartheta/2} \Delta N_D(\vartheta') d\vartheta'}{\Delta\vartheta}$$

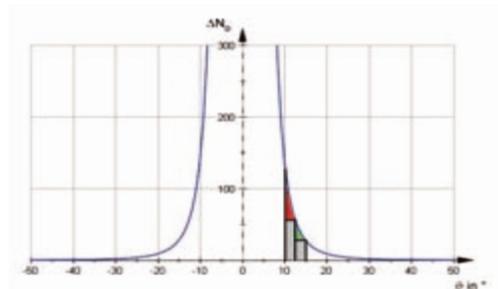


Fig. 25: Graphical illustration of the alpha particles registered by the detector.

$\Delta N_D$  is determined to be too large: If a scattering angle interval is selected that is symmetrical to the set scattering angle, the red area in Fig. 25 is always larger than the green area because of the steeper curve segment. The height  $\Delta N_D$  of the rectangle of gray, red and green area with width  $\Delta\vartheta$  is thus larger than  $\Delta N_D(\vartheta)$ . With numerical or analytical calculation one obtains e. g.  $\Delta N_D(10^\circ) = 134.5$  and  $\langle \Delta N_D(10^\circ) \rangle = 138.7$ .

- b) The difference between  $\Delta N_D(\vartheta)$  (Fig. 26, red curve) and  $\langle \Delta N_D(\vartheta) \rangle$  (Fig. 26, blue curve) towards smaller scattering angles can not be seen because of the increasing steepness of the curves. The more meaningful representation of the relative error  $f(\vartheta)$  in Fig. 27 shows that  $f$  increases towards smaller scattering angles and amounts to  $\approx 3\%$  at the lower limit of  $10^\circ$  of the range of validity of the Rutherford scattering formula. This systematic error is thus at tolerable measurement times below the statistical error. Since, for scattering angles of less than  $10^\circ$ , smaller particle counts occur due to the nuclear forces (compare theory) than according to the Rutherford scattering formula, the two errors are in opposite directions and can simulate an excessively wide range of validity of the scattering formula.
- c) By a wider slit diaphragm in front of the sensitive detector area of the detector diode, the number of detected alpha particles, in particular at larger scattering angles, are doubled or tripled. The measured number  $\Delta N_D$  can then be corrected downwards with b).

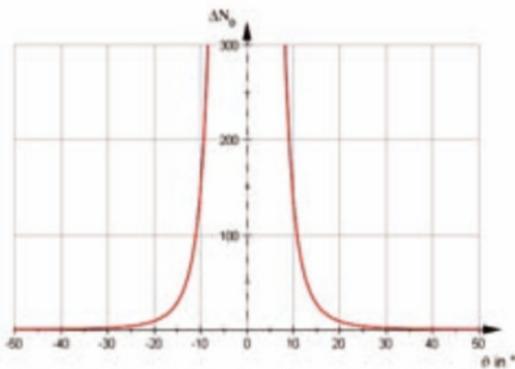


Abb. 26: Vergleich der Anzahl detektierter Alpha-Teilchen mit ungenutzter (rot) und genutzter (blau) Detektorfläche.

Fig. 26: Comparison of the number of detected alpha particles with unconsidered (red) and considered detector area (blue).

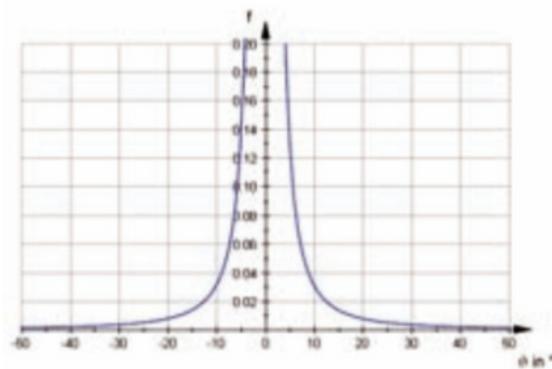


Abb. 27: Relativer Fehler durch die Detektorfläche.

Fig. 27: Relative error due to detector area.

## 5.5 Literature

- [1] LD Didactic. [559 01] Window counter for alpha, beta and gamma and x-ray radiation.
- [2] LD Didactic. [559 56] Scattering chamber after Rutherford.
- [3] Coach 6 Studio MV. Amsterdam. url: <http://cma-science.nl/english/software/coach6/coach6studiomv.html>
- [4] LD Didactic. [559 54] Gold foil in frame. url: <http://www.ld-didactict.de/phk/a.asp?a=55954>
- [5] LD Didactic. [559 52] Aluminium foil in frame. url: <http://www.ld-didactict.de/phk/a.asp?a=55952>
- [6] Gröber, S., Vetter, M., Eckert, B. and Jodl, H.-J. Experimenting from a distance in the case of Rutherford scattering. In: Eur. J. Phys. 31.4 (2010), p. 727.



# 6 Electron Diffraction

## 6.1 Introduction

The experiment electron diffraction on a graphite foil is the classic experiment to demonstrate the wave properties of electrons. How did that happen? Even before the wave properties of particles -such as the electron - could be detected (Davisson and Germer 1926), de Broglie suggested in 1924 that particles can also be attributed wave properties.

$$\left. \begin{aligned} \lambda &= \frac{h}{p} = \frac{h}{mv} \\ E_{\text{kin}} &= \frac{1}{2}mv^2 \\ E_{\text{kin}} &= E_{\text{elektrisch}} = eU \end{aligned} \right\} \lambda_{\text{dB}} = \frac{h}{\sqrt{2meU}}$$

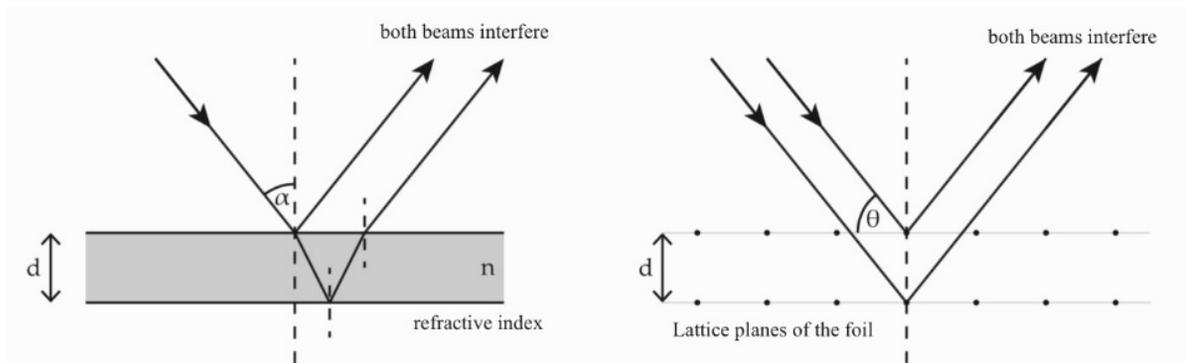
The particle properties:  $m$ -mass,  $v$ -velocity,  $p$  - momentum,  $E_{\text{kin}}$  - kinetic energy,  $e$  - elementary charge,  $U$  - voltage, by which a particle is accelerated;  $\lambda_{\text{dB}}$  - de-Broglie wavelength of the particle.

At the time, many experiments were performed with electrons as particles (experiments with channel- and cathode rays). Davisson and Germer had the idea, in 1926, to confirm the wave nature of electrons in scattering electrons on a crystal film and thus detecting diffraction and interference as wave properties. They thus applied the known experiment of optics to this case.

After further experiments of a different kind, they confirmed this new model concept - particles have wave properties -, the wave-particle dualism was prevailed:

particle	wave	connection
momentum $p$	$\lambda$ wavelength	$p = k h/2\pi$
energy $E$	$f$ frequency	$E = h f$
with $h$ Planck constant; $k = 2\pi/\lambda$ wave vector.		

The importance of this classical experiment in physics was given Nobel Prizes (de Broglie 1929, Davison 1937). The apparent contradiction expressed by the term wave-particle dualism is removed by quantum electrodynamics (R. Feynman, 1950s).



a) Light interferes after reflection on a thin layer.

Optical path difference between beam 1 and 2

$$\Delta s = s_2 - s_1$$

$$\Delta s = 2nd \cos \beta$$

Condition for interference

$$\Delta s = n \cdot \lambda \quad (\text{with } n = 0, 1, 2, \dots)$$

(b) Electrons scattered by atoms of a foil.

Bragg condition

$$2d \sin \theta = n \cdot \lambda$$

(with  $n = 0, 1, 2, \dots$ )

Figure 6.1: Both phenomena - interference of light on a thin layer / electrons scattered on a film - are different, but are described in the same way in the wave model.

In physics lessons this experiment has to be presented if, as a teacher, one wants to satisfy the demand for teaching modern physics in the classroom, such as quantum mechanics, experiments in atomic physics, Special Theory of Relativity; although these are already 100 years old. The teacher can in principle choose two approaches (see section 6.4):

- The structure of the crystal (lattice planes) is known and one can then determine the de Broglie wavelength of the electron.
- The de Broglie wavelength of the electron is known and one can deduce from this the geometry of the lattice planes (of graphite).

There are a whole series of experimental methods to demonstrate the wave character of particles, such as Bragg scattering, Debye-Scherrer methods, Laue methods. ., but as a school experiment, only the variant of Leybold [1] has prevailed: If a graphite foil is irradiated by accelerated electrons, then one observes a pattern of two concentric

rings on the fluorescence screen. The astonishing fact is that with matter particles (electrons) structurally the same diffraction patterns can be generated as with X-rays, i.e. short-wave electromagnetic radiation.

Since simulation programs are written in physics, electron diffraction is a standard topic. For this RCL, applets for Bragg reflection [2], images of X-ray diffraction and electron diffraction of the Davisson-Germer experiment as well as applets for electron diffraction at the single slit [3] are suitable as media.

As far as we know, the real experiment electron diffraction is not performed in the classroom for the following reasons:

- The central device - the electron diffraction tube - is missing in the physics collection.
- If the experiment is shown in class, it is necessary to darken the room and read rings from the fluorescent screen (diameter about 4 to 10 cm); which is not easy.
- For students not too exciting: different acceleration voltage, different ring diameter.
- Both the wave-particle dualism is conceptually not easy; as well as the formation of the diffraction rings is not directly traceable.

For this reason, the majority of teachers questioned during our training courses in dealing with RCLs, that the experiment electron diffraction is very well suited as an RCL variant [4].

## 6.2 Experiment and RCL variant

### 6.2.1 Experimental setup and function

The electron diffraction tube from LD Didactic has two special features (Fig. 6.2): the graphite sample (6) and the fluorescent screen (7). The knowledge of the geometry of this tube - see later - is important to be able to evaluate the experiment using ring diameter and scattering angle. The RCL version (Fig. 6.3) has only been changed slightly: a webcam picks up the two rings at a distance of about 10 cm from the front of the fluorescence screen. Most of the electrons are not scattered / deflected by the atoms of the graphite foil; to prevent that the camera

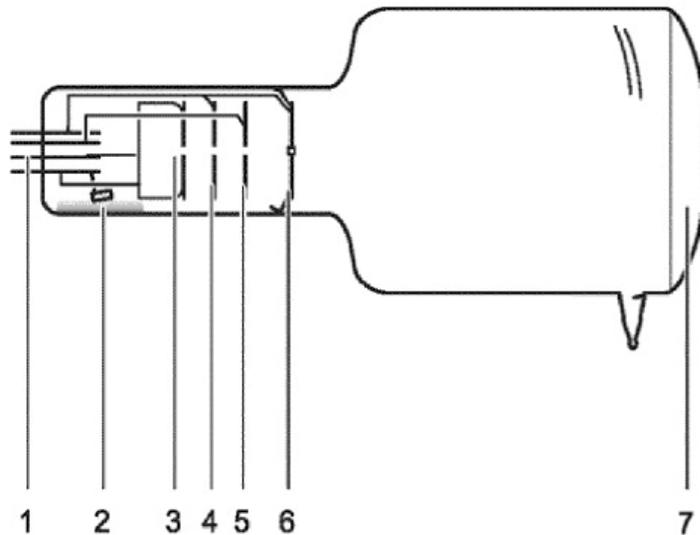


Figure 6.2: Experimental set up of the electron diffraction tube (Source: LD System). Base of tube with contacts for heating voltage and electrodes (1), getter mirror for maintaining the vacuum (2), cathode cap (3), anode plate 1 (4), focusing electrode (5), anode plate 2 with graphite sample (6) and fluorescent screen which electrons hit (7).

is overdriven by the zero th diffraction maximum, we glued a black paper disk of about 1 cm in the centre of the screen so that you can read the ring diameters.

### 6.2.2 Navigation menu

After the menu point *Experimental set up* follows the menu point *Theory*. Here we briefly describe the following:

- How to get the wavelength of the electrons?
- How do you get the Bragg condition when electron beams are reflected at lattice planes and then interfere?
- How the two lattice plane distances of a graphite crystal structure are defined?
- How are the two diffraction rings formed?



Figure 6.3: Experimental setup of the RCL. Interface (1), high voltage power supply (2), electron diffraction tube (3) and webcam (4).

The formulas necessary for the evaluation are derived and interpreted.

In the menu point *Tasks* we ask some questions about theory, experimental set up, measurement plan and evaluation. One can use the experiment in the menu point *Laboratory* if it is free. In the middle of the website, the experimenter recognizes the webcam image with the fluorescent screen as just described. Furthermore, a millimetre scale attached to the screen can be seen for the purpose of quantitative evaluation. On the right side of the website you can see the control panel: above the remaining time until a technical parameter should be changed. (Usually our RCLs turn off if the experimenter does not do anything). First, the user must turn on the tube and select an acceleration voltage. Here the range of high voltage is limited to 5 kV because of technical reasons. Since, for technical reasons, the interface allows only gradual voltage changes, the actual voltage is reported back to the experimenter. The menu point *Evaluation* shows an example of how to read the ring diameter at an acceleration voltage of 4 kV and how to determine the lattice plane distances  $d_1$  and  $d_2$  with the corresponding formulas.

The menu point *Discussion* contains questions that are intended to test the experimenter's understanding of the RCL experiment (Table 6.1). The last menu point *Material* keeps ready all technical details of this experiment and didactic materials (see next section 6.4)

- A possible lesson,
- a collection of tasks,
- a didactic analysis of the RCL,
- a possible work sheet,
- a lesson sketch for the hand of the teacher and the student.

Table 6.1: Discussion

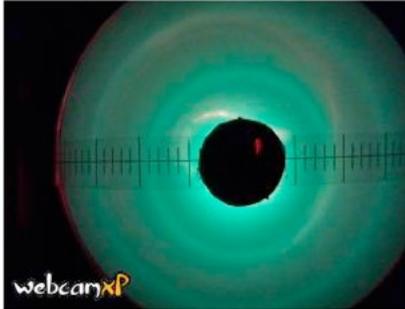
1. Experimental set up
  - a) How is an electron beam generated?
  - b) What is the function of a "getter mirror"? How does this work?
2. Theory
  - a) The atoms of graphite foil are arranged regularly: Why are there two different lattice planes?
  - b) Establish the relationship between the acceleration voltage and the electron wavelength.
  - c) The scattering of light at multiple slits creates an interference pattern: what is the interference condition? Here in the experiment, electrons are scattered as matter waves at the lattice planes of a graphite lattice: What is the interference condition here?
  - d) Explain qualitatively the formation of diffraction rings on the diffraction screen of the electron diffraction tube. Derive a formula for the experimental determination of the lattice plane distance  $d$ .
  - e) Discuss the ring pattern in the particle model (scattering) and in the wave model (diffraction).
  - f) Given is a lattice plane distance  $d = 310$  pm and an acceleration voltage  $U = 4,3$  kV: Calculate the diameter  $D$  of the diffraction rings up to the 3rd order.
3. Laboratory
  - a) Why are the diffraction rings out of focus?
  - b) Why do you "only" see two diffraction rings?
4. Evaluation
  - a) Determine the relative error of an experimental wavelength determination of the electrons with the help of the error propagation law.

**Remotely Controlled Laboratories - RCLs**  
experimenting from a distance

Home RCL-Project **RCLs** Technical Notes Contact Legal Notice

**Electron Diffraction**

Introduction  
Setup  
Theory  
Tasks  
**Laboratory**  
Analysis  
Discussion  
Material  
Support



Screenshot

Electron tube Turns off automatically  
1 Skt.  $\approx$  2 mm.

**Electron Diffraction**  
**Please wait**

The experiment is currently being used by another visitor.  
You will be redirected in 36 seconds.

Figure 6.4: Laboratory page of RCL electron diffraction.

### 6.2.3 Operating the experiment

What are the interactions for the user here?

- The scattering material (graphite) is given.
- The distance from graphite foil to fluorescent screen is given.
- The ring diameters are measured and determined.
- The lattice plane distances are given / are determined from the measured values.
- The acceleration voltage is selected and applied.
- The mean velocity of the electrons and their wavelength are determined.
- As well as Planck's constant  $h$ .

Behind the mere pressing of buttons by the experimenter are the following interactions:

- Switch device on / off (glow cathode),
- Measure sizes (ring radii),
- Store measurement results (screenshots of diffraction patterns),
- Measuring series recording (acceleration voltage and ring diameter),
- Characterize the electron beam (velocity and wavelength of the electrons).

These 6 interactions represent typical learning goals in a lab for students and experimental skills.

#### 6.2.4 Measurement result

In the menu point *Theory, Evaluation* or from literature one can read the lattice plane distances of graphite (Fig. 6.5).

How the diffraction rings are created and how is the scattering geometry composed?

The graphite in the film is polycrystalline, i.e. it consists of crystalline particles (crystallites), which are spatially disordered and therefore their lattice planes are also irregularly ordered (Figure 6.6).

Since the diameter of the electron beam is much larger than the size of the crystallites, it always encounters a large number of crystallites and thus lattice planes with different positions in space. In Fig. 6.6, the Bragg condition for the two crystallites on the far right is fulfilled and two reflections are obtained in the plane of the drawing (points P and Q on screen). However, the Bragg condition is also fulfilled for crystallites whose position results from rotation of the two crystallites about the direction of incidence of the electron beam. Accordingly, one obtains as an interference pattern not two individual reflections but, as a result of rotation, a circular ring on the fluorescent screen of the electron diffraction tube. The diameter of this ring depends on the order  $n$ , the wavelength  $\lambda$  and the lattice plane distance  $d$  (Debye-Scherrer method).

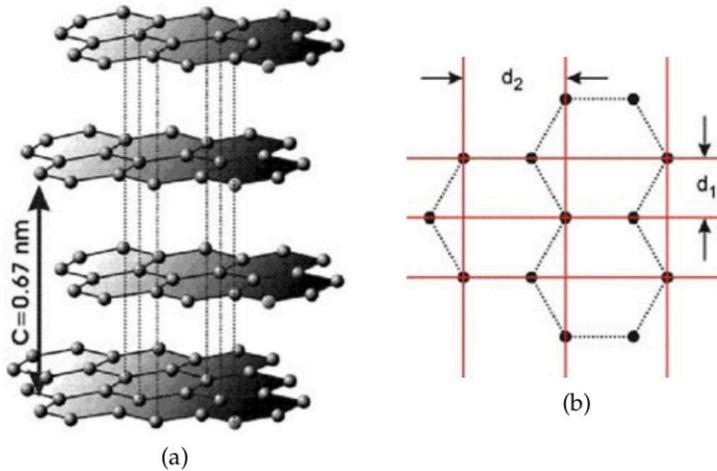


Figure 6.5: (a) Layer structure of graphite [5]. (b) Lattice plane distances of graphite.  $d_1 = 123 \text{ pm}$ ;  $d_2 = 213 \text{ pm}$ .

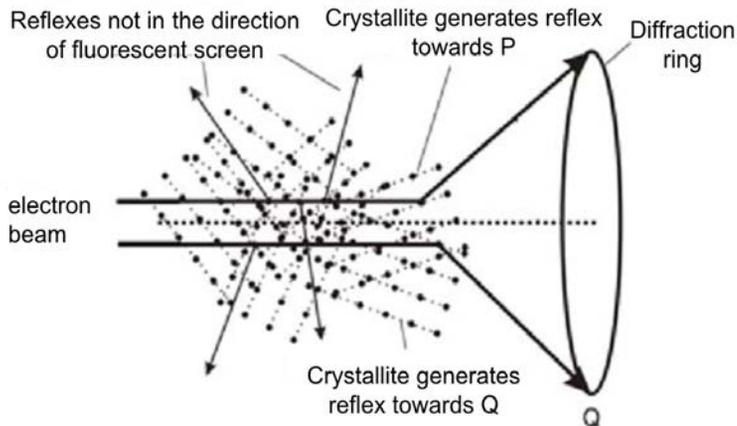


Figure 6.6: Formation of a diffraction ring for fixed wavelength  $\lambda$  and fixed lattice spacing  $d$ .

In order to experimentally determine the de Broglie wavelength  $\lambda$  of the electrons or the lattice plane distance  $d$ , the geometry of the arrangement must be considered (fig. 6.7).

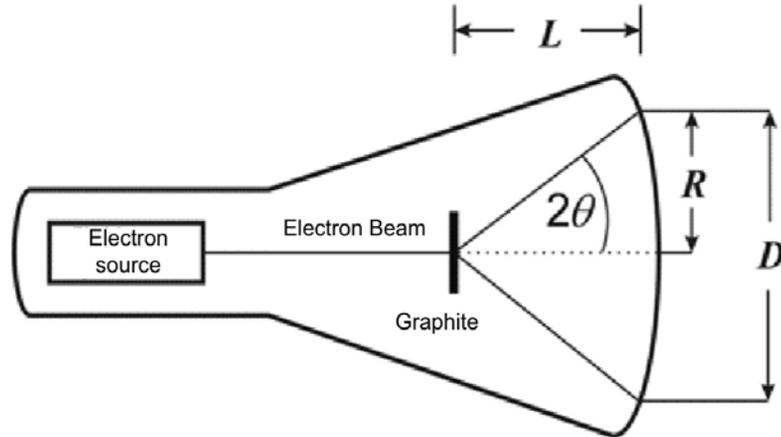


Figure 6.7: Geometry of the experimental setup [Source: Leybold Didactic].

With the approximation for small angles the following is valid:

$$\tan(2\theta) = R/L = D/(2L) \approx \sin(2\theta) \approx 2\sin\theta$$

Thus we get with the Bragg condition:

$$2d\sin\theta = n\lambda$$

the de Broglie wavelength of accelerated electrons

$$\lambda = d \cdot (R/L)$$

and the distance  $d$  of the lattice planes

$$d = (L/R) \cdot h / \sqrt{2eUm_e}$$

Figure 6.8 shows a series of diffraction patterns for increasing voltages (3 kV to 5 kV) taken with the webcam.

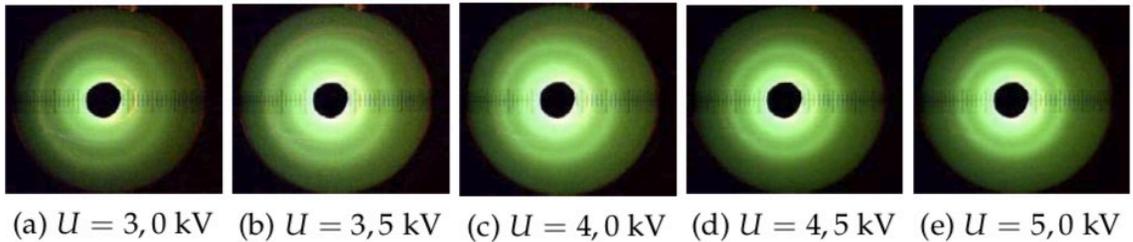


Figure 6.8: Diffraction pattern with increasing acceleration voltage.

In order to be able to quantitatively evaluate these raw data as exact as possible – i.e. not only reading on the scale with the naked eye – we have written an instruction for determining the ring diameters from the screenshots with the help of image processing program (Table 6.2).

If we evaluate the raw data of the mentioned image series with this tool, we obtain the measurement results in Table 6.3. This gives us average values  $d_1 = 119 \text{ pm}$  and  $d_2 = 198 \text{ pm}$ .

In the case just described, the "research question" was: how to get the size of the lattice plane distances if the wavelength of the electrons is known? The scenario could also be reversed; or one might want to determine Planck's constant  $h$  as precisely as possible.

Table 6.2: Instructions for determining the ring diameter in the diffraction pattern with Paint



Start Paint, load image file with File / Open, choose Pen in Toolbox. If you move your pen over the image, the coordinates of the pen tip are displayed in pixels (px) in the status bar. Coordinate origin is the left upper corner.

Determine the x-values  $x_1$  and  $x_2$  of the points  $P_1$  and  $P_2$  in px on the centimetre scale, enter them in an Excel spreadsheet and calculate the conversion factor  $k = 4 \text{ cm} / (x_2 - x_1)$ .

Select the thinnest line and color white in the toolbox. Draw a diameter of the diffraction ring. Determine the coordinates  $(x_1, y_1)$  and  $(x_2, y_2)$  of the two points of intersection  $Q_1$  and  $Q_2$  of the diameter and centre of the ring with the pen and enter them in an Excel spreadsheet. Repeat this procedure several times (at least five times) with different diameters.

Distinguish the points  $Q_1$  and  $Q_2$  by  $d = k\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$  in Excel spreadsheet. Have the mean and standard deviation output.

Calibration					
	x1 in px	x2 in px	k in cm/px		
	67	240	0.023121387		
Measurements					
coordinates of the points Q1 and Q2					
Nr.	x1 in px	y1 in px	x2 in px	y2 in px	d in cm
1	106	56	202	226	4.51
2	164	46	140	238	4.47
3	214	68	87	212	4.44
4	243	109	59	167	4.46
5	242	177	64	99	4.49
				mean value	4.48
				standard deviation	0.03

Table 6.3: Measurement results

$U$ in kV	$\lambda$ in pm	$D_1$ in cm	$D_2$ in cm	$\theta_1$ in Grad	$\theta_2$ in Grad	$d_1$ in cm	$d_2$ in cm
3,0	22,4	5,2	3,1	5,45	3,27	117,9	196,3
3,5	20,7	4,6	2,9	4,83	3,06	122,8	193,9
4,0	19,4	4,4	2,6	4,62	2,75	120,2	202,2
4,5	18,3	4,2	2,5	4,52	2,64	116,1	198,6
5,0	17,4	4,0	-	4,21	-	118,4	-

### 6.3 Evaluation and experience

The deviation of the measurement results for the lattice plane distances from the literature values (see Fig. 6.5b) is 3 to 4%. We estimate the reading error for the ring diameter to be  $\pm 1$  mm, so the relative error  $\Delta R/R$  is about 4%. We assume the other geometric sizes of the tube without errors. This is a very convincing result for a school experiment. A single measurement takes a relatively short time ( $< 1 / 2$  min), as does a series of measurements (a few minutes); the analysis of the screenshots at different voltages with the evaluation tool (Tab. 6.2) is much more time consuming.

What is the added value of implementing and using this experiment as an RCL? The RCL makes the experiment possible if the electron diffraction tube is not available. A central phenomenon / experiment in the introduction of quantum physics can be carried out independently by pupils. The diameters of the diffraction rings can be specified more precisely in the webcam image (and use of the evaluation tool) than in the real experiment on site. The activity of students, which gets too short in pure experimenting (only vary voltages), is shifted to the evaluation of the raw data (i.e. screenshots).

How is the RCL experiment being used, which has been usable on the Internet since 2001 and is available 24 hours without care / repairs? Our system is designed such that when a user calls up the experiment, we record everything: duration, which actions are taken etc. The analysis of these "tracking data" since 2002 shows the following picture:

1. In recent years, around 12 visitors a day with an upward trend (about 1-2 users per day more per year).
2. As shown in Figure 6.9, there are two types of experimentation: on average about 1 minute (qualitative experimenting, perhaps taking one measurement); on average about 7 minutes (quantitative experimenting, record series); the latter group is significantly smaller in number.
3. In an observation period from 2007 to 2009, we had one user experimenting for up to 1.5 hours at a time and performed about 140 interactions.
4. In Figure 6.10 we have shown the frequency of certain actions to investigate the nature of experimentation.

In 41% of the visits, the RCL is tried out: the laboratory page is called up without experimenting (in Figure 6.10 no action), one or more voltages are selected without first switching on the electron diffraction tube (voltages) or only the electron diffraction tube is switched on (tube). The RCL is qualitatively experimented in 31% of the visits: the electron diffraction tube is switched on and one acceleration voltage (tube on and one voltage) or several, arbitrarily selected acceleration voltages (tube on and several voltages) are applied. The RCL is quantitatively experimented in 28% of visits: the electron diffraction tube is switched on and one (tube on, one measurement series) or several series of measurements (tube on and several measurement series) are systematically recorded.

Conclusion: the RCL experiment is very well accepted and it is measured qualitatively, quantitatively and experiment specific.

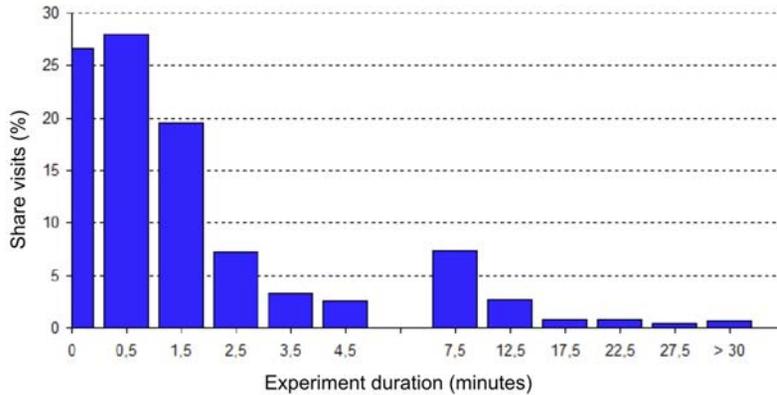


Figure 6.9: Distribution of the experiment duration by users of RCL electron diffraction (interval widths of one minute between 0 and 5 min and five minutes between 5 and 30 min of experiment duration,  $N = 1629$  visits).

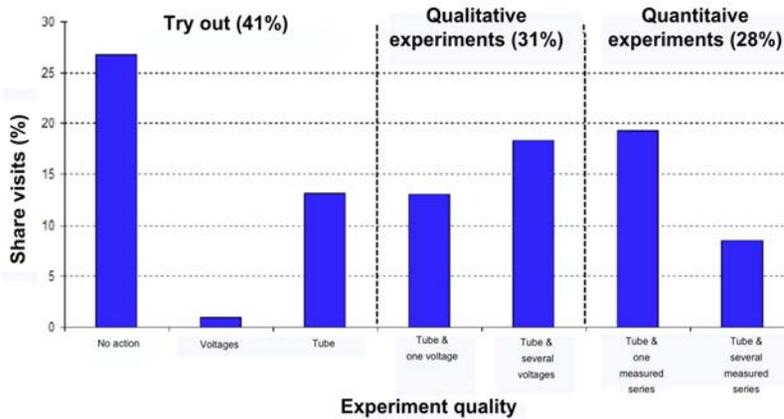


Figure 6.10: Experimental quality of experimentations of visitors of the RCL electron diffraction ( $N = 1629$  visits).

## 6.4 Didactic material

As in most cases, this RCL is also suitable for experimental homework in group work. Table 6.4 contains a proposal for a worksheet.

In short, a few preliminary considerations that should prepare a lesson: Like the majority of upper-level experiments in high schools, the experiment on electron diffraction must be carried out as a teacher demonstration experiment with restricted opportunities for participation of the pupils. In the case of electron diffraction, it is obvious that the phenomenon (particle-wave-dualism) itself is not known to the learner and that it is difficult for them to describe previously classically considered matter as particles now as waves. This easily creates a teacher-centred situation in which information flows unilaterally from teacher to student.

This module aims to create a learning-friendly environment through two methodological measures:

- The Debye-Scherrer method using X-ray radiation is treated before electron diffraction using the example of polycrystalline graphite (see learning prerequisites). As a result, the focus of the experiment electron diffraction is on the recognition and understanding of the wave property of electrons. Furthermore, the Debye-Scherrer method can be used more deeply by the students.
- For the first time, learners do not observe electron diffraction together in a course, but individually (possibly in small groups) with the RCL on their home computer. This gives them the opportunity to deal with the phenomenon independently, at their own pace and without the direct influence by the teacher.

Table 6.4: Worksheet.

Worksheet --- electron scattering on graphite

1. Questions:

- Graphite has a layer-like structure. Take a look at the simulation under the point theory.
- Why do you see rings? Why two?
- Make the scattering geometry clear to you.

2. Select the following voltages and take screenshots.

2,5	3,0	3,5	4,0	4,5 kV	Group 1
2,6	3,1	3,6	4,1	4,6 kV	Group 2
2,7	3,2	3,7	4,2	4,7 kV	Group 3
2,8	3,3	3,8	4,3	4,8 kV	Group 4
2,9	3,4	3,9	4,4	4,9 kV	Group 5

3. Create the following table for data analysis:

U (kV)  $\lambda$  (nm)  $D_1$  (cm)  $D_2$  (cm)  $\theta_1$   $\theta_2$   $d_1$  ( $\mu\text{m}$ )  $d_2$  ( $\mu\text{m}$ )

Also determine the mean value of  $d$  and the error  $\Delta d$

4 Discussion:

- Take all values of the 5 groups to determine the averages of  $d_1$  and  $d_2$ .
- Compare their values with the literature values of graphite.
- The diffraction of electrons at lattice planes of graphite behaves in a similar way to the diffraction of light on a grating. Consequently, one has to interpret electrons as a matter wave and not as a particle. Why, what for and in which model?

The following lesson (Table 6.5) has the following structure:

- Electron diffraction as a phenomenon,
- Theory of the experiment
- Wave-particle dualism,
- Tasks and text to deepen.

The collection of tasks for RCL electron diffraction can be found in the portal under book materials or in the respective RCL under the menu point *Material*. The collection contains 3 tasks on theory, 3 on experimental set up and 3 on measurement / evaluation with a total of 24 subtasks; 14 of them address high school level, 8 can be used in high school and college, only 2 of them are more suitable for university. Table 6.6 presents some examples of the type of task and the type of model solution.

Finally, the lesson sketch of a physics teacher, who supervised the RCL for a long time, is mentioned. In this sketch, the scenario for teachers with detailed student guidance, which has been mentioned already several times, is worked out: With known lattice plane differences, the dimensions for the scattering geometry and from the measured ring diameters, the de Broglie wavelength of the electrons is deduced. Students learn how to use spreadsheets, another tool to evaluate screenshots and word processing programs. This lesson sketch (teacher-student manual) can be found under the menu point *Material*.

Table 6.5: Lesson unit.

**Module "Electron as Wave" with RCL "Electron Diffraction"**

Phase	Contents and forms of work
<b>Electron diffraction as a phenomenon</b>	<p>Preparing the homework assignment (material: RCL portal, instructions for image evaluation of the diffraction pattern)            Purpose of homework: Explain to pupils that it is about a physical one to observe and investigate phenomenon itself            Study Materials: Teacher sets learning environment of the RCL without the lab page with the RCL shortly before. Teacher prepares distance measurement with Paint on any picture.            Learning organization: Processing of homework assignments over 2-3 days in small groups (2-3 students). Group independently collects their results, one presents results. Other learning resources (textbook, Internet) can also be used. Subsequent learning tasks do not have to be handled by the students in the given order. Depending on the course, more open or narrower tasks may be formulated.</p> <p>Learning tasks (goal / intention of the task)            Explore the experiment on the lab side            What is the amazing / explanatory need of the experiment? (To arouse interest, Problem of detecting wave particles)            Determines the wavelength of the radiation used based on the experimental data. Write the result on the board(task can be left open, whether wavelength is calculated from Bragg's equation or according to the experimental theory from the acceleration voltage).            Examine quantitatively the relationship between the acceleration voltage and the ring radii. Represent the results in tabular, graphical and mathematical form (practice of methodical skills, measurement results can be compared later with theory)</p> <p>Discussion of homework            2-3 groups present their results. Discussion of the wave character of matter. Accuracy of the measured quantities, merging the measured data from the groups for better statistics, hypotheses on the mathematical relationship between acceleration voltage and ring radius.</p>

<b>Theory to experiment</b>	Teacher lecture on the idea of De Broglie: Light has wave and particle character, matter has particle and wave character Comparison of experiment and theory. Determination of Plank's constant from the measured data
<b>Universal wave character of matter</b>	Further experiments such as electron and neutron diffraction at a slit and double slit showing the universal wave character of matter (Material: Simulation program "The Quantum Mechanical Double-Slit Experiment")
<b>Tasks and test for deepening</b>	Tasks for electron diffraction (Material: Collection of tasks for electron diffraction) Test for the wave character of matter.

Table 6.6: Tasks RCL "Electron Diffraction".

**To the theory****Tasks for diffracting matter waves on crystals**

- a) Derive the Bragg equation in text-based steps.  
 b) Determine a formula for calculating the interplanar spacing  $d$  for small diffraction angles from the measured values of radius  $r_n$  of the  $n$ -th order diffraction circle, acceleration voltage  $U$  and the distance  $L$  between the grating and the fluorescent screen.

As a result of half-quantitative considerations, the radius of the annular rings has changed as the acceleration voltage  $U$  is increased.

Which largest order can be theoretically observed on a fluorescent screen with the radius  $R_{\max} = 4.5$  cm (VII.1.) in the electron diffraction on graphite for  $U = 4$  kV and  $L = 13.5$  cm (VII.1.)?

- c) Determine the lowest possible acceleration voltage from which theoretically diffraction rings are to be expected.

Tip: condition under which ever Bragg reflection can occur.

**Solution for diffracting matter waves on crystals**

- a) For the derivation of the Bragg equation, the interference of two consecutive lattice planes with lattice plane distance  $d$  "reflected" electron beams is considered as a model (observation in reflection). For the path difference  $\Delta x$  between these electron beams:

$$\Delta x = 2d \sin \theta$$

Constructive interference occurs when  $\Delta x = n\lambda$ :

$$2d \sin \theta = n\lambda \quad n \in \mathbb{N}$$

- b) The following relations apply:

$$n\lambda = 2d \sin \theta \approx 2d \theta \quad r_n/L = \tan(2\theta) \approx 2\theta \quad \lambda = h/\sqrt{2eUm_e}$$

Inserting the last two relationships in the first returns:

$$dr_n/L = nh/\sqrt{2eUm_e} \Leftrightarrow d = nLh/(r_n\sqrt{2eUm_e})$$

Larger  $U \rightarrow$  smaller  $\lambda$  after  $\lambda = h/\sqrt{2eUm_e}$ , smaller  $\lambda \rightarrow$  smaller  $\theta$

behind  $2d \sin \theta = n\lambda$  for  $d, n = \text{const.}$ , Smaller  $\theta \rightarrow$  smaller  $r$  after  $\tan(2\theta) = r/L$ .

After b) you get:

$$d = \frac{nLh}{r_n\sqrt{2eUm_e}} \Leftrightarrow r_n = \frac{nLh}{d\sqrt{2eUm_e}} \leq R_{\max} \Leftrightarrow n \leq \frac{R_{\max} d \sqrt{2eUm_e}}{Lh}$$

For the maximum  $n$ , the larger interplanar spacing  $d_2 = 213$  pm must be used. This gives  $n$  smaller than 3.65 and thus  $n_{\max} = 3$ .

c) To determine the lowest possible voltage  $U_{\min}$ , you have to go to

$$\lambda = h / \sqrt{2eUm_e}$$

search for the largest possible electron wavelength  $\lambda_{\max}$ . This is determined from the consideration of the electron beam interference at the lattice planes or from the Bragg equation

$$\Delta x = 2d \sin \theta = n\lambda$$

The maximum possible wavelength  $\lambda_{\max}$  occurs when the path difference  $\Delta x$  (left side of the Bragg equation) for  $\theta = 90^\circ$  assumes the maximum value  $2d$  and  $n = 1$  is selected in the right-hand side. This is also obtained in a more formal way:

$$2d \sin \theta = n\lambda \leq 2d \Rightarrow \lambda \leq \frac{2d}{n} \leq 2d = \lambda_{\max}$$

$$2d = \frac{h}{\sqrt{2eU_{\min}m_e}} \Leftrightarrow U_{\min} = \frac{h^2}{8d^2em_e}$$

For  $d_1 = 123 \text{ pm}$ ,  $\lambda_{\max} = 246 \text{ pm}$  and  $U_{\min} = 24.9 \text{ V}$ . For  $d_2 = 213 \text{ pm}$ ,  $\lambda_{\max} = 426 \text{ pm}$  and  $U_{\min} = 8.3 \text{ V}$ . The onset of the diffraction pattern at these voltages is not observable because the high voltage power supply is not controllable in this voltage range (VII.2.) And the electron beam intensity is not independent of the electron energy is controllable. The intensity increases with increasing acceleration voltage.

## The experimental setup

### Tasks to disturbing and useful interactions of the electrons

- Why should the electron diffraction experiment not be operated with acceleration voltages above 5 kV?
- Why is the glass bulb evacuated? How many air particles are still in one cubic centimeter of air at a pressure of 10<sup>-6</sup> hPa (VII.1.)? How do electrons interact with air? Explain the mechanisms and the dependencies.
- What is the getter mirror for? Explain how it works.
- What is fluorescence? Which materials can be used for electrons?

### Solution to disturbing and useful interactions of the electrons

- For  $U = 5$  kV, the short-wave end of the bremsstrahlung caused by the interaction of the electrons with the tube materials is given by  $\lambda_{\min} = \frac{hc}{eU} = 248$  pm. Higher acceleration voltages reduce  $\lambda_{\min}$  and generate higher-energy X-ray radiation. The local dose rates generated in this case are well below the permissible limit value of 1  $\mu$ S /h in 10 cm distance under normal operating conditions given in the X-ray Ordinance (RöV), § 5 (2) (VII.5.). The electron diffraction tube from Phywe (VII.6.) can therefore also be operated up to a maximum of 12 kV.
- By evacuation of the glass bulb hardly any interactions of the electrons with air molecules take place. Compared to the air pressure at sea level of about 1000 hPa it is smaller by a factor of 10<sup>9</sup> in the tube. Assuming an ideal gas, one obtains with the general gas equation at  $T = 293$  K (20 ° C):  $pV = NkT \Leftrightarrow N/V = p/kT \approx 2,5 \cdot 10^{10}$  air particles/cm<sup>3</sup>. The deceleration of electrons occurs by ionization and excitation of shell electrons of the collapsed atoms (Coulomb interaction). Electrons of approx. 5 keV only have a range of a few centimeters in air of normal pressure, so that the air has to be evacuated in a glass bulb. For a constant absorption distance and temperature, the intensity of the electron radiation is  $I = I_0 e^{-\beta p}$ .
- The gettering mirror serves to capture remaining residual gases after the evacuation (from "to get" = catch, VII.7.). A getter material (barium, aluminium or magnesium alloy) located on a metal ring is evaporated by heating. In the process, the getter bonds by reaction with the remaining air and gas residues and the reaction product settles on the tube piston as a reflecting coating.
- Fluorescence is the spontaneous emission of light during the transition of an electronically excited system into a state of lower energy. The fluorescent screen is the oldest - very insensitive - method for visualizing charged particles. Zinc sulfide is used as fluoride.

**For measuring / evaluating****Tasks to the blurred diffraction rings**

- a) Through which experimental modification of the experimental setup can it be shown that at least a part of the blur of the diffraction rings is due to a velocity distribution around a mean velocity of the electrons in the glowing emission?
- b) Determine the maximum and minimum electron velocity.

**Solutions to the blurred diffraction rings**

a) A Wien filter is inserted between the electron gun and the graphite plate, which only allows monoenergetic electrons to strike the graphite plate. Then the diffraction rings would have to gain significantly in sharpness.

b) For  $UB = 4 \text{ kV}$  the diameter  $D$  of the outer diffraction circle is between  $D_1 = 4,2 \text{ cm}$  and  $D_2 = 4,8 \text{ cm}$  and for radius  $r_1 = 2,1 \text{ cm}$  and  $r_2 = 2,4 \text{ cm}$ . The velocity  $v$  of the electrons can be determined for small angles as follows:

$$\tan(2\theta) = \frac{r}{L} \approx 2\theta \quad \lambda = 2d \sin\theta \approx 2d\theta \quad \lambda = \frac{h}{p} = \frac{h}{m_e v}$$

$$\lambda = d \frac{r}{L} = \frac{h}{m_e v} \Leftrightarrow v = \frac{hL}{m_e dr}$$

With  $h = 6.626 \times 10^{-34} \text{ Js}$ ,  $L = 0.135 \text{ m}$ ,  $m_e = 9.1 \times 10^{-31} \text{ kg}$ ,  $d = d_1 = 123 \text{ pm}$  and the radii measured we get  $v_{\min} = 3.3 \times 10^7 \text{ m/s}$  and  $v_{\max} = 3.8 \cdot 10^7 \text{ m/s}$ .

## 6.5 Literature

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# 7 Photo electric Effect

## 7.1 Introduction

The greatest importance of this experiment (for short photo effect) is undoubtedly in technical applications of everyday life: whenever a light signal is to be converted into an electrical signal, one uses this effect. If a photocell is actuated, then a mechanical process is triggered via an electrical signal. For example, open/close a lift door, tap on/off, digital cameras. By measurement, photo resistors, photocells, photodiodes, phototransistors, CCD sensors, photomultipliers, etc. are used. For around 30 years, extensive material prepared for physics lessons has been available for this application.

The meaning in physics dates back many years. Hallwachs (1888) irradiated metal surfaces with light, not only observed released electrons but also the threshold value of a limit frequency. Albert Einstein was able to explain all experimental findings in 1905; in 1926 he received the Nobel Prize for this theory. It should be noted that Einstein wrote in this famous year (anus mirabilis) two further publications, on diffusion and on the Special Theory of Relativity, which were far more important / demanding. The technical use of the phenomenon photoelectric effect did not take place until the middle of the 20th century, when the semiconductor industry was looking for suitable applications on a large scale.

The significance for physics education is that the photoelectric effect shows the particle character of light and that it is relatively easy to be performed, in contrast to the Compton effect, for example. For teaching physics, all teaching equipment manufacturers offer suitable experimental units. For the RCL photoelectric effect we used the system of Phywe [1-3].

If this experiment is so important for the understanding of many technical applications in everyday life, why is it rarely performed real and why is it suitable as an RCL?

- To prepare the Hallwachs experiment, the surface of the zinc plate must be sanded and cleaned; this metal surface oxidizes.

- In older types of photocells, which use an alkali metal as the cathode material, the anode must be periodically baked to remove the deposition of the cathode material from the anode. This procedure should be done with caution and may damage the photocell.
- In general, only three filters are available for different wavelengths in the Hg spectrum. As one knows from evaluations, one should set a straight line through these 3 measuring points. Our RCL offers five filters for wavelengths.
- If one wants to interpret the result of the experiment, one encounters several problems, if one uses only the wave model of light:
  1. It must be experimentally shown that the result is independent of light intensity. But how? Our RCL offers in addition to an open and a closed aperture 3 neutral or grey filters of different transmission.
  2. The famous time factor, i.e. electrons are released and detected quickly.
    - Finally, some physics teachers avoid, that they perform the experiment as a whole, because here for the first time the modern model "light as particle / quantum" has to be introduced. It is also not very easy, to work out clean argumentatively the failure of the wave model in the interpretation of the experiment (see later).

The majority of participants in teacher training courses on the use of RCL experiments in physics lessons judged that the photoelectric effect was quite well suited as an RCL.

## 7.2 Experiment and RCL variant

### 7.2.1 Experimental setup and function

The measuring principle according to Phywe [1-3] is easy to understand and the experimental setup is clear. The light of a mercury vapour lamp (2) falls on the photocell (5); the released electrons are amplified as a current in the measuring amplifier (6) and detected as voltage (7) (see Fig. 7.1).

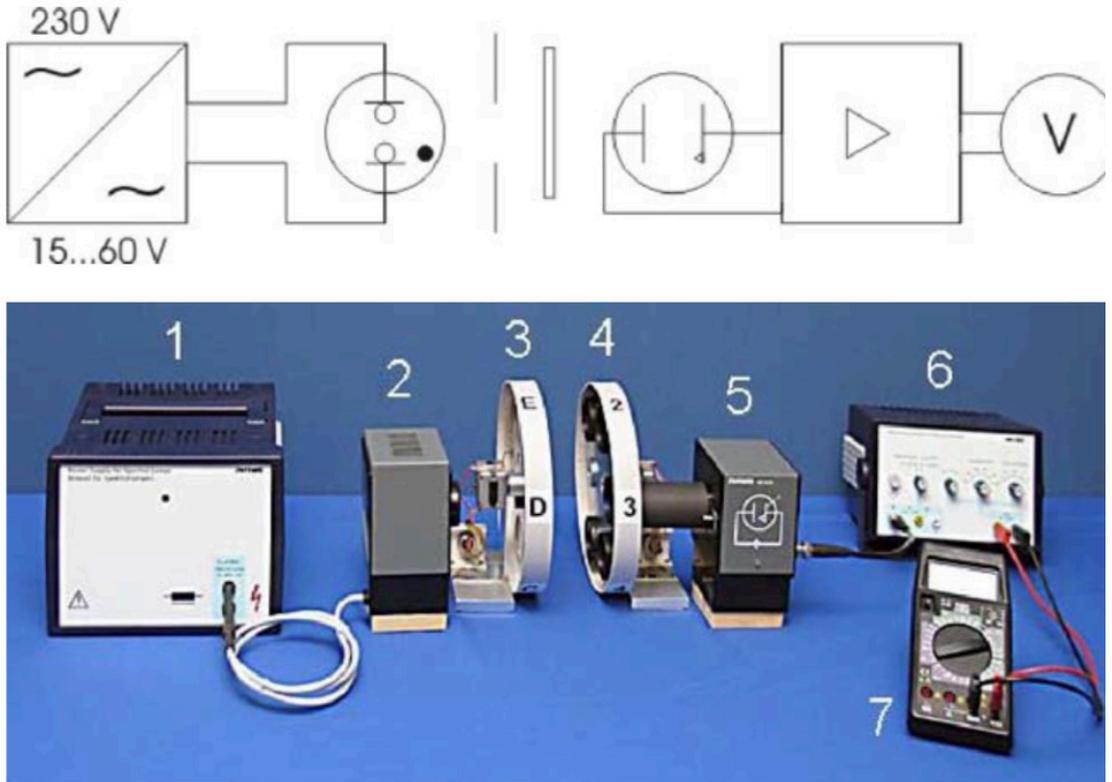


Figure 7.1: Schematic and pictorial representation of the components of the experimental setup: power supply for mercury vapour lamp (1), mercury vapour lamp (2), wheel with grey filters (3), wheel with colour filters (4), PbS photocell (5), measuring amplifier (6), Voltmeter (7).

The photosensitive layer used was potassium (K) in earlier used photocells, which had to be baked out because of the oxide layer that formed. Newer photocells use - as in this experiment - lead sulphide (PbS) as the cathode material. This is to avoid that one measures instead of the work function of the cathode material a contact potential that exists between the anode and cathode material due to the deposition [4].

Two filter wheels are positioned in the beam path: one for the grey filters (3) and one for the spectral filters (4), which transmit light of only one wavelength (Table 7.1). Here the RCL variant differs from the

Table 7.1: Spectral and grey filters in the experiment.

Spectral Filter	Wavelength $\lambda$ in nm	Grey Filter	Transmission $T$ in %
1	366	A	100
2	405	B	75
3	436	C	50
4	546	D	25
5	578	E	0

standard school experiment: Instead of the commercial product of the educational materials industry, we used 5 spectral filters. In addition, in order to check the independence of the measurement results from the light intensity, we have installed grey filters. The experimenter therefore selects one filter each and reads voltages; According to his research question, he will take a series of measurements and evaluate the raw data independently. As always, we have largely dispensed with semi-automatic / fully automatic evaluation.

### 7.2.2 Navigation menu

The menu point *Experimental set up* is followed by the point *Theory*.

- The photo effect as a contradiction to classical physics

Towards the end of the 19th century, it was observed that the irradiation of metal surfaces with light causes electron emission if the frequency of light exceeds a certain limit frequency (Heinrich Hertz 1887, Wilhelm Hallwachs 1888, Philipp Lenard 1899). This process is referred to as photoelectric effect and the released electrons are called photoelectrons. Below a material-specific threshold frequency  $f_g$  of the incident light, no photoelectrons are observed, no matter how high the light intensity.

According to the classical wave theory of light, the free electrons in the metal are accelerated by the electric field of the light wave. The energy of the electron should grow with the field strength and thus with the intensity of the light wave. With sufficiently high light intensity, it should therefore be possible to release electrons from any metal, regardless of the light frequency. The existence of a threshold frequency can not be explained with the classical wave model of light.

It was only in 1905 that Einstein explained photoelectric effect by the absorption of light quanta (photons) of energy

$$E = hf$$

(Nobel Prize 1926), where  $h$  is Planck's constant and  $f$  the frequency of the light. Each released electron has absorbed the energy of a photon. The electron retains the amount of energy exceeding the work function  $W_A$  from the metal as the kinetic energy  $E_{kin}$ . Below the threshold frequency  $f_g$ , the energy  $E$  of the photons is insufficient to generate the work function  $W_A$ . The photoelectric effect is therefore considered as one of the key experiments in the field of quantum physics.

It must be remembered that M. Planck demanded the existence of light quanta in 1900 in order to conclusively reinterpret the known radiation laws.

- The measuring method

The kinetic energy of the electrons released from the conduction band is governed by the law of energy

$$E_{kin} = hf - W_A$$

If the kinetic energy  $E_{kin}$  of the photoelectrons is measured as a function of the light frequency  $f$ , the graph shows a straight line with the gradient

$$h = (E_{kin} + W_A)/f$$

$E_{kin}$  is measured using the device shown under the menu point *Experimental set up*.

The electrons released from the photocathode reach the anode because they also receive kinetic energy from the absorbed light. A constant voltage is established between the cathode and the anode after the kinetic energy of the electrons has been used up to overcome the potential difference cathode-anode. This voltage corresponds to the maximum energy of the released electrons

$$E_{kin} = eU$$

minus the energy needed to eject the electron (work function  $W_A$ ). If the frequency  $f$  of the light is known, and the photo voltage  $U$  is measured, then one can determine Planck constant  $h$ , the material-specific work function  $W_A$  and the limit frequency  $f_g$  at  $E_{kin} = 0$  eV and  $U = 0$  V, respectively with the known electron charge  $e$  from the energy conservation.

$$hf = eU + W_A$$

In the next menu point *Tasks*, we present some tasks to encourage the experimenter to conclusively interpret the expected measurement data in both the wave and the photon model of light.

In the menu point *Laboratory* the experimenter must register. If the experiment is free, he sees the remaining experimentation time on the top right until he activates a parameter. In the middle of this page he sees the webcam image of the experimental setup from the front; including the overview of both filter sets. In the right part of this page the control panel: switch on the lamp, select both filters and read off the measured value from the voltmeter and record this measured value.

In the menu point *Evaluation*, the measured values for 2 spectral filters and for each 4 grey filters are given to show the independence of the light intensity experimentally. So then the dependence of the kinetic energy of the electrons on the light frequency is demonstrated for all 5 spectral filters; then, as usual, these raw measured data are evaluated graphically.

In the following menu point *Discussion*, we deepen and expand the knowledge and understanding of the experimenter by asking questions about experimental set up, theory, laboratory and evaluation (Table 7.2).

As usual, the menu point *Material* follows, where first all necessary informations about the devices are presented. Then a short collection of didactic material for the interested physics teacher:

- A possible worksheet,
- A collection of tasks,
- A didactic analysis of the RCL experiment,
- A possible lesson,
- As well as an article demonstrating how this RCL experiment can be used in new ways of teaching / learning (station learning) [5].

Table 7.2: Discussion.

## 1 Experimental set up

- a) Which light source is used (continuous spectrum, line spectrum) and why?
- b) Why was this set of five filters chosen?
- c) Which other methods of performance do exist?

## 2 Theory

- a) Understand the work function in the energy band model for metals and semiconductors (conduction band, valence band, Fermi level).
- b) What is the difference between work function and contact voltage?
- c) Make again clear why the interpretation in the model "light as a wave" fails.
- d) What is meant by the dualism wave - particle for light?
- e) What is the difference between "external photo effect" and "internal photo effect"?

## 3 Laboratory

- a) Pay more attention to the time behaviour of the photo voltage. Alternately select filter 1 and filter 5; how long does it take for a "sensible", readable voltage value to occur? How do you explain this behaviour?
- b) Interestingly, the above time behaviour is also different, depending on which filter was in the beam path before the current measurement. Check it by changing the filters 5 - 4 - 3 - 2 - 1 in both directions. How do you explain this fact? Tip: What happens microscopically in a photocell? How does it discharge?

- c) Where can technical applications of the (internal) photo effect be found?

## 4. Analysis

- a) Consider the measuring error for every measured value.
- b) Does it make sense to set a straight line through the five measuring points?
- c) Compare Planck constant obtained from the slope of the line with the literature value. How good is your measurement result?
- d) How can the work function of the cathode material be read from the diagram  $U(f)$ ?
- e) What is the significance of the threshold frequency  $f_g$ ?

### 7.2.3 Operating the experiment

Fig. 7.2 shows the laboratory page of this experiment.

If you switch on the lamp, you have to wait a few seconds until you can see on the first filter wheel an increasingly brighter light spot, originating from the round opening of the lamp housing; typical behaviour for a mercury lamp. If one selects a filter, the experimenter clearly sees what happens in the experimental setup; the operation is intuitive and self-explanatory. Due to the measuring principle you have to wait a short while to read the respective photo voltage.

How can the experimenter operate the experiment? And which learning goals in a lab are intended here?

- One can select wavelengths for the incident light through the colour filters,
- As well as vary the light intensity via grey filters.
- One reads the measured photo voltage.

The work function of the material of the photocell is given by the literature value and can be determined in the experiment.

- The Planck constant is determined from the measured data.

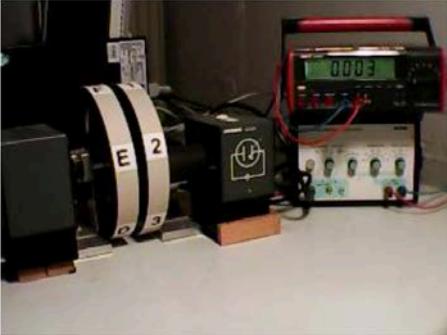
Or more generally:

- Measurement series are recorded (wavelength versus photo voltage, light intensity versus photo voltage).
- Shape incident light (wavelength, light intensity).
- Adjust experiment (bring wheels with colour filter and grey filter into defined starting position).

We were able to fully realize the experimenting with the RCL as in the real experiment in class.

### 7.2.4 Measurement result

- Independence of the kinetic energy of the electrons from the light intensity



Voltmeter is switched on automatically.  
Voltage is displayed in unit Volt.

## Photoelectrical Effect

### Labor

Verbleibende Experimentierzeit: 10: s

Status: Lampe ausgeschaltet.

Graufilter (Buchstabe) - Transmission

[A - 100 %](#)  
[B - 75 %](#)  
[C - 50 %](#)  
[D - 25 %](#)  
[E - 0 %](#)

Farbfilter (Nummer) - Wellenlänge

[1 - 366 nm](#)  
[2 - 405 nm](#)  
[3 - 436 nm](#)  
[4 - 546 nm](#)  
[5 - 578 nm](#)

**Table of filters**

grey filters	
A	T = 100 %
B	T = 75 %
C	T = 50 %
D	T = 25 %
E	T = 0 %

spectral filters	
1	366 nm
2	405 nm
3	436 nm
4	546 nm
5	578 nm

Figure 7.2: Laboratory page.

For the most accurate measurement of the photo voltage  $U$ , please note that

- the mercury vapour lamp after switching on for about 1 min. takes time to reach the operating temperature and maximum light intensity,
- due to the capacitive behaviour of the photocell and the input capacitance of the measuring amplifier (see data sheet in the menu point *Material*), the photo voltage only gradually approaches a stable final value.

Tab. 7.3 shows for two wavelengths measurement results for the investigation of the dependence of the photo voltage  $U$  or the kinetic energy  $E_{kin} = eU$  of the electrons on the transmission  $T$  of the grey filters or the light intensity  $I$ . Fig. 7.3 shows the measurement results together with a linear fit.

The small, possibly systematic drop of the photo voltage  $U$  with increasing transmission  $T$  for 578 nm is difficult to explain and is probably due to the behaviour of the measuring amplifier in combination

Table 7.3: Relationship between photo voltage  $U$  and transmission  $T$  of the grey filter for two different wavelengths.

	T=25%	T=50%	T=75%	T=100%
$\lambda=578$ nm	0,46 V	0,44 V	0,43 V	0,43 V
$\lambda=366$ nm	1,42 V	1,42 V	1,42 V	1,42 V

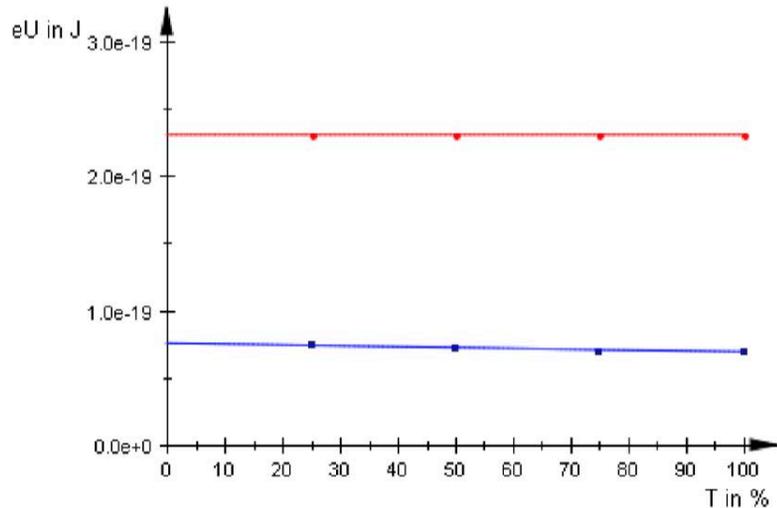


Figure 7.3: Relationship between kinetic energy  $E_{kin} = eU$  of the electrons and the light intensity for  $\lambda = 578$  nm (blue squares) and  $\lambda = 366$  nm (red circles) with a fitting straight line ( $e = 1.6 \cdot 10^{-19}$  C).

with the smaller number of electrons. The fluctuations in the measured values amount to a maximum of 30 mV for 578 nm and 0 mV for 366 nm. They are thus below the sum of the measuring errors of the measuring amplifier and the digital voltmeter. The kinetic energy of the electrons is thus in a very good approximation independent of the light intensity.

Why is it not possible to release electrons with a higher kinetic energy at a chosen frequency, if only the light intensity is increased (failure of the wave model, therefore, to explain Fig. 7.3): Light is an electromagnetic wave. Intensity  $I \propto \text{Amplitude}^2 \propto \text{Electric field } E^2$ . If a metal surface is irradiated by light a force is acting on the free electrons  $F = eE$ . If  $I$  increases,  $E$  and consequently  $F$  are getting larger, so

electrons with higher kinetic energy should be released; which is not the case.

- Dependence of the kinetic energy of the electrons on the light frequency

Since the kinetic energy of the electrons is independent of the light intensity, the relationship between the energy  $E_{kin} = eU$  of the electrons and the frequency  $f$  of the light need be performed for one value of  $T$  only. Table 7.4 shows the result for  $T = 100\%$ .

In Fig. 7.4 the kinetic energy  $E_{kin} = eU$  of the electrons released is plotted versus the frequency  $f$  of light.

According to Einstein's equation

$$hf = eU(f) + W_A = E_{kin}(f) + W_A \text{ therefore } E_{kin}(f) = hf - W_A$$

with the constant work function  $W_A$  and Planck constant  $h$ , a linear relationship between the kinetic energy  $E_{kin}$  of the electrons and the frequency  $f$  of the light is predicted (see menu point *Theory*). The measuring points are in fact approximately on a straight line. With a regression line (determined here with linear regression), the slope - Planck's constant  $h$  -, the amount of the intercept with the y-axis - the work function  $W_A$  - and the intercept with the x-axis - the threshold frequency  $f_g$  - can be determined.

Table 7.4: Examination of the dependence of the photo voltage  $U$  on the frequency  $f$  for transmission  $T = 100\%$  ( $c = 2.998 \cdot 10^8 \text{ m/s}$ ).

Wavelength $\lambda$ in nm	Frequency $f=c/\lambda$ in $10^{14}$ Hz	Photo voltage $U$ in V	Electron energy $E_{kin} = eU$ in $10^{-19}$ J
578	5,187	0,43	0,67
546	5,491	0,52	0,83
436	6,876	1,02	1,63
405	7,402	1,16	1,86
366	8,191	1,42	2,27

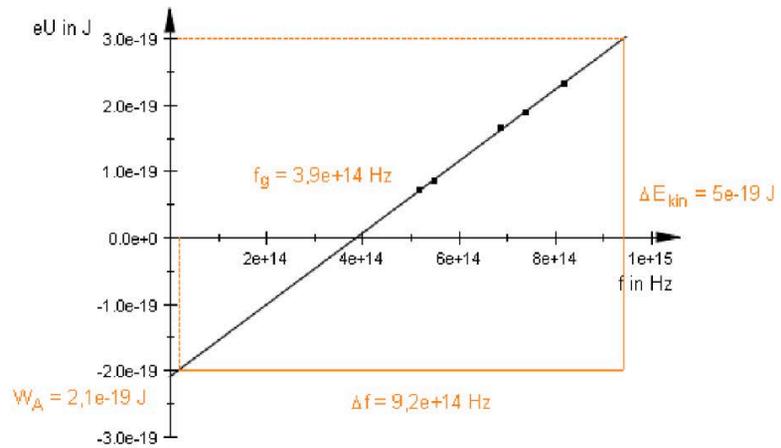


Figure 7.4: Relationship between kinetic energy  $E_{kin} = eU$  of the electrons released and the frequency  $f$  of the light for transmission  $T = 100\%$ .

## 7.3 Evaluation and experience

After usual analysis of data one gets:

- $h = 5.40 \cdot 10^{-34}$  Js with linear regression and  $h = \Delta E_{\text{kin}} / \Delta f = 5.44 \cdot 10^{-34}$  Js with the gradient triangle in Fig. 7.4. The deviation from the literature value  $h = 6.626 \cdot 10^{-34}$  Js amounts to approx. 18%.

This is just outside the maximum uncertainty of 15% guaranteed by the manufacturer (see material). The reproducibility of the photo voltage, on the other hand, is better than 5%.

- $W_A = 2.10 \cdot 10^{-19}$  J = 1.31 eV with linear regression and  $W_A = 2.1 \cdot 10^{-19}$  J = 1.31 eV from Fig. 7.4. The light quanta must therefore have energy of at least 1.31 eV in order to release electrons from the cathode material lead sulfide (PbS).
- $f_g = 3.9 \cdot 10^{14}$  Hz from Fig. 7.4. The incident light must therefore have at least this frequency  $f_g$  and the wavelength must be smaller than  $\lambda = c / f_g = 770$  nm to release electrons. Red light therefore releases electrons in this material.

It should be remembered that it is not important to determine the Planck's constant as precisely as possible, but that the quantum hypothesis can be confirmed experimentally with this demonstration experiment. In order to measure some data points for a straight line, the experimenter needs a few minutes; for the entire measuring program (all filters) about 15 minutes.

The RCL has been online since 2005, without any problems. The added value, i.e. the experiment as RCL, can be seen in the following: firstly, there is no need for a complex experimental set-up; second, there are no problems with the performance of this experiment (such as leakage currents, photocell to be heated, only three colour filters); thirdly, series of measurements can be performed quickly by different groups (identical measurements, multiple repetitions, measurement errors) leaving more room to interpret the measurement data in the wave model as well as in the photon model of the light.

The tracking, the user analysis, shows that the RCL photo effect has been called about 10 times a day in recent years, with an upward trend (2 visitors more a day in one year) The distribution of visit duration shows two maxima; 50% remain on the website less than 10 seconds;

10% of users each stay 10-30 seconds, 30-60 seconds, 60-180 seconds, 180-600 seconds, and 600-1800 seconds; Depending on the duration of the visit 20% of the experimenters perform 0-5 actions, 30% 6-10 actions and 50% more than 10 actions.

Conclusion: The users operate the RCL both qualitatively / quantitatively according to their research question as well as experiment-specific; i.e. all technical parameters are used.

## 7.4 Didactic material

The RCL experiment is definitely suitable as an experimental home work and can certainly be carried out in group work. Table 7.5 contains suggestions for a worksheet.

Some preliminary considerations that may lead to a possible lesson (Table 7.6):

- Didactic analysis

The wave and photon model of light are very different in their structure: In the wave model the energy is distributed across space, depending on the amplitude and independent of the frequency of the electromagnetic wave; In the photon model the energy is concentrated in an individual photon and frequency dependent. It is not easy to guide students with the photoelectric effect from the wave to the photon model: on the basis of this experiment, relevant experimental results are to be obtained and recognized as unexplainable in the wave model. The photon model is introduced and the photo effect explained. This lesson follows this path and experiments to differentiate these steps as clearly as possible for a better understanding of the learners. The RCL *Photoelectric Effect*, a table and tasks are the main media and materials of this lesson.

- Learning goals

The students should

- be able to interpret qualitative experiments on the photo effect,
- formulate hypotheses on the relationship between magnitudes of the incident light and magnitudes of the electrons released,

Table 7.5: Worksheet.

Worksheet --- photoelectric effect

1. Question

- a) When did Albert Einstein receive the Nobel Prize for the interpretation of this experiment?
- b) Why do we use these filters for the wavelength and for the transmission of light?
- c) Which light source is used and why? (With continuous or discrete spectrum)

2. Measure the photo voltage  $U$  in volts for one wavelength but with all transmission filters ( $T = 100, 75, 50, 25, 0\%$ ).

Wavelength (nm)	
366	Group 1
405	Group 2
436	Group 3
546	Group 4
578	Group 5

3. Measure this value at least 5 times and determine the error.

4. Create a graph: Photo voltage  $U$  versus transmission.

5. Discussion

- Create a graph for all measurements of the 5 groups: Voltage  $U$  versus frequency  $f$  in units of  $10^{14}$  Hz.
- Determine the slope of this line; according to theory that is Planck constant  $h$ .
- Compare this measured value for  $h$  with the literature value.
- How do you interpret this graph (photo voltage versus transmission) in both models: light as a wave and light as a particle?

- examine the relationship between the energy of the electrons and the frequency versus the intensity of the light with the RCL photoelectric effect,
  - give a meaningful argument which experimental results for the photoelectric effect can not be explained in the wave model and how these are explained in the photon model,
  - get to know technical-physical applications of the external and internal photo effects.
- Learning prerequisites of the lesson unit

The following learning prerequisites are desirable:

- Students understand the charging and discharging of capacitors and can safely handle terms such as energy and work in the electric field as well as electrical potential.
  - Discrete spectra have already been investigated in wave optics.
  - The intensity of an electromagnetic wave has already been dealt with.
- Lesson in keywords:
    - Preparatory knowledge,
    - Qualitative experiments,
    - Quantitative experiments with the RCL photoelectric effect,
    - Interpretation of the results in wave and photon model of light,
    - More detailed tasks and technical-physical applications.

This lesson offers a variety of student lectures / projects based on the following texts:

- Wikipedia entries for the internal and external photoelectric effect,
- Internet search on technical applications such as photo resistance, CCD sensor and much more,
- Historical text by M. Planck and A. Einstein [6].

Also for this RCL we have created a collection of tasks but without model solutions. Here is a selection (see Tab. 7.7). The tasks are more

in the field of basic physics at universities, but may serve as a stimulus for more demanding tasks in a high school course.

Finally, we refer to an article in which we have embedded the RCL photoelectric effect into new form of teaching [5]. Figure 7.5 shows the structure of the learning unit with 8 learning circles. Table 7.8 shows details of the first learning station of Fig. 7.5 top left.

For the teacher's hand, the experimental results of the photoelectric effect, as well as the explicability in the wave model and explanations in the photon model are summarized in tabular form (Table 7.9).

We also have positive experiences with this RCL in project work: In a first version, the RCL was set up, programmed, tested and released to the public within a week by a group of students at a summer camp of the Technical University of Munich and at the German Museum (Table 7.10: Poster of the student group).

Table 7.6: Lesson unit.

**Module "Photoelectric effect and photon model of light"**

Phase	Contents and forms of work
<b>Preparatory knowledge</b>	<p><b>Experiments on the light intensity, for example by a photodiode:</b>            Introducing / repeating the concept of light intensity,            Measuring light intensity of different light sources,            Increasing and decreasing light intensity through lenses,            Measuring transmission of materials,            Gaining distance law inductively.</p> <p><b>Tasks for light intensity:</b>            Relation to everyday life,            Dealing with the term light intensity,            Frequency independence and amplitude dependence of the light intensity in the wave model.</p>
<b>Qualitative experiments</b>	<p><b>Introduction of the photo effect:</b>            Perform experiments after Hallwachs with positively and negatively charged zinc plate, Hg lamp and electrometer,            Define external photo effect: emission of electrons (effect) by irradiation of materials with light (cause).</p> <div style="text-align: center;"> </div> <p><b>To encourage students to study this effect more closely:</b>            How can the effect be studied more closely?            Visualize students' suggestions (see picture) and note suspected relationships            Interaction mechanism between light and material is excluded (material as black box).</p> <p><b>Qualitative investigation:</b>            Irradiation with incandescent lamp, red light lamp or with Hg lamp + glass plate leads to no electron emission (frequency dependence) even with the highest possible light intensity (vary light intensity!),            Smaller distance of the Hg lamp to the zinc plate leads to faster discharge of the electroscope (intensity dependence),            Negatively charged, not polished zinc plate or lead plate will not discharge when irradiated with Hg lamp (material dependency).</p>

<p><b>Quantitative experiments with RCL "Photo Effect"</b></p>	<p><b>Clarify experimental setup and its performance:</b>          Show lab page of the RCL in the lesson without explanation and have students express it freely,          Discuss frequency and energy measurements,          Perform example measurement for <math>f</math> and <math>E_{kin}</math>,          Questions after the examined relations,          Formulate hypotheses for <math>E_{kin}(f)</math> and <math>E_{kin}(I)</math> (<math>I</math> light intensity).  <b>Measurement and evaluation of <math>E_{kin}(f)</math> and <math>E_{kin}(I)</math> as homework or in class:</b>          Let relationships be graphically represented,          Insert in <math>E_{kin}(f)</math> -diagram at least the measured values of another photographic material, Problematize whether an infinite straight line may be placed through the measured values of <math>E_{kin}(f)</math>,          Relate to the frequency dependence of the photo effect in qualitative preliminary experiments,          Introduce the term frequency threshold,          Slope for all photo materials is the same, set up function equation (parameter function with <math>W_A</math>)          To emphasize the independence of <math>E_{kin}</math> from <math>I</math>,          To insert all previously obtained and complementary further experimental results in the table.</p>
<p><b>Interpretation of the experimental results in the wave and photon model of light</b></p>	<p><b>Discussion on the explainability of the photo effect in the wave model:</b>          Using Table **, do elaborate those results, which can not be explained in the wave model.  <b>Introduction of the photon model:</b>          Immediate release of electrons, therefore energy can no longer be distributed continuously in the flow of light          Photon term: Use microscope image of blackened photographic paper using to identify the product <math>hf</math> as the energy of a photon using the result <math>E_{kin}(f)</math>, understand the photo effect as a photon-electron interaction, Planck's constant and work function.  <b>Explanation of the Photo Effect in the Photon Model:</b>          Complete Table **. Insert text material **.</p>
<p><b>Advanced tasks, technical-physical applications</b></p>	<p><b>Use of tasks *:</b></p>

Table 7.7: Tasks.

### 1. Intensity of light

As light sources a laser pointer (light power  $P_L = 3 \text{ mW}$ , beam diameter  $d = 3 \text{ mm}$ ), a light bulb (electrical power  $P_e = 60 \text{ W}$ , efficiency 4%) and the sun (radiated power  $P = 3.86 \times 10^{26} \text{ W}$ ) are available. Absorbance, scattering and reflection losses are neglected in the following:

- With which light sources is the light intensity dependent on the distance? Why and how?
- Tissue can coagulate ("melt") by a light intensity of  $1 \text{ W/m}^2$  and more and thereby be irreversibly damaged: Estimate for the three light sources whether direct view of light can endanger the retina of the eye.
- The average intensity  $\langle I \rangle$  of a plane electromagnetic wave propagating in the  $x$ -direction with electric field strength  $E(x,t) = E_0 \sin[2\pi ft - (2\pi/\lambda)x]$  is given by  $\langle I \rangle = (1/2) \epsilon_0 c E_0^2$

Which amplitude  $E_0$  has the electric field strength vectors of the laser and sunlight? What amount of energy hits an area of  $1 \text{ cm}^2$  in one second? Of which size does  $\langle I \rangle$  not depend on these light sources?

### 2. Independence of the photoelectric effect from the light intensity

An area of  $0.5 \text{ cm}^2$  of the photo-layer of a potassium photocell ( $W_A = 2.25 \text{ eV}$ ) is irradiated with light of wavelength  $\lambda = 500 \text{ nm}$  and intensity  $I = 20 \text{ W/m}^2$  ( $h = 6.626 \cdot 10^{-34} \text{ Js}$ ). 90% of the incident light energy is reflected by the potassium photo-layer, only the remaining 10% are absorbed by the potassium atoms with a quasi-free electron (potassium atom density  $n = 1.3 \cdot 10^{22} \text{ potassium atoms/cm}^3$ ) to a depth of  $0.1 \cdot \lambda$ .

- How long would it take for these data to release electrons, assuming that the absorbed light energy is evenly distributed among the potassium atoms? What conclusion can be drawn from this result?
- Which changed conditions lead to a shorter time to release electrons? Justify with qualitative arguments.

### 3. Light intensity in everyday life

Red light (wavelength  $\lambda = 600 \text{ nm}$ , power of light  $P = 0,06 \text{ mW}$ ) is emitted by the rear light of a bicycle evenly distributed in all directions. A pedestrian recognizes this rear light from a distance of  $100 \text{ m}$  (eye pupil diameter  $d = 4 \text{ mm}$ ):

- What is the light intensity  $I$  of the rear light at the pedestrian's location? What light power  $P$  falls into his eye?
- How many photons per sec pass the eye pupil?
- At what distance does the pedestrian see the rear light, if our eye needs a minimum power  $P_{\min} = 1.7 \cdot 10^{-18} \text{ W}$  to see in principle? Justify whether the result is realistic.

#### 4. Applications of the photoelectric effect

Answer the following questions by obtaining more information by oneself:

- What is the principal difference between the external and internal photoelectric effect?
- Which electronic components are shown in Fig. 1. Which of them use the external, which the internal photoelectric effect?
- In which technical and physical applications / devices are which of the components used?

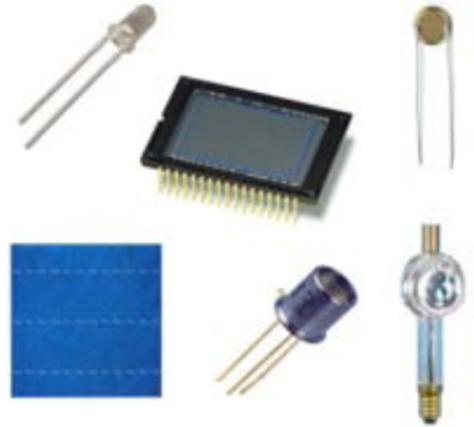


Fig. 1: Electronic components that use the photoelectric effect.

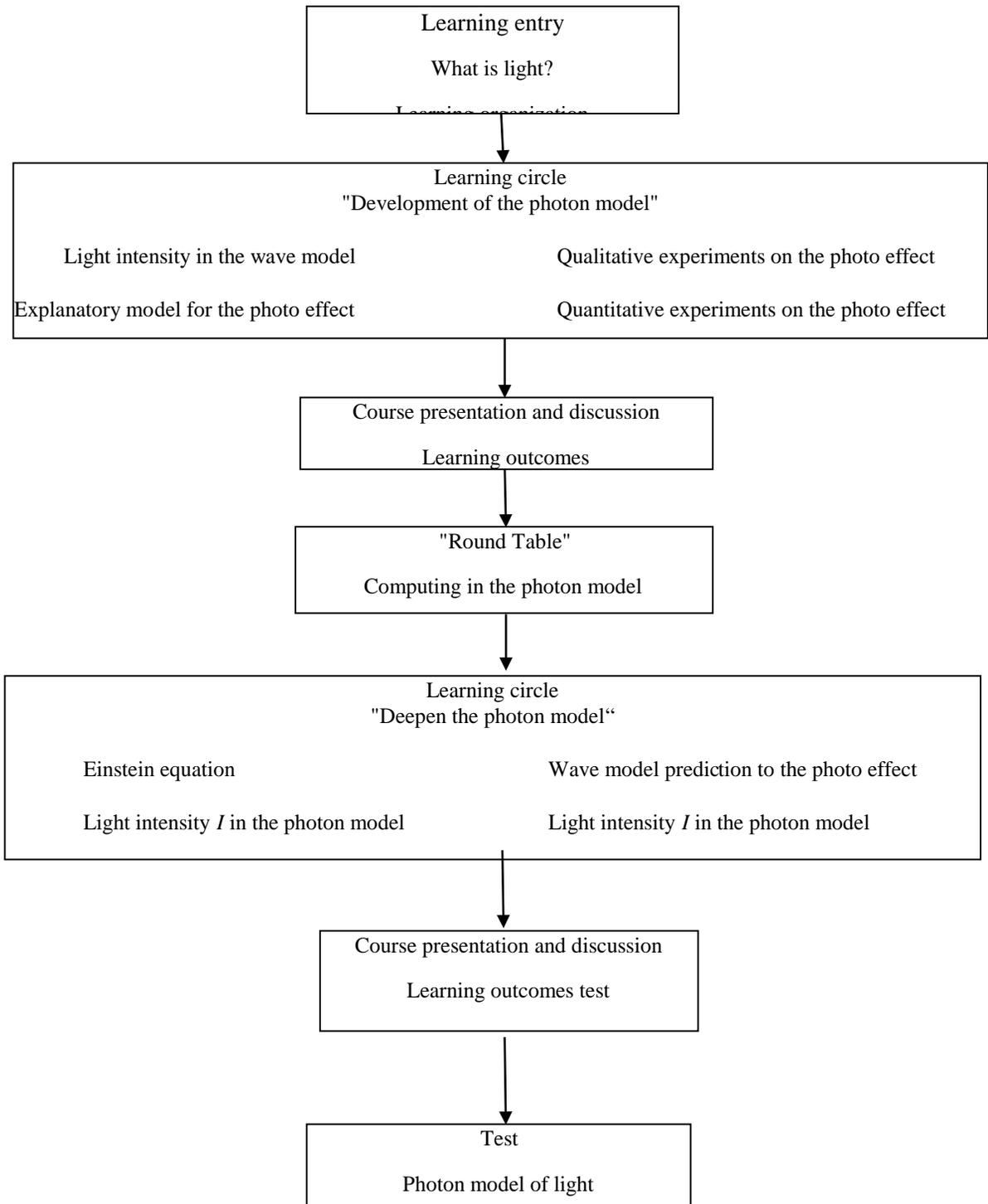


Fig. 7.5: Structure of the lesson "photon model of light".

Table 7.8 Learning circle

**Learning circle "Development of the photon model"****Station: Light intensity in the wave model****Materials**

Laser pointer ( $P < 0.1$  mW (laser class II),  $640 \text{ nm} < \lambda < 660 \text{ nm}$ )

Light bulb with power supply

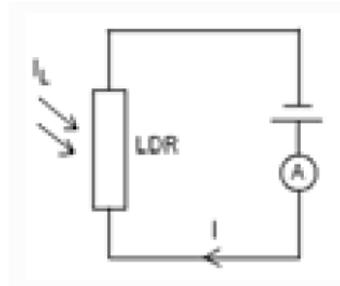
Double slit with  $d = 0.3$  mm

LDR (Light Detectable Resistor), battery and ampere-meter

Collecting and diverging lens, grey transparency film

Ruler/scale

Various supports and connecting materials

**Experiments**

1. Illuminate the double slit vertically with laser light:

- Explain the origin of the light distribution behind the double slit.
- Check the wavelength of the laser pointer.

2. In the measurement circuit with an LDR, the larger the current  $I$  is the higher is the light intensity.

- Investigate the relationship between light intensity and distance of light source for laser light and for light bulb.
- Investigate the effect of the collecting and diverging lens.

3. The light intensity  $I$  is defined by  $I = (P/A) = E/(At)$  (light power  $P$  in W: emitted by the light source - also referred to as radiation flux, area  $A$  in  $\text{m}^2$ : area on which the radiated power is distributed, light energy  $E$  in J, time  $t$  in s: energy is emitted in time  $t$ ):

- Determine the light intensity of the laser light in  $\text{W}/\text{m}^2$ .
- Determine the light intensity of the light bulb at a distance of 1 m in  $\text{W}/\text{m}^2$ .
- Determine the transmission  $T$  of the grey transparency film in %.

**Tasks**

1. Calculate the light intensity of the sun ( $P = 3.86 \cdot 10^{26}$  W) at the earth's surface (influence of the earth's atmosphere should be disregarded; the calculated value is called solar constant).

2. Tissue can coagulate ("melt") even at a light intensity of  $1 \text{ W}/\text{m}^2$ . Does the view into the laser light or into the sun really endanger our retina?

3. By an internet search one will find animations of the propagation of a harmonic plane electromagnetic wave:

Mention by name characteristic features of a plane electromagnetic wave.

Calculate the amplitude  $E$  of the electric field strength vector from  $I = \epsilon_0 c E^2/2$  for the laser light. The light intensity does not depend on what? Compare the amplitude with the field strength of a plate capacitor with  $U = 3$  kV and  $d = 3$  cm.

Table 7.9: Table to complete in the course of the lesson to clarify the photo effect.

**Explanation of the photo effect****Description of the photon model**

Light consists of small concentrated energy packets (light quanta, photons) with the energy  $E_{Ph} = h f$ . Their velocity in vacuum is the speed of light and their energy is greater, the greater the frequency or the smaller the wavelength of the light. The photon density of light is larger, the larger the light intensity.

**Sizes**

Light frequency  $f$ , cut-off frequency  $f_g$ , Planck constant  $h$ , photon energy  $E_{Ph}$ , release energy  $E_A$ , kinetic energy of electrons  $E_{kin}$ , light intensity  $I$ , photocurrent  $I_e$ , photon density  $n$ .

☺ = explainable, □ = not explainable

<i>Experimental result</i>	<i>Explainability in the wave model</i>	<i>Explainability in the photon model</i>
For $f > f_g$ electrons are released without delay after irradiation by light	□ The energy of an electromagnetic wave is distributed throughout space. It therefore takes time until at least the energy $E_A$ is irradiated. A computational estimate gives too long releasing times.	☺ A photon can transfer its concentrated energy to an electron without loss of time.
For $f = \text{const.}$ , $E_{kin}$ does not depend on $I$ .	□ A larger $I$ (greater amplitude and energy of the wave) would lead to greater $E_{kin}$ .	☺ After $E_{kin} = h f - E_A$ , then $E_{kin}$ is independent of $I$ .
The larger $f$ , the larger $E_{kin}$ of the released electrons.	□ The intensity of an electromagnetic wave is independent of $f$ . Therefore, $E_{kin}$ is not likely to depend on $f$	☺ For $E_A = \text{const.}$ , after $E_{kin} = h f - E_A$ the energy $E_{kin}$ increases with $f$ .
Independently of $I$ no electrons are released for $f < f_g$ .	□ $I$ of an electromagnetic wave is independent of $f$ . Therefore, electrons would have to be released independently of $f$ .	☺ For $h f > E_A$ , respective $f > E_A / h = f_g$ . then $E_{kin} > 0$ .
For $f = \text{const.}$ , $I_e$ increases with $I$ .	☺ A larger $I$ in the wave model means a larger amplitude of the wave. Therefore, more electrons are released.	☺ A larger $I$ means larger $n$ .
Most of the electrons are emitted perpendicular to the direction of incident light.	☺ The field strength vector of an electromagnetic wave is perpendicular to the propagation direction. The electrons are therefore accelerated in the direction field strength.	□ Most of the electrons should be emitted in the direction of the incident photon flux.

Table 7.10: Poster of the student group, TU Summercamp, Munich, 2005.

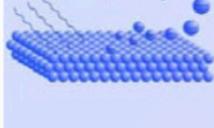
# Summercamp 2005

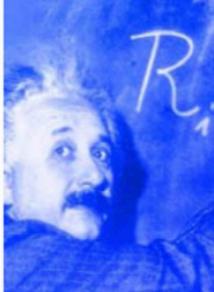
## Photoeffekt

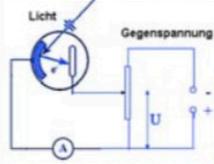
Licht ist Energie.



$E = h\nu - e^-$













Frédéric Jahn      Beinda Tschangel      Andreas Friedberger

**Was ist das?**  
 Unter Photoeffekt versteht man das „Herausschlagen“ von Elektronen aus einer Metallschicht durch Photonen (Licht). Für die Entdeckung dieses Effektes erhielt A. Einstein 1923 den Nobelpreis.

**Wofür wird er gebraucht?**  
 Die wahrscheinlich bekannteste und aktuellste Nutzung findet sich bei Solarzellen, deren (wesentlich komplexeres) Prinzip auf dem Photoeffekt basiert. Eine weitere Anwendung stellt zum Beispiel das Nachtsichtgerät dar.

**RCL?**  
 Remote Control Lab ist eine zukunftsorientierte Möglichkeit Versuche über Befehle aus dem Internet zu steuern.



**Filterrad**  
ermöglicht durch Schrittmotor das Wechseln der Filter (bestimmen die Wellenlänge des Lichtes)

**Blendenrad**  
ermöglicht durch Schrittmotor das Wechseln der Blenden (verkleinert den Lichtstrahl = Intensität)

**Messverstärker**  
wird benötigt um die sehr kleinen Photoströme messbar zu machen

**Photozelle**  
Zelle, in der der Photoeffekt statt findet und die entstehende Spannung gemessen wird

**Interface**  
übermittelt Befehle vom PC an die Motoren

**Voltmeter**  
zeigt die aktuelle Spannung an

**Quecksilberdampflampe**  
sendet charakteristische Spektrallinien aus

**Drossel**  
Begrenzt den Stromfluss (um den Betrieb der Spektrallampe zu ermöglichen)



Eberhard von Kuenheim Stiftung  
Stiftungs-Nr. 000-001





Technische Universität München  
Lehrstuhl für Experimentalphysik  
September 2005





## 7.5 Literature

- [1] Phywe. [06778.00] Photocell.
- [2] Phywe. [08120.14] Spectral lamp.
- [3] Phywe. [13626.93] Throttle for spectral lamp.
- [4] Herrmann, F. and Job, G. *Altlasten der Physik*. Volume 2. 2012,
- [5] Gröber, S., Vetter, M., Eckert, B. and Jodl, H.-J. »The Photon Model of Light - A Learning Unit with Learning Circles and a Remotely Controlled Laboratory (RCL)«. In: *PdN-PhiS 56.2* (2007), p. 12-19.
- [6] Flax, E. *One hundred physics puzzles*. Klett, 1991, sections 113 and 114.

# 8 Radioactivity

## 8.1 Introduction

The topic of radioactivity has three social aspects that physics lessons have to support: background knowledge on energy policy, nuclear weapon technology and medical issues. Artificial radioactivity is encountered in everyday life in a variety of ways, such as:

- For energy production in nuclear power plants,
- In medical therapy and diagnostics (such as irradiation of cancer tissue, thyroid, szintigram),
- In the preservation of food by irradiation.

The fact that we do not have a direct organ that is sensitive to radioactive radiation - such as the ear for sound and the eye for light - and that in everyday life one can not do much with appropriate units (Becquerel, Gray, Sievert), commits physics lessons to help.

Depending on how long reactor accidents belong to the past (Harrisburg 1979, Chernobyl 1986, Fukushima 2011), the topic of radioactivity has a firm place in all syllabuses for physics / chemistry: mostly at the end of secondary I level (age of 10-16 years) in qualitative form with pupil experiments and in the secondary II level (age of 17-19 years) as part of nuclear physics. The degree of obligation to treat this topic is very heterogeneous in the individual federal states.

Radioactivity was equally important in chemistry as in physics, from the late 19th century to about 1950:

- Becquerel 1896 discovery of natural radioactivity,
- P. and M. Curie 1898 manufacture the elements polonium and radium,
- Around 1900 identification of the three types of radioactive radiation  $\alpha$  -  $\beta$  -  $\gamma$ ,
- Moseley 1913 correlation between chemical atomic number and x-ray line,

- Rutherford 1919 first artificial nuclear conversion,
- Chadwick 1932 discovery of the neutron,
- I. and F. Joliot-Curie 1933 generation of artificial radioactivity,
- Hahn and Strassmann 1938 fission of uranium nuclei with neutrons,
- Fermi 1942 controlled chain reaction.

In physics lessons / chemistry lessons two types of experiments are usually demonstrated:

1. Qualitative experiments on natural / artificial radioactivity, radiation protection, on the properties of radioactive radiation.
2. Qualitative experiments with continuous cloud chamber (range of  $\alpha$  radiation),  $\gamma$ -spectroscopy, decay-law, Compton effect, etc.

Why are both types of experiments so seldom used in class?

- The latter apparatus is very expensive (1000 Euro) for one result and one use per year.
- Usually there are no suitable  $\alpha$  -  $\beta$  -  $\gamma$  radiation sources in the physics collection.
- Radiation protection (the so-called 4A rules) should be taught, but the experiment still poses dangers, especially with long series of measurements.
- From the point of view of the pupil, it does not happen too much in all these experiments: it cracks on an acoustic display or one reads events as numbers.
- To be able to make quantitative statements one needs long series of measurements with a high expenditure of time (absorption by material, statistical processes).
- In addition, a sound, profound treatment requires sufficiently detailed mathematical knowledge, such as exponential function or Poisson and Gaussian distribution.
- For safety reasons, teachers must be radiation protection officers and only weakly radioactive radiation sources may be used (resulting in long measuring times).

- Physics oriented experiments generate far less interest for students than application-oriented experiments or those with an everyday relevance (alternative: visit of appropriate medical practices, X-ray clinics or nuclear power plants).

In our teacher training courses on the use of RCLs in physics lessons, physics teachers estimate the value of radioactivity experiments as an RCL very high.

## 8.2 Experiment and RCL variant

### 8.2.1 Experimental setup and function

Figure 8.1a shows the schematic experimental set-up, where the individual components were purchased, rebuilt and assembled into a compact set up. To familiarize yourself with the structure, it is recommended to play through all functions (wheel with sources, wheel with absorber, detector).

The radiator wheel (1) is equipped with three radioactive sources (Americium 241 as a  $\alpha$ -radiator, Strontium-90 as a  $\beta$ -radiator, Cobalt-60 as a  $\gamma$ -radiator [1]) and a rod without a source for determining the zero rate. On the absorber wheel (2), 46 material samples of Lead, Aluminium, steel, stainless steel and PVC with thicknesses between 0.1 and 9.0 mm are arranged. Furthermore, on the absorber wheel for measurements of the law of distance, there is a simple opening and a Lead collimator for producing a sufficiently narrow beam. To deflect  $\beta$ -rays, an inhomogeneous magnetic field of fixed average field strength  $B \approx 20$  mT, extension 6 cm in beam direction and two selectable directions (upwards, downwards perpendicular to the beam direction) can be generated by means of an electromagnet between the pole shoes of a ring iron core (3).

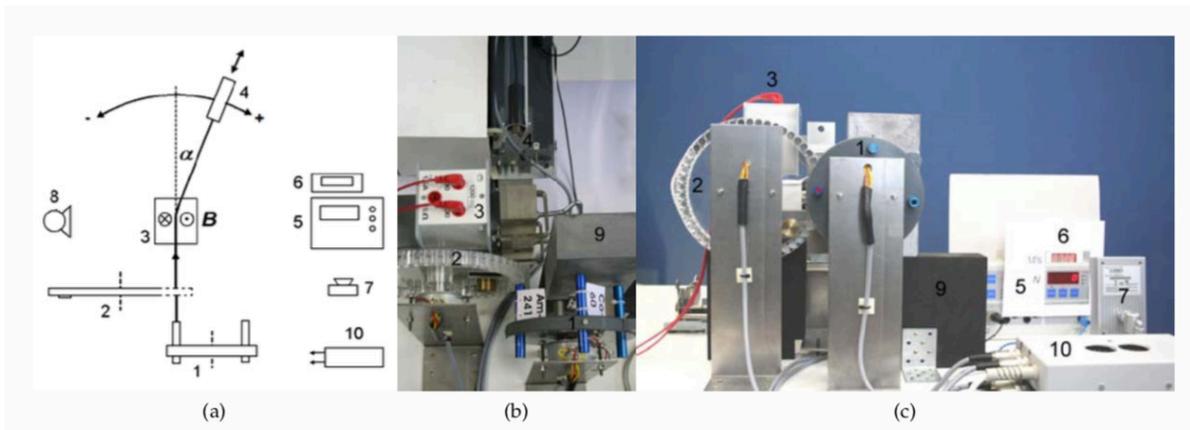


Figure 8.1: Experimental setup: (a) and (b) from above, (c) in beam direction.

The radiation is detected by a window counter tube (4) [2], whose distance from the beam source can be adjusted between 0, 3 cm (through the opening in the absorber wheel) and 2, 7 cm (with absorber) and up to 30 cm. To detect the deflected rays, the window counter tube is swingable at a fixed distance of 11 cm in steps of 5 degrees by  $\alpha = \pm 45$  degrees with the magnetic field switched on. The number of registered signals is measured by a counter (5) [3]. In addition, to study the statistics of radioactive decay, the time between two signals can be measured and shown on a display (6). The user can read both displays (5, 6) in the image of a webcam (7). Another webcam (8) shows the user a picture of all mobile experimental components. Lead bricks (9) shield the radiation of the non-selected radiation sources at all relevant points.

Figure 8.1b shows a photograph of the central part of the experiment from above; Fig. 8.1c a photo of the overall experimental set up from the front.

An interface (10) is connected between the web server and the experiment, which controls the stepper motors for the radiation source wheel and the absorber wheel, the stepper motors for the distance and angle adjustment of the window counter tube, the power supply of the magnet, the counter and the electronics for measuring the time interval between two signals.

Table 8.1 contains all the necessary details on the radioactive sources, as well as Table 8.2 on the absorber materials.

Table 8.1: Radioactive sources of the experiment.

Radioactive element			Radiation	Activity A	Half-life
Name	Symbol	Atomic number Z		in kBq (date)	in years
Strontium	Sr	90	$\beta$	74 (20.10.2005)	28,8
Cobalt	Co	60	$\gamma$	74 (19.09.2005)	5,27
Americium	Am	241	$\alpha$	74 (20.10.2005)	433

Table 8.2: Thicknesses of the absorber materials.

Material	Absorber thickness in mm
Lead (Pb)	0,1; 0,2; 0,4; 0,5; 0,6; 0,8; 1,0; 1,2; 1,4; 2,0; 2,5; 2,9; 3,0; 3,7; 4,0; 5,0; 5,3; 5,8; 9,0
Aluminium (Al)	0,5; 1,0; 1,5; 2,0; 2,5; 3,0; 3,5; 4,0
Stainless steel (VA)	0,5; 1,0; 1,5; 2,0; 3,0; 4,0
Polyvinyl chloride (PVC)	0,5; 1,0; 1,5; 2,0; 3,0; 4,0
Iron (Fe)	1,0; 1,5; 2,0; 3,0; 4,0

## 8.2.2 Navigation menu

The menu point *Experimental set up* follows the menu point *Theory*, which is suitable for self-study. The topic of radioactivity is not that difficult in our opinion, it is usually not taught. For all three types of radiation used in the RCL, the term scheme of the respective element (Am-241, Sr-90, Co-60) with the most important decay channels, their energies and branching ratios is described. The law of distance ( $dN/dt \propto 1/r^2$ ) is made geometrically plausible and the absorption law (counting rate as a function of absorber thickness) is derived. The mode of action of the detector (Geiger-Müller counter tube) is explained. The mathematical terms necessary for the evaluation of the statistical processes - such as zero-rate measurement, Poisson distribution, Gaussian distribution, relative error - are described. Finally, the Lorentz force is explained, according to which moving charged particles are deflected in a magnetic field. The 5 rules for radiation protection (the 5 As) are illustrated:

- A - maximize distance,
- A - minimize duration of stay,

- A - limit activity to a reasonable level,
- A - use shielding,
- A - avoid picking up.

In the following menu point *Tasks*, the user can check his knowledge of the experiment and get suggestions for a self-designed measurement program (see Tab. 8.3).

In the menu point *Laboratory*, the user sees the image of the webcam from the experimental setup from diagonally above, as well as by a second webcam, the display for the number of registered decays. On the right side of the lab page is the control panel where the user can design his experimenting: choice of radioactive source, choice of absorber material, magnetic field, position of the detector, measurement of decays (details see later).

In the menu point *Evaluation*, the 4 most important types of measurements are shown as examples:

- Deflection of  $\beta$ -rays in the magnetic field,
- Distance-law for  $\beta$ -rays,
- Absorption law for  $\beta$ -rays,
- The statistics of radioactive decay.

The menu point *Discussion* poses questions about the experimental setup, the theory, the laboratory, the evaluation (see Tab. 8.4).

In the last menu point *Material*, both the experimental material - instructions for use of the teaching material manufacturer - as well as didactic material is made accessible:

- Didactic analysis of the RCL experiment.
- Publication of this RCL with exemplary measurement series and careful data discussion.
- Bibliography for teachers, pupils and students in general on radioactivity, nuclear physics and radiation protection.

Table 8.3: Tasks.

- 1) Absorption of  $\alpha$ ,  $\beta$ ,  $\gamma$  radiation
  - a) Investigate the absorption of  $\alpha$ ,  $\beta$ ,  $\gamma$  radiation in different absorber materials of equal thickness. Make a statement about the shielding of the respective radiation in relation to the absorber material.
  - b) What is the significance of your results for radiation protection?
- 2) Range of  $\alpha$  radiation
  - a) Measure with the Americium source the range of  $\alpha$ -radiation. Draw a distance versus counting-rate diagram and discuss the behaviour.
- 3) Distinction of  $\beta$  and  $\gamma$  radiation
  - a) Which size must be kept constant for a comparison of both radiations?
  - b) Measure the counting rate with the electromagnet switched off and switched on and with pinhole (collimator) depending on the deflection angle.
  - c) For each radiator, draw the angle versus counting rate diagram with the electromagnet switched on and off. What can be recognized? What conclusions can be drawn about the different types of radiation?
- 4) Distance law for  $\beta$  and  $\gamma$  radiation
  - a) Investigate the relationship between the detector-emitter distance and the counting rate for the two types of radiation. Draw distance versus-counting-rate diagrams and determine the constants in this law of absorption.
- 5) Absorption of  $\beta$  radiation in Aluminium and  $\gamma$  radiation in Lead
  - a) Carry out measurements without absorber.
  - b) For both radiations, examine the relationship between counting rate and absorber thickness.
  - c) Draw counting rate versus absorber thickness diagrams and determine the constants in this law of absorption.
- 6) Statistics of radioactive decay by measuring the zero rate
  - a) Measure the zero rate at a suitable time interval at least 30 times and draw the abundance distribution in a diagram.
- 7) Statistics of radioactive decay by measuring the time between two decays
  - a) Measure the time between two decays at least 30 times.
  - b) Draw the experimental abundance distribution in a diagram. What can be concluded from the result?

Table 8.4: Discussion.

- 1) Experimental set up
  - a) What is the detection sensitivity of Geiger-Müller counter tubes for  $\gamma$ -radiation? What are the consequences for the experiment?
  - b) Which detectors are available besides to the Geiger-Müller counter tube? For which types of radiation are they suitable?
  - c) Can one determine the energies of radioactive radiation with a Geiger-Müller counter tube?
- 2) Theory
  - a) Which natural decay series are there?
  - b) Which radiation (s) emits the radioactive sources Am-241, Sr-90 and Co-60?
  - c) What kind of secondary radiation can occur if different types of radiation interact with matter?
  - d) What do the terms body dose, equivalent dose and energy dose mean?
  - e) What is meant by the term quality factor? What are the different biological effects of different types of radiation?
  - f) What is the natural and civilizational caused radiation exposure per year in Germany?
  - g) Which biological damages can be caused by radioactive radiation?
- 3) Laboratory
  - a) Why do we get for Americium-241 a higher counting rate than the zero rate, even though the detector-emitter distance has already exceeded the maximum range of  $\alpha$ -radiation?
  - b) Which conclusions for radiation protection can be drawn from this experimental result?
- 4) Evaluation
  - a) How should the course of the distance versus counting rate diagram for Am-241 theoretically look like?
  - b) Which effect is expected on the counting rate versus angle diagram for Cobalt-60 compared to Strontium-90?

### 8.2.3 Operating the experiment

Figure 8.2 shows the lab page - on the left the webcam image of the entire setup, including the webcam image of the counting unit; - on the right the control panel.

In order to familiarize ourselves with the initially confusing because spatially compact experimental setup, we propose to pay attention to the webcam image every time a technical parameter changes:

- Choice of 3 radioactive sources and rod without source (for background radiation measurement);
- Choice of one absorber from around 50 samples;
- Choice of the counter tube distance of 0.3 cm (without absorber) or 2.7 cm (with absorber) to 29 cm. (Note: To protect the counter tube, it is only possible to change the distance after pressing the switch off button (of the magnetic field);
- Choice of magnetic field with north pole above (LED red), north pole below (LED green), magnetic field off (LED off); see photo of the experimental set up top left;
- Choice of angle between beam direction and detector;
- Choice of time interval when measuring decays;
- Measurement of the time interval between two decays.

We designed the control panel in such a way that the experimenter can intuitively press the appropriate control elements - that is, measure immediately. Which learning goals in a student lab are linked to this?

- Select source (kind of radiation);
- Select object (absorber material and its thickness);
- Take measurement series (detector distance - number of decays, absorber thickness - number of decays, time - number of decays, detector angle - number of decays);
- Select parameters (magnetic field and direction);

**Radioactivity**

Introduction

Setup

Theory

Tasks

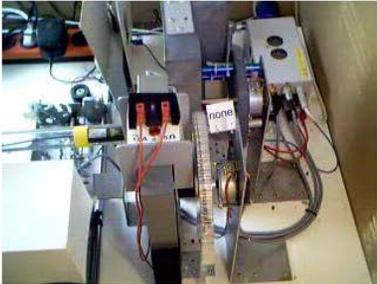
**Laboratory**

Analysis

Discussion

Material

Support



**Magnetic field** None (off), upwards directed (LED): (green), downwards directed (red)



Upper counter: Time between two decays in s  
Lower counter: Number of decays

### Radioactivity Laboratory

Remaining time to perform experiment:  s

Hint: To prevent the counter from damages the distance is only adjustable after pushing the button "None" of magnetic field.

Radioactive source:

Absorber:

Distance of counter: (1.2/3.5 - 29.1 cm)  cm

Magnetic field:

Angle of counter: (.45°-45°, 5°-steps)  °

Number of decays in time interval: (0 - 60 s)  s

Time between two decays:

Figure 8.2: Laboratory page of the experiment: webcam images (left) and control panel (right).

- Adjust experimental set up to initial state - realign.

These interactions are also experiment specific. This RCL is authentic, i.e. the experimenter receives self-acquired measured data for later analysis.

### 8.2.4 Measurement result

We assume that the majority will use the RCL radioactivity for self-study or for a radiation protection project; that is why we go into details of almost all types of measurements / phys. questions, so that the user gets a comparison for all types.

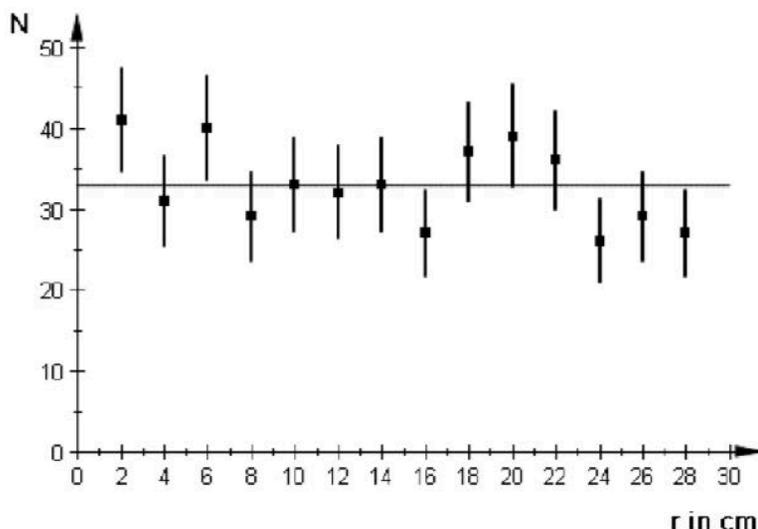


Figure 8.3: Result of background radiation measurement:  $N$  Number of events as a function of the distance  $r$  between detector and rod without source.  $\langle N \rangle = 33$  events in 60 seconds measurement time interval.

In order for the experimenter to familiarize himself with the apparatus, the first experiment is to measure the background radiation (see Fig. 8.3). It can be seen that this "zero rate" is independent of the distance  $r$  between rod without source and detector and that the counting rate  $N$  is about 33 events in the measurement interval 60 sec.

In a measurement series, the number of events is registered as a function of the distance between source and detector. For geometry reasons, we expect  $N(r) \propto r^{-2}$ , because the radioactive radiation ideally propagates like a spherical surface from a point like source. Figure 8.4 shows the result for  $\beta$ -rays and  $\gamma$ -rays.

The experiment confirms the law of distance very well; the measuring points are lying practically on a regression line. Coming into the distance range of about 3 cm ( $r^{-2} \sim 0,08\text{mm}^{-2}$ ), i.e. into the range where source in the specimen holder and detector window are close to each other, we recognize deviations from the purely geometrical consideration. Although both radioactive sources (Sr-90, Co-60) have approximately the same activity (see Table 8.1), the number of registered  $\gamma$  quanta is about 20 times smaller than in the case of the  $\beta$  rays. The reason is that the Geiger-Müller counter tube is less sensitive to  $\gamma$ -rays.

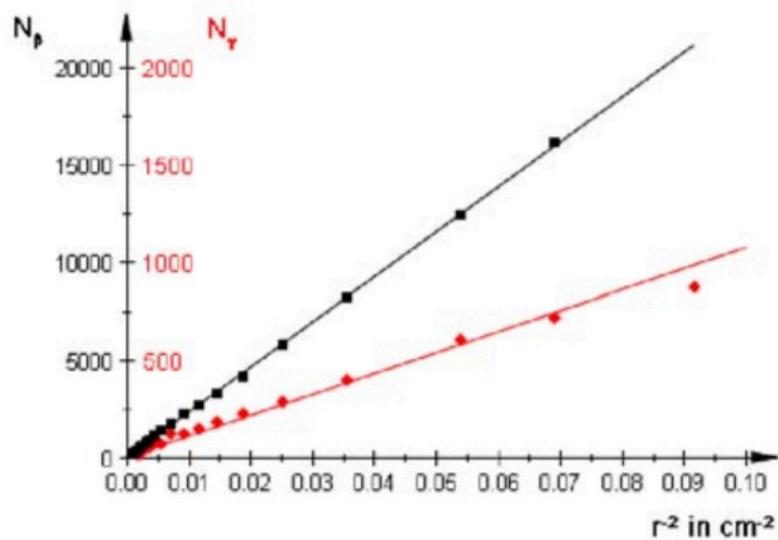


Figure 8.4: Number of events  $N$  as a function of the reciprocal of the distance square in the case of  $\beta$ -rays of Sr-90 (squares) and  $\gamma$ -radiation of Co-60 (diamonds). Range:  $3 \text{ cm} < r < 29 \text{ cm}$ .

Next, let us take a closer look at the law of distance in the case of  $\alpha$  radiation (range in air typically a few cm). Of the  $\alpha$  particles emitted by the Am-241 source, 85% have a kinetic energy of 5.48 MeV, which reduces to 4.5 MeV due to the embedding of the source in gold foil. Because of the window material of the Geiger-Müller counter tube, the measured range of the law of distance is additionally reduced [4, 5]. The daughter nucleus Neptunium-237 is in its excited state, which passes directly or via a cascade into the ground state. In this case, two  $\gamma$ -quanta of energies 26 keV and 33 keV or a  $\gamma$ -quant of the energy with almost 60 keV are emitted. The latter process is the more frequent one, whereby beside emission also conversion occurs with approximately equal probability (see the term scheme in the menu point *Theory*). For this reason we expect a long-range component caused by  $\gamma$ -radiation and a short-range component caused by  $\alpha$ -radiation. Figure 8.5a confirms the law of distance  $N(r) \propto r^{-2}$  for a range  $r > 4,3 \text{ cm}$  ( $r^{-2} \sim 0,054$ ), which is to be expected for  $\gamma$  radiation.

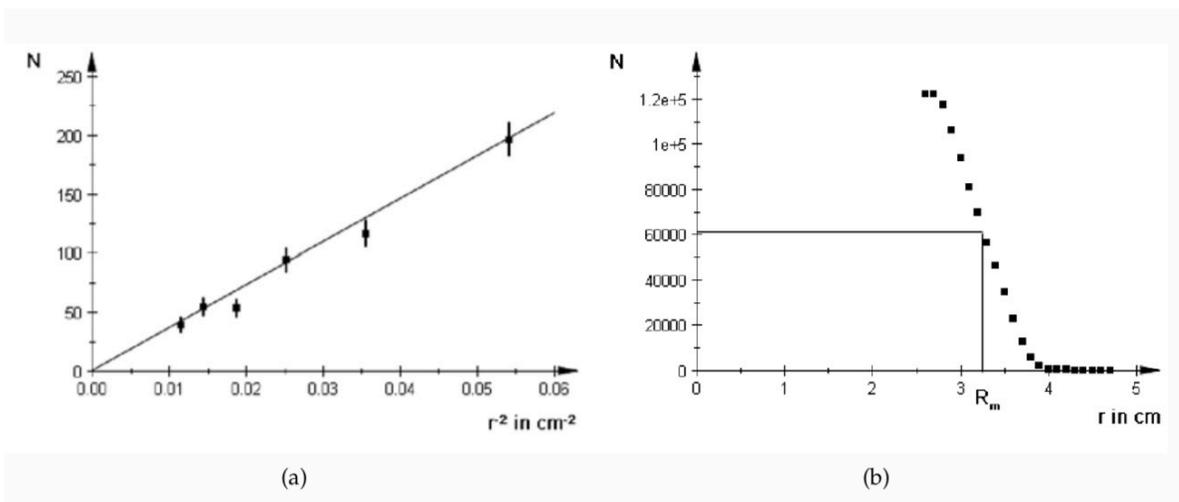


Figure 8.5: (a) Confirmation of the law of distance  $N(r) \propto r^{-2}$  for  $\gamma$  radiation of Am-241. Regression-line  $N(r) = 3640 \text{ cm}^2 \cdot r^{-2}$ . (b) Number of measured  $\alpha$ -particles after correction by the long-range component of  $\gamma$ -rays; average range of  $\alpha$  particles in air  $R_m \sim 32$  mm.

Figure 8.5b shows the result in the case of  $\alpha$  -radiation: number of events  $N$  after subtraction of the component by  $\gamma$ -radiation ( $N(r) = 3640 \text{ cm}^2 \cdot r^{-2}$ ). Since the entrance window of the Geiger-Müller counter tube consists of mica, the energy of the  $\alpha$  particles is reduced and one must correct the distance  $r$  by an equivalent size in air  $\Delta r = 1,4$  cm (see manufacturer [2]). In general, the mean range  $R_m$  is defined as the distance at which the number of events  $N$  falls to 0,  $5N_0$  (see Fig. 8.5b). In the experiment we determine the average range  $R_m$  of  $\alpha$  particles in air to about 32 mm. Theoretically,  $R_m$  is expected to be 30 mm at  $E \sim 4,5$  MeV, using the empirically known relation  $R/\text{mm} = 3,18 (E/\text{MeV})^{3/2}$ . Both values for  $R$  - experiment / theory - agree very well.

In the classroom, the absorption of radioactive radiation by various materials and thicknesses is usually shown only qualitatively. If you want to measure quantitatively – i.e. determine the absorption coefficient  $\mu$  – this is not that easy. Figure 8.6 shows the absorption of  $\beta$ -rays on the left and that of  $\gamma$ -rays on the right: the logarithm  $N(d)/N_0$  is plotted as a function of the sample thickness  $d$ .

In the logarithmic representation, we expect a straight line, where the slope represents a measure of the absorption coefficient  $\mu$ . If the

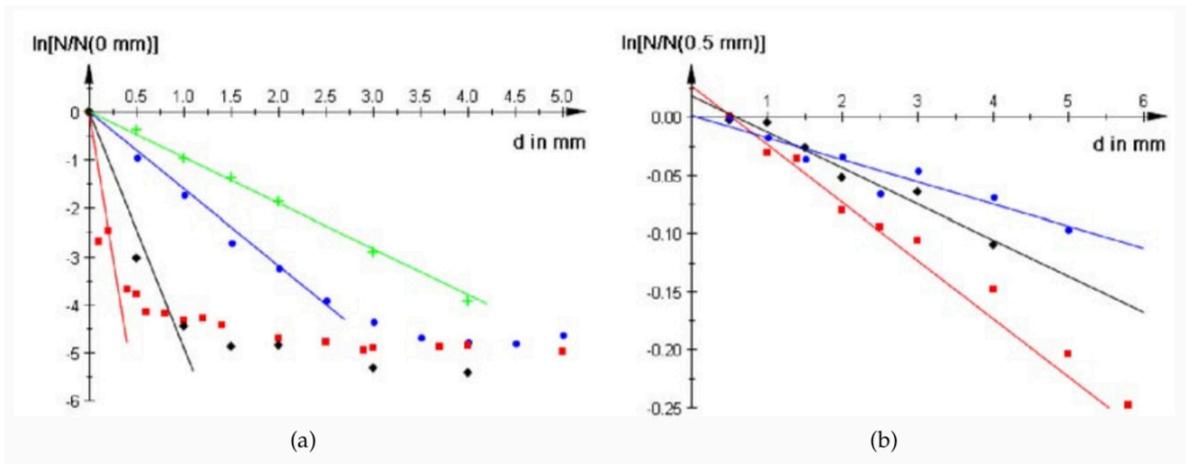


Figure 8.6: Experimental confirmation of the law of absorption  $N(d) = N_0 \exp(-\mu d)$  ( $d$  - thickness of the sample,  $\mu$  - linear absorption coefficient of the material): (a) 2,3 MeV  $\beta$  radiation of Sr-90 is absorbed by lead (squares), steel (diamonds), aluminium (circles) and PVC (crosses). (b) Co-60  $\gamma$ -radiation is absorbed by lead (squares), steel (diamonds), aluminium (circles). Measuring time is always 300 seconds.

lines change into a plateau, one recognizes that at this sample thickness practically all electrons have lost their kinetic energy. In that case only the zero rate is measured practically. Table 8.5 shows how well our measured results for  $\mu$  agree with literature values (in brackets).

In those days in the past, when there was no knowledge about the nature of radioactive radiation ( $\alpha$ ,  $\beta$ ,  $\gamma$ ), it was an obvious experiment, to control the deflection of this radiation/particles by magnetic fields; one can deduce a possible charge of this radiation/particles via the Lorentz force. Fig.8.7.a shows our results for  $\beta$  radiation in three cases: without magnetic field, magnetic field upward and downward.

The maximum (in Fig. 8.7a) of registered events without magnetic field is at about  $\alpha \sim 5$  degrees; because the geometry of the experimental setup was not optimally aligned; but a typical laboratory situation is reflected. With magnetic field, we recognize a clear deflection; i.e. the maximum of registered events is shifted depending on the direction of the magnetic field. We can conclude that  $\beta$ -rays must be negatively charged particles: under the effect of the Lorentz force  $\vec{F} = q(\vec{v} \times \vec{B})$ , the ray is deflected to the right ( $\alpha > 0$ ) or to the left ( $\alpha < 0$ ), if we change the direction of the magnetic field. (See in Fig. 8.1a. for the

Table 8.5: Comparison of measured results for  $\mu$  with literature values

(Data in 1 / mm, literature values in parentheses). Data compiled from various information sheets of industry as well as from books of nuclear physics; see [6].

Material	$\beta$ -radiation	$\gamma$ -radiation
PVC	0,95/mm (0,76)	– (0,008)
Al	1,6/mm (1,42)	0,02/mm (0,015)
Stainless Steel	5/mm (4,08)	0,03/mm (0,034)
Lead	12/mm (5,93)	0,05/mm (0,066)

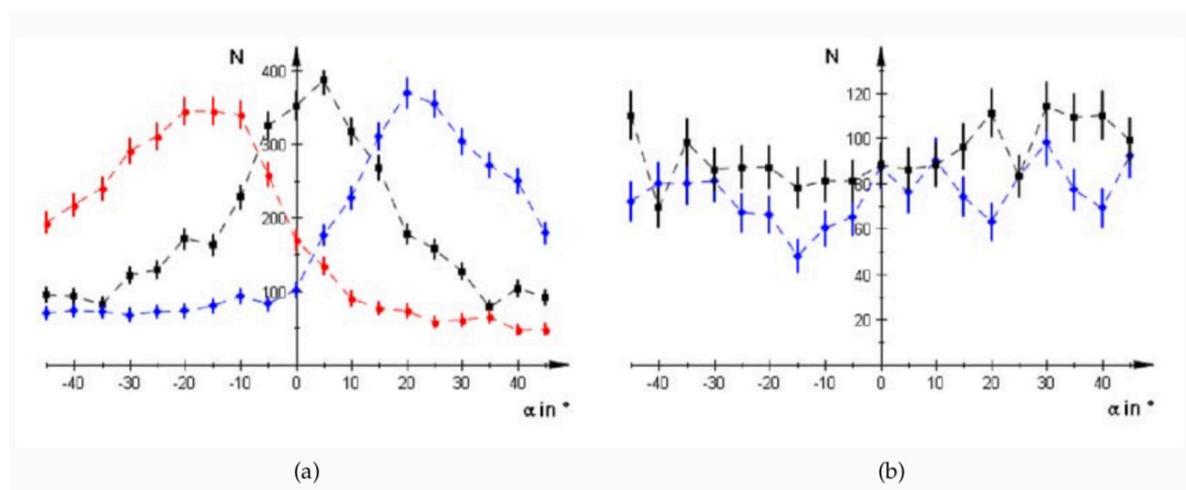


Figure 8.7: Deflection of radioactive radiation in the magnetic field: (a)  $\beta$  radiation from Sr-90, without magnetic field (squares), with magnetic field upward (circles), magnetic field downward (diamonds). (b)  $\gamma$ -radiation from Co-60, magnetic field downward, with collimator (diamonds), without collimator (squares). Dashed lines should help to recognize the associated measured values.

direction of the magnetic field) Note: the amount of the velocity  $v$  of the negative charges is always the same. For these measurements, using the collimator is recommended to narrow the  $\beta$  beam.

A similar experiment with  $\gamma$ -radiation shows that  $\gamma$ -quanta have obviously no charge. Figure 8.7b shows an almost constant number of registered  $\gamma$ -quanta independent of the magnetic field  $B$  or the use of the collimator.

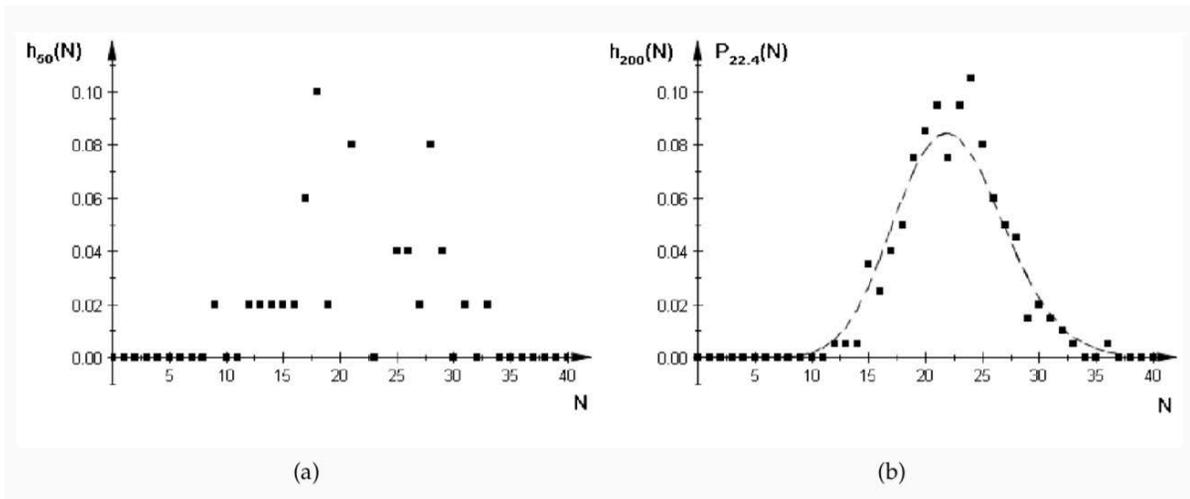


Figure 8.8: Statistics of radioactivity: (a) relative abundance  $h_{50}(N)$  versus number  $N$  of background radiation,  $n = 50$  measurements, mean 22 events. (b) Relative abundance  $h_{200}(N)$ ,  $n = 200$  measurements, mean 22.4 events. The dashed line corresponds to a Poisson distribution  $P(N)$  with an average of 22.4 events.

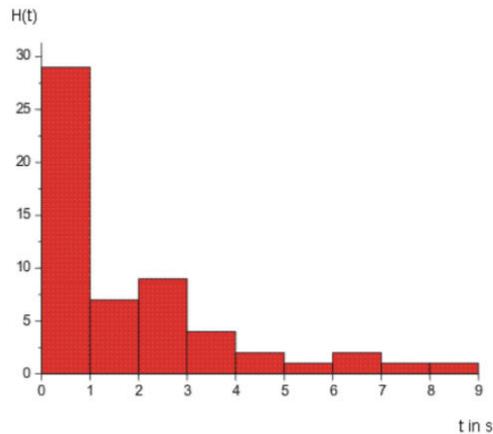


Figure 8.9: Abundance distribution for time intervals between two decays ( $t > 9$  s omitted).

Finally we present two measurement results on the statistical nature of the radioactive process. If one measures several times the number  $N$  of events per time interval, e.g. of the background radiation, so certain abundance  $h$  for these different numbers  $N$  occur. Figure 8.8

shows the abundance distribution for 50 measurements on the left and for 200 measurements on the right.

One can see two things: one needs enough measurements to be able to achieve a reliable average  $\langle N \rangle$ . For smaller numbers of  $N$ , the distribution  $h(N)$  is best described by a Poisson distribution (see menu point *Theory*).

Figure 8.9 shows the abundance distribution for the time intervals between two decays for a total of 81 measurements.

It can be seen from the histogram that most often (28 times) time intervals (between two decays) occur shorter than 1 s. However, 53 times longer than 1 s also occur. Consequently, one can not accurately predict the exact time between two decays.

### 8.3 Evaluation and experience

In the previous section, we have analyzed some measurement series examples:

Measuring the background radiation,

- Law of distance for point like  $\alpha$ ,  $\beta$ ,  $\gamma$ -ray sources,
- Absorption law of materials for  $\beta$  and  $\gamma$ -rays,
- Deflection of radioactive radiation in a magnetic field,
- Statistical nature of radioactivity.

The quantitative evaluation is fully satisfactory and corresponds to literature values. If one wants to quantitatively perform one of these measurement series with sufficient data points, one needs 10-30 minutes easily; regardless of the data evaluation and presentation.

This experiment as an RCL variant offer in our opinion the following added value:

- As a »remote« experimenter, the experiment can be operated completely safely against radioactive irradiation, even with long series of measurements.
- Both individual measurements and measurement series are easy to carry out, since the experimental set up is permanently mounted; in addition, the RCL experiment offers a number of different types of measurements.

- Especially with long series of measurements, the fact that the RCL can always be operated from anywhere; even if at low counting rates one must measure several times under the same conditions.
- A comparison and a simple characterization of radioactive radiation ( $\alpha$ ,  $\beta$ ,  $\gamma$ ) is possible because all sources are available.
- The flexible experimental set up of the RCL makes it possible to adapt measurements to the level and age of the experimenter: Pupils of secondary I level (age of 10-16 years) attend a radiation protection course; Students at universities are required to explain the deviation of experimental data from theoretical expectations (beam geometry and finite size of source and detector, sensitivity of the detector to the 3 types of radiation, absorption of radiation in the detector window, and necessary correction).
- Learners can set up their own measurement program according to questions to the experiment.
- Groups of experimenters can share, compare, and gather data using advanced communication methods.

The RCL has been online since 2006 with only occasional problems. In recent years we had around 15 visitors a day. In the period from June 2008 to June 2009 we examined the experimental behaviour more closely: of 924 users, 19% only served the experiment briefly with less than 5 actions; 16% carried out 5-20 actions; 65% more than 20 actions up to 250 actions. The actions are distributed as follows: 10% of the users change the distance of the detector, 20% change the angle of the detector, 5% change the absorber thickness, 5% change the absorber material, and 60% of the experimenters change almost all technical parameters. I.e. the RCL sensibly mirrors the real experiment in class; it is in addition experiment specific.

## 8.4 Didactic material

We see the following possible scenarios of teaching methods (see [7]):

- Traditional physics lessons: The teacher prepares the theory in the classroom as part of a classical course on radioactivity

and shows demonstration experiments or introduces experiments with the RCL. In experimental homework with the RCL, the students confirm the expected physics laws, repeat or supplement the measurements from the demonstration experiments, or continue the measurements with the RCL.

- Project-oriented physics lessons: Especially in basic courses it is favourable to learn the physics of radioactivity based on everyday reference and motivation. Student groups organized according to topics perform measurements with the RCL as independently as possible.
- Interdisciplinary teaching of physics and mathematics: If the topic of radioactivity is treated towards the end of the upper secondary level, the theory of Poisson distribution from mathematics lessons and measurements of statistics of radioactive decay from physics lessons can be harmonized (Definition and characteristics of Poisson distribution, relation between empirical distribution and Poisson distribution, Gaussian distribution).
- Self-study: In addition to traditional teaching, learners who are eager for knowledge and learning can acquire the basics of radioactivity by the learning environment of the RCL in direct relation to the performance and evaluation of experiments. The RCL offers to interested laymen the opportunity to perform experiments to all the topics of radioactivity. Emotionalised or politicized information of mass media can be put on a more rational basis by basic physical knowledge and can be questioned.

In the frame of self-study offers the following systematic series of measurements are offered:

- Measurement of the background radiation (Fig. 8.3),
- Distance law for  $\beta$  and  $\gamma$  rays (Fig. 8.4),
- Range of  $\alpha$  particles (Fig. 8.5),
- Absorption law of materials by  $\beta$ -rays (Fig. 8.6a),
- Absorption law of materials by  $\gamma$  rays (Fig. 8.6b),
- Deflection of  $\beta$  and  $\gamma$  -rays in the magnetic field (Fig. 8.7),

- Poisson and Gaussian distribution (Fig. 8.8),
- Time interval between two decays (Fig. 8.9).

So that the learner is not left alone here with his own measured data, we have included exemplary results as a reference in section 8.2.4 - Measurement results.

In addition to these quantitative series of measurements, there are experimental lectures possible on radiation protection; the RCL can be used to present the 5 A rules (distance, time spent, activity, shielding, picking up).

## 8.5 Literature

- [1] LD Didactic. [559 83] Set of radioactive sources.
- [2] LD Didactic. [559 01] Window counter for  $\alpha$ -,  $\beta$ -,  $\gamma$ - and x-ray radiation.
- [3] LD Didactic. [575 41] Counter.
- [4] Kuthe, W. und Timmermann, K. Radioaktivität im Unterricht. Braunschweig: Amersham, Buchler, 1985.
- [5] Kuhn, W., Hrsg. Handbuch der experimentellen Physik: Sekundarstufe II. Band 9 - Kerne und Teilchen. Köln: Aulis, 2000.
- [6] Gröber, S., Vetter, M., Eckert, B. und Jodl, H.-J. »Experimenting from a distance in case of radioactivity«. In: submitted to Eur. J. Phys (2013).
- [7] Gröber, S., Vetter, M., Eckert, B. und Jodl, H.-J. »Experimente zur Radioaktivität«. In: PdN-PhiS 58.1 (2009), S. 33.

# 9 Diffraction and interference

## 9.1 Introduction

The phenomena of diffraction and interference belong to wave theory and are taught as standard in the field of wave optics in the gymnasiale Oberstufe (age 17-19 years) and university. Continuations and applications in pure physics are e.g. X-ray diffraction, quantum physics and metrology (namely, the resolution and the principle of interferometers, spectrometers, microscopes, etc.). In order to be able to observe diffraction and interference in nature and in everyday life, one needs sufficiently coherent light as well as diffraction objects of the order of magnitude of the wavelength of light used. We know colour effects on soap bubbles, butterfly wings, on the rainbow, on thin oil layers, light scattering on DVDs, holograms or on coated eye glasses lenses.

The experimental set-up for the demonstration and investigation of diffraction and interference in the case of light is absolutely standard, extremely simple and mostly self-built: light source, scattering object, observation screen: all kinds of laser pointers are used as light sources for the sake of simplicity; The objects of diffraction are either mechanically scratched, periodic structures or photo lithographically produced objects - kind of slides. The observation on the screen is realized qualitatively by eye or quantitatively by a horizontally movable light detector.

The media offers a wealth of animations and simulations. This is one reason according to our opinion, why the experiment is rarely performed real. Ever since physics simulations have been programmed (since about 1980), the subject of diffraction and interference has been a "classical" subject of programming:

- In a qualitative way, to introduce the phenomenon;
- To visualize the rather demanding mathematics of intensity distribution;
- To generate the diffraction pattern stepwise from the superposition of elementary waves;

- To simulate diffraction and interference phenomena of all wave types (water, sound, electromagnetic waves);
- In preparation for quantum mechanics (matter waves).

In addition, there are other reasons why the experiment is not actually carried out in teaching practice:

- Missing experimental material (laser, photo objects).
- Room must be darkened to observe the diffraction pattern on the wall, rarely to measure it.
- With a few individual measurements, the formulas derived for the single slit, double slit and grating are checked; unconvincing.
- Students have little opportunity for experimenting, teacher-centred demonstration predominates.
- The demonstration of diffraction and interference at the single slit, double slit and grating have little to do for the student with the phenomena in nature and everyday life.
- The experimental set-up (laser of one wavelength, diffraction objects with little variation in number of slits  $N$ , slit width  $b$ , distance between two slits  $d$ ) does not allow to vary as many parameters as possible for the intensity distribution and to test the influence by those parameters on the diffraction pattern.
- Mechanically and photo lithographically produced objects allow only a few main maxima (position, relative intensity) to be investigated; not to mention secondary maxima and main minima.

If one has theoretically derived the general case of diffraction and interference by objects, this final formula (product of slit function and grating function) is excellently suited to discuss this function for the intensity distribution; e.g. the dependence on  $N$  - number of slits, on  $b$  - slit width, on  $d$  - slit distance, on the scattering angle  $\alpha$ , on the wavelength  $\lambda$ , on the incident intensity  $I_0$ . This part is the absolute standard knowledge of relevant books on wave optics. However, in order to carry out the appropriate experiments, to verify the theoretical

predictions, the current experiment has crucial shortcomings; despite some efforts, it remains qualitative, semi-quantitative.

The advantage of our RCL *diffraction and interference II* is in addition to the fact of remote control, especially in the enormous improvement and development of the previous experimental set up:

- Instead of photo lithographically produced objects we offer objects produced by electron beam lithography (comparison of both see later);
- Instead of less than 10 objects, which exist in class, we provide about 150 well-chosen objects;
- Instead of a laser we use 5-6 laser diodes of different wavelengths;
- Fast measurement of the intensity distribution of the diffraction pattern by a light sensor.

The diffraction patterns obtained in this way are so rich in contrast that all properties of the intensity distribution can be quantitatively verified. Teachers of our training courses on the use of RCLs have rated this experiment as an RCL as very good.

## 9.2 Experiment and RCL variant

### 9.2.1 Experimental setup and function

Over the years we have tried three RCL variants of this experiment:

With the first variant, in 2005 [1] we reproduced the simple qualitative demonstration experiment: a commercially available laser pointer ( $\lambda = 620$  nm), a screen at a distance of about half a meter, and 6 diffraction objects in the form of self-made slides on a horizontally rotateable plate. The photographically generated objects were shaped as a single slit, double slits and gratings. With a webcam one could view the diffraction pattern and take a screenshot of it for further evaluation. Apart from the remote control aspect, this first variant offered no added value as an RCL compared to the easy-to-build real experiment; the measurement result, i.e. the intensity distribution, was not very convincing. We used Fischer Technik for all mechanical parts as well as an interface by Fischer Technik; however, the disadvantages

outweighed (insufficient precision of the electromechanical components, too little data transfer).

In a second variant, in 2007 [2] we extended the experiment as RCL by the following dimensions: about 50 photo lithographically produced objects (in form of a slide about 1 cm<sup>2</sup> large, exposed on a high-contrast film as used in blank exposure of electronic devices) on a vertically mounted large wheel, which was rotateably mounted about an axis; The diffraction pattern could be viewed directly by a web cam on a screen, which was positioned in a light-tight housing. With the following advantages: because of the large number of diffraction objects, systematic measurements were carried out on the single slit, double slit and grating (slit width  $b = 30$  to  $150 \mu\text{m}$ , slit distance  $d = 100$  to  $200 \mu\text{m}$ ); the diffraction image, as a photo of a webcam, is less noisy, but still weak (one can see, for example, only about 5 secondary maxima at the triple slit). The experiment as an RCL is very robust and has been online since 2007.

With the third variant, we made the breakthrough in 2009 [3] with three technical improvements, also in comparison to the traditional demonstration experiment: instead of photo lithographic objects we use specially prepared electron beam lithographic objects; with 150 diffraction objects we can systematically vary the parameters number of slits  $N$ , slit width  $b$ , slit distance  $d$ ; we use 6 laser diodes to allow the variation of the wavelength of the light. In addition, we offer 3 recording techniques for the diffraction pattern. With this RCL version, we have achieved a real added value in terms of the available scope of experimentation. In detail, first these 3 technical innovations and then the experimental set up.

Photographically produced objects can be produced relatively easily [4]. The electron beam lithographically produced objects used here were generated according to our specifications at an institute for nanotechnology [5]. The former ones are typically 1cm x 1cm in size, exposed to film material, smallest distance typically  $30 \mu\text{m}$ . The second ones are typically 1mm x 1mm in size, mounted on a glass plate as carrier material; smallest distances typically  $1 \mu\text{m}$ . Due to the approximately 100 times better resolution in manufacturing, smaller-area diffraction objects can be produced, which are nevertheless fully illuminated without beam widening and imaging lenses. A chromium layer deposited on the glass substrate gives a very high contrast of the diffraction object structures and consequently almost ideal diffraction

patterns. The approximately 150 diffraction objects are housed on a 5 cm  $\times$  5 cm large glass plate, which can be precisely and reproducibly moved and positioned using high-resolution x and y control gears.

The diffraction objects (see Tab. 9.1) are divided into three groups:

- 134 standard objects,
- 2 x 6 objects for resolution,
- 7 special objects: 5 objects unknown to the experimenter, 1 bridge – looks like a wire – for the Babinet's theorem, 1 double slit with two different slit widths.

If one wants to convince oneself about the enormous quality improvement, use the RCL *diffraction and interference I* (with photolithographic objects) and *diffraction and interference II* (with objects produced by electron beam lithography). Figure 9.2 shows the diffraction pattern taken with the webcam from the screen and the intensity measurement taken with the light sensor as a comparison.

A fine detail: the theory (see RCL, menu point *Theory*, Section 2.3) predicts that between two absolute maxima there are  $N-2$  relative maxima (here 2) and  $N-1$  minima (in this case 3).

We have selected the diffraction objects such (Table 9.1) so that measurement series can be recorded on the following topics:

- Relationship between slit width  $b$ , slit distance  $d$ , slit number  $N$ , order and distance of the maxima and minima from the central maximum.
- Transition between geometrical optics and wave optics.
- Relationship between the number of slits  $N$  and the intensity distribution of the diffraction patterns.
- Dependence of the resolution of a grating on the illuminated (!) number of slits.
- Wavelength dependence of diffraction.
- Adaptation of measured intensity distribution to the theoretical curve by means of simulation programs (relative intensities of the main maxima, relative intensities of main maxima left to right of the central maximum).

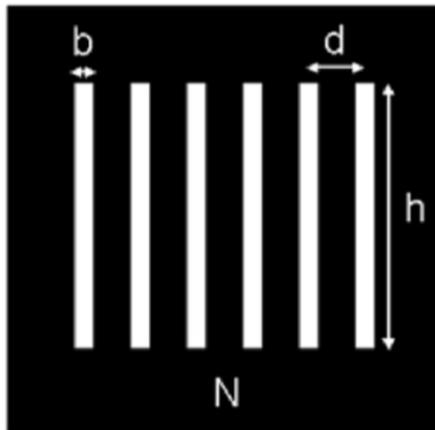


Figure 9.1: Geometry of the diffraction objects (number of slits  $N$ , slit width  $b$ , slit distance  $d$  and slit height  $h = 2 \text{ mm}$ )

Table 9.1: Overview of the diffraction objects of the experiment (definition of the geometrical quantities see Fig. 9.1).

Number of slits $N$	Slit width $b$ in $\mu\text{m}$	Slit distance $d$ in $\mu\text{m}$
1	1, 5, 10, 15, 20, 25, 30, 60, 90, 800	-
1	90	-
2	1 10, 15 2, 25 30	60 20, 30, 40, 60, 90 30, 40, 60, 90 40, 60, 90
2	15/20	60
3,4,5,6	10, 15 10, 15 20, 25 30	20, 30, 40, 60, 90 20, 30, 40, 60, 90 30, 40, 60, 90 40, 60, 90
10	5 10 20	10, 20, 30, 40, 50, 60, 80 20, 30, 40, 50, 60, 80 30, 40, 50, 60, 80
4,5,6,8,10,12	5	60
5 "unknown" objects		

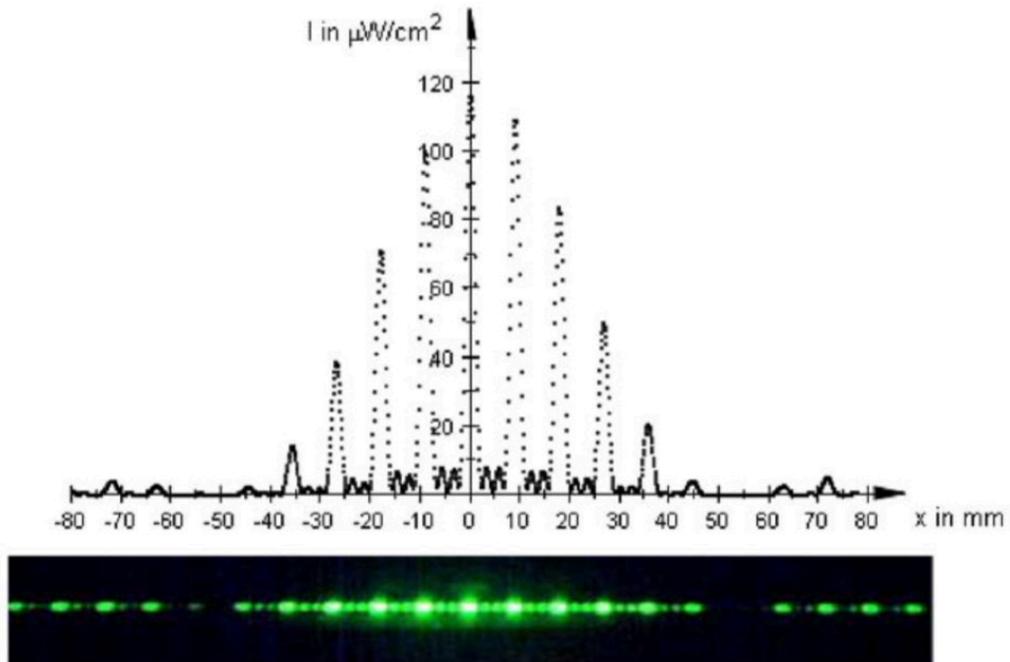


Figure 9.2: Diffraction pattern and intensity measurement ( $\lambda = 532 \text{ nm}$ ,  $N = 4$ ,  $b = 10 \text{ }\mu\text{m}$ ,  $d = 60 \text{ }\mu\text{m}$ ).

Two other technical improvements: five laser diodes (532 nm, 635 nm, 670 nm, 780 nm, 850 nm); simultaneous operation of the laser diodes 635 nm and 670 nm, ( $\Delta\lambda = 35 \text{ nm}$ ) for the determination of the resolution capability.

Diffraction patterns can be qualitatively observed by a web cam on the screen. If one wants to measure structures roughly quantitatively, the experimenter can switch on an illuminated centimeter scale. If one wants to measure the intensity distribution of the diffraction pattern quantitatively relatively quickly ( $<1 \text{ min}$ ), one can use a light sensor that is fixed behind a hole on the screen, which scans the diffraction pattern horizontally.

In order to ensure the high quality in the experimental set-up (Fig. 9.3), the beam path had to be prepared carefully. Only the selected diffraction object on the slide (4) or the two diffraction objects for the resolution capability is fully illuminated by the selected laser beam (2a,2b) by the square diaphragms (3a, 3b); in addition neighbouring objects are shadowed. In order to avoid disturbing refractions of light

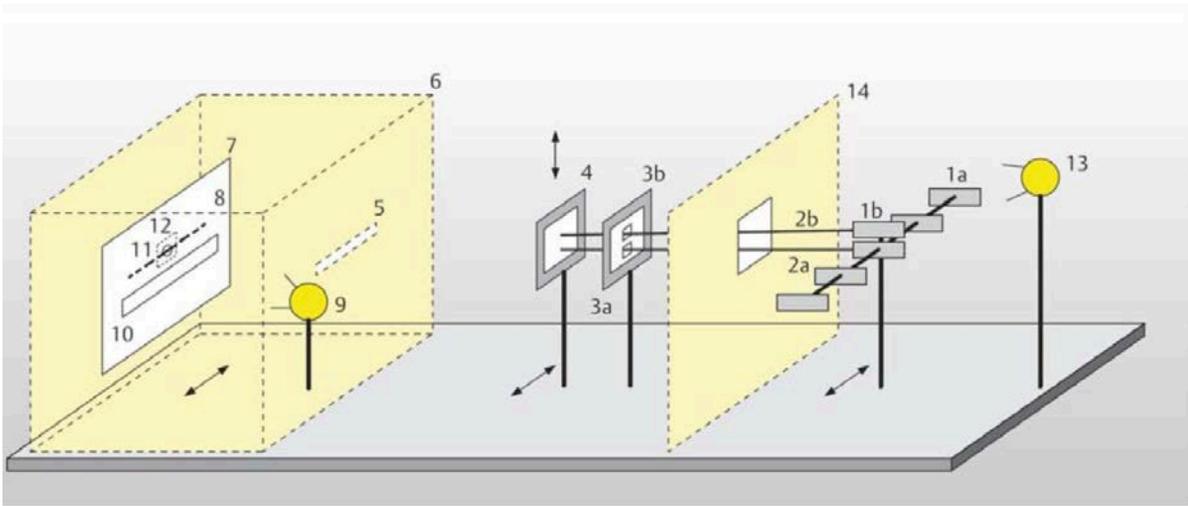


Figure 9.3: Schematic representation of the experimental set-up: Five lasers (1a), laser for resolution (1b), laser beam of 1a (2a), laser beam of 1b (2b), square diaphragms (3a, 3b), diffraction slide (4), Slit (5) in the dimming box (6), screen (7), diffraction pattern (8), first webcam (9), illuminated centimeter scale (10), hole (11) in the screen, light sensor (12), second webcam (13), Not shown: Motors, interface and cable connections - Double arrows: Movement directions of screen, diffraction slide and lasers - Distance of diffraction object to screen: 1.005 m - Dimensions of the whole equipment: 2.0 m x 0.6 m x 0.6 m.

and reflections, the laser light first hits the uncoated side of the glass carrier with objects. The diffracted light passes a slit (5) in a dimming box (6). On a screen (7), the diffraction pattern (8) is visible. For the experimental part of the resolution, the experimental geometry is designed in such a way that the two diffraction patterns on the screen are exactly superimposed and can be compared on the basis of the position of maxima.

Diffraction patterns can be examined qualitatively with the first webcam (9) and geometrically with an illuminated centimeter scale (10). By a light sensor (11), which is mounted behind a hole (12) in the screen, the intensity distribution of the diffraction pattern can be measured as a third possibility of investigation by moving the screen horizontally. On a second webcam (13) one can observe the experiment, more precisely the mechanism for selecting a laser, and the light beam irradiating diaphragms or diffraction objects. The screen (14) provides a neutral background in the webcam image.

## 9.2.2 Navigation menu

The menu point *Experimental Set Up* contains all the details of the experimental setup, of the diffraction objects (all parameters as well as the position of the objects on the glass plate) and, for the quantitative analysis of the measured values, all experimental quantities with accuracy information.

The menu point *Theory* has two sections:

- Interference of waves in the pointer diagram model and matching simulations
- Diffraction of light at one-dimensional periodic diffraction objects:
  - maxima and minima of single slit, double slit and grating,
  - intensity distribution of the diffraction pattern,
  - resolution of gratings,
  - asymmetrical double slit,
  - Babinet's principle.

In this section the focus is more on the discussion of the properties of these functions (slit function, grating function, overall function) than on the derivation step by step (in Section 9.2.3 there is a link "Derivation of the intensity distribution" by Fourier transformation), Our goal is that the user can theoretically interpret his measured diffraction pattern- such as Fig. 9.2.

In the menu point *Tasks* (Tab. 9.2 to 9.4), the user will find a large number of suggestions for individual examinations or for systematic measurement series.

With the menu point *Laboratory* the experimenter chooses the access to the experiment (Fig. 9.8): in the middle of the screen the user can see two web cam images - whereby a first webcam (13 - see Fig. 9.3) is looking in the beam direction from the laser to the diffraction objects. If he selects a laser diode, he can see the lateral displacement of the laser holder with 6 laser diodes and their labeling  $\lambda / \text{nm}$ . The second web cam (9 - see Fig. 9.3) shows the diffraction pattern on the screen. Underneath the webcam images, various illuminating objects can be set or screenshots can be taken via various control elements. On the right the usual control panel for all parameters such as laser wavelength, the characteristics of the diffraction objects, for controlling the intensity measurement.

Table 9.2: Tasks. Single slit ( $N = 1$ ).

Parameters:

Wavelength  $\lambda$ , number of slits  $N$ , slit width  $b$ , slit distance  $d$ , distance  $e$  between diffraction object and screen, diffraction angle  $\alpha$ , distance  $a_n$  of the (main) maximum  $n$ -th and distance  $a_{n'}$  of the  $n$ -order minimum from the optical axis, position  $x$  of the light sensor, experimental intensity distribution  $I(x)$ , light intensity of the central maximum  $I(0) = I_0$ , theoretical intensity distribution  $I_{theo}(x)$ .

- 1) Qualitative observation and empirical relations
  - a) Investigate qualitatively, of which quantities depends on the values  $a_n$  and  $a_{n'}$  or in which way.
  - b) Complete the formula  $a_n = \dots\dots\dots$  for the maxima on the basis of experimental investigations.
  - c) Investigate if there is a simple relationship between the width of the central maximum and parameter  $b$ .
  
- 2) Comparison of experiment and theory
  - a) Compare the distance  $a_n$  of a maximum for  $\lambda = 532 \text{ nm}$  and  $b = 60 \text{ }\mu\text{m}$  with the theoretical prediction.
  - b) Is there a laser, where the maxima and minima of the diffraction pattern for  $b = 30 \text{ }\mu\text{m}$  are in the same positions as at  $\lambda = 532 \text{ nm}$  and  $b = 25 \text{ }\mu\text{m}$ ?
  - c) Determine what percentage of the light power falls within the central maximum between the minima of orders  $\pm 1$ .
  
- 3) Limiting cases
  - a) Consider how the diffraction patterns of diffraction objects look like with  $b \gg \lambda$  and  $b \sim \lambda$ . Experimentally check your thoughts. Explain the differences to the mathematical ideal case.
  
- 4) Experimental and theoretical intensity distribution
  - a) Observe diffraction patterns for different  $b$ : Draw qualitative graphs  $I(x)$  for two different values of  $b$ .
  - b) Measure  $I(x)$  for  $\lambda = 532 \text{ nm}$  and  $b = 25 \text{ }\mu\text{m}$ : Compare experimental data with theory.
  - c) Examine experimentally and theoretically whether there is a simple mathematical relation between  $I_0$  and  $b$ .
  
- 5) Babinet's principle
  - a) Compare  $I(x)$  of the single slit for  $b = 90 \text{ }\mu\text{m}$  with  $I(x)$  of the "wire" (special

Table 9.3: Tasks. Double slit ( $N = 2$ ).

Parameters:

Wavelength  $\lambda$ , number of slits  $N$ , slit width  $b$ , slit distance  $d$ , distance  $e$  between diffractive object and screen, diffraction angle  $\alpha$  distance  $a_n$  of the (main) maximum  $n$ -th and distance  $a_n'$  of the  $n$ -order minimum of the optical axis, position  $x$  of the light sensor, experimental intensity distribution  $I(x)$ , light intensity of the central maximum  $I(0) = I_0$ , theoretical intensity distribution  $I_{theo}(x)$ .

- 1) Qualitative observation and empirical relations
  - a) Investigate qualitatively, of which quantities depends on the values  $a_n$  and in which way.
  - b) Complete the formula  $a_n = \dots\dots\dots$  on the basis of experimental investigations for the maxima.
  - c) Determine  $d$  for a double slit in a suited manner.
  
- 2) Modulation of the diffraction pattern
  - a) Choose  $\lambda = 635$  nm and constant  $b$ : What is the relationship between the position  $x$  of the minima at the single slit and the position  $x$  of the missing maxima at the double slit?
  - b) Determine for  $\lambda = 635$  nm  $b$  and  $d$  from the diffraction pattern of a double slit.
  
- 3) Experimental and theoretical intensity distribution
  - a) Measure  $I(x)$  for  $\lambda = 532$  nm,  $b = 15$   $\mu\text{m}$  and  $d = 90$   $\mu\text{m}$ : Compare  $I(x)$  with  $I_{theo}(x)$  of the double slit and with  $I_{theo}(x)$  of the single slit for  $b = 15$   $\mu\text{m}$ .
  
- 4) Limiting cases
  - a) Investigate how the intensity distribution of an ideal double slit ( $b \sim 0$   $\mu\text{m}$ ) differs from a real double slit.
  
- 5) Unsymmetrical double slit
  - a) Choose  $b = 15/30$   $\mu\text{m}$  and  $d = 60$   $\mu\text{m}$  for the asymmetric double slit: Does the position of the maxima and minima agree with theory? Do theoretically and experimentally obtained  $I(x)$  agree?

Table 9.4: Tasks. Grating ( $N > 1$ ).

Parameters:

Wavelength  $\lambda$ , number of slits  $N$ , slit width  $b$ , slit distance  $d$ , distance  $e$  between diffractive object and screen, diffraction angle  $\alpha$ , distance  $a_n$  of the (main) maximum  $n$ -th and distance  $a_{n'}$  of the  $n$ -order minimum of the optical axis, position  $x$  of the light sensor, experimental intensity distribution  $I(x)$ , light intensity of the central maximum  $I(0) = I_0$ , theoretical intensity distribution  $I_{theo}(x)$ .

- 1) Relationship between sizes and determination of sizes
  - a) Select  $N = 10$ ,  $b = 5 \mu\text{m}$  and  $d = 50 \mu\text{m}$ : Determine  $\lambda$  of the selected laser from several measurements within a series of measurements.
  - b) Determine experimentally for a selected grating the value of  $d$ . Experimentally determine the distance  $e$  to the screen.
- 2) Dependence of the diffraction pattern of  $N$  for  $\lambda = 532 \text{ nm}$ ,  $b = 10 \mu\text{m}$  and  $d = 20 \mu\text{m}$ 
  - a) Which quantities remain constant when changing  $N$ , which ones change and in which way?
  - b) Investigate and formulate the quantitative relationship between  $N$  and the number of secondary maxima and the number of minor minima.
  - c) Investigate and formulate the quantitative relationship between the intensity  $I(0)$  of the central maximum and  $N$ . Does this relationship apply to all major maxima?
  - d) Compare  $I(x)$  for  $N = 4$  and  $N = 10$  with each other: Which other physical variable (except  $\lambda$ ,  $b$  and  $d$ ) remains unchanged and why?
- 3) Identify unknown diffraction objects
  - a) Arrange the unknown diffraction objects in a meaningful order. Determine of two of these diffraction objects  $N$ ,  $b$  and  $d$ .
- 4) Resolution of a grating
  - a) Investigate qualitatively with the laser pair  $635 \text{ nm}$  &  $670 \text{ nm}$  and the diffraction objects to the resolution of which sizes depends the separability of two wavelengths.
  - b) Confirm the formula for the resolving power  $A$  by a series of measurements with different gratings.

In the menu point *Evaluation*, three measurement types are compared to the three measurement methods on selected diffraction objects:

- Qualitative observation

Dependence of the diffraction pattern of a single slit on the slit width ( $b = 10 \mu\text{m}$ ,  $30 \mu\text{m}$ ,  $60 \mu\text{m}$ ,  $90 \mu\text{m}$ ).

- Measure with centimeter scale

Determine slit width  $b$  and slit distance  $d$  of a double slit with % accuracy.

- Measuring with light sensor

Comparison of experimental and theoretical intensity distribution for diffraction object with  $\lambda = 532 \text{ nm}$ ,  $N = 5$ ,  $b = 10 \mu\text{m}$ ,  $d = 20 \mu\text{m}$ . Deviations are generally discussed.

In the menu point *Discussion*, we ask questions about experimental set up, theory, laboratory and evaluation (Table 9.5).

The menu point *Material* contains technical information about the laser diodes, light sensor and webcams. In addition, didactic material (see later):

- Worksheet,
- Teaching unit,
- A publication on this RCL [3],
- Simulations and in-depth literature.

Table 9.5: Discussion.

- 1) Experimental set up
  - a) Why is the experimental setup without lenses?
- 2) Theory
  - a) In theory, table 2, how does one obtain the formula for an approximate determination of the maxima of the slit function  $s$ ?
  - b) The slits of a double slit are irradiated separately with light from two lasers of the same wavelength: Can one observe a diffraction pattern?
  - c) What presuppositions, assumptions and approximations or specializations are made in the experiment with light, diffraction object and with the experimental geometry?
  - d) Explain the following statement: For a number of slits  $N \rightarrow \infty$  the grating function  $g$  scans the slit function  $s$ .
  - e) Which largest order of main maxima can be observed with a grating?
  - f) Why does it make sense not to consider  $I(\alpha)$  but  $I(\alpha) / I_0$ ?
  - g) Show that for  $x = \pi \sin \alpha / \lambda \ll 1$  the slit function  $s$  is  $s \approx 1 - x^2 / 6$
- 3) Laboratory
  - a) Are maxima and minima in the diffraction pattern on the screen principally equidistant?
  - b) How does the intensity distribution of a grating change qualitatively if either the slit width  $b$ , the slit distance  $d$ , the number of slits  $N$  or the wavelength  $\lambda$  are increased / decreased?
  - c) Why does the slit height  $h$  play no role in the experiment?
  - d) Why one can experiment with infrared light here in this experiment?
  - e) Why is the modulation with the slit function  $s$  often not observed when studying the diffraction at a grating?
  - f) The position of which maximum is the same for any experimental parameter and why?
  - g) Justify which diffraction pattern is observed on the screen for  $\lambda \gg b$  and  $\lambda \gg d$ .
- 4) Evaluation
  - a) Which maximum error occurs in the experiment by the approximations  $\sin \alpha \approx \tan \alpha \approx \alpha$ ?
  - b) How does the light-irradiated area of the light sensor play a role?
  - c) How exactly one can determine the wavelength  $\lambda$  in this experiment?
  - d) Using a computer algebra system, determine what percentage of the light energy falls into the central maximum in case of a single slit?

### 9.2.3 Theoretical principles

These are to prepare and accompany the detailed quantitative measurement results in the next section. Figure 9.4 shows the experimental quantities, the diffraction object and the intensity distribution.

The intensity distribution  $I(\alpha)$  of a diffraction pattern is usually represented as the product of the slit function  $s(\alpha)$  and the grating function  $g(\alpha)$ :

$$\begin{aligned} \frac{I_{N,b,d,\lambda}(\alpha)}{I_0} &= s(\alpha) \cdot g(\alpha) = \left[ \frac{\sin\left(\frac{\pi b}{\lambda} \sin \alpha\right)}{\frac{\pi b}{\lambda} \sin \alpha} \right]^2 \cdot \left[ \frac{\sin\left(N \frac{\pi d}{\lambda} \sin \alpha\right)}{\sin\left(\frac{\pi d}{\lambda} \sin \alpha\right)} \right]^2 \\ &= \left[ \frac{\sin u}{u} \right]^2 \cdot \left[ \frac{\sin(Nv)}{\sin(v)} \right]^2 \end{aligned}$$

Figure 9.5 shows the 3 functions with adjusted parameters in units of wavelength.

As already noted, the properties of these three functions are described in detail in the menu point *Theory*, with the aim of finding meaningful dependencies in measurement series: i.e. width  $B$  of the main maxima as a function of the number of slits  $N$  ( $B \propto 1/N$ ).

The resolution  $A$  of a grating is derived from the Rayleigh criterion - standard in any textbook: the separability of the main maxima improves by increasing the order  $n$ , (Figure 9.6).

With the formulas for the position of the main maxima (in Fig. 9.6 the same order  $n = 1, n = -1$ ) one obtains immediately:

$$A = \lambda / \Delta\lambda \leq n N$$

Finally, Babinet's principle (J. Babinet 1837). The principle says, "The intensity distribution of the diffraction patterns of two complementary diffraction objects is identical throughout the whole geometric shadow." Two diffraction objects are complementary to each other if one transmits light at those points where the other does not transmit light:

- circular aperture and circular disc of the same diameter,
- slit and wire of equal width.

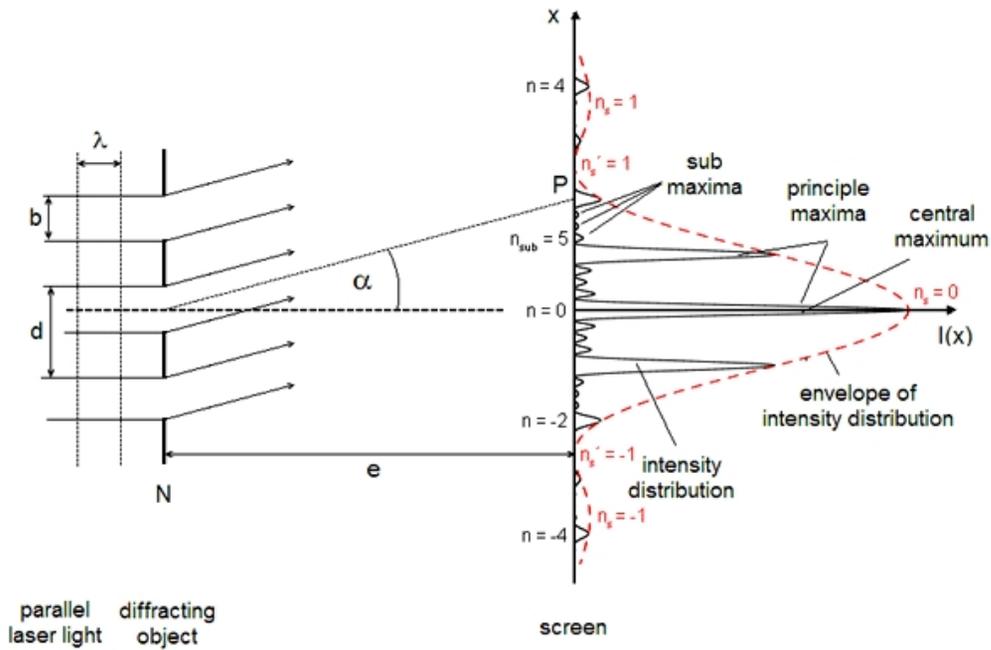


Figure 9.4: Horizontal section through the experiment with diffraction object (magnified), intensity distribution and experimental quantities.

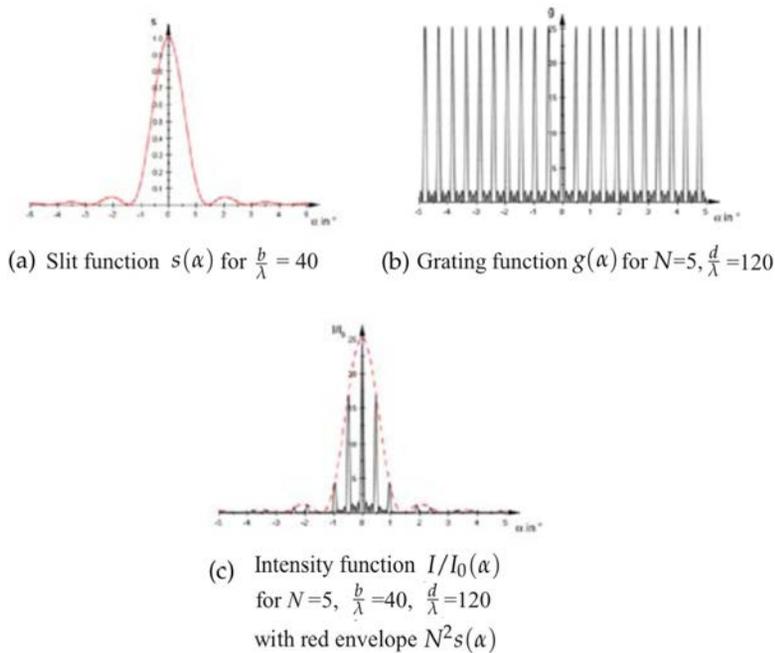


Figure 9.5: Slit, grating and intensity function

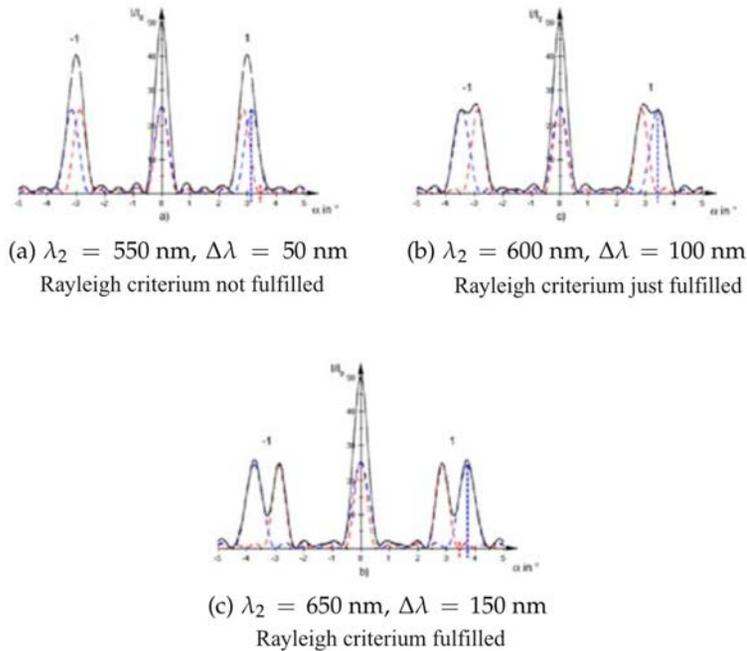


Figure 9.6: Grating  $N = 5$ ,  $\lambda_1 = 500 \text{ nm}$  (red curve),  $\lambda_2$  (blue curve), observed intensity (black curve).

Figure 9.7 shows the three cases (without object, slit, wire); from the left, the object is illuminated with a homogeneous laser beam of diameter  $D > b$ . As it is customary in Fourier optics, the geometry of the diffraction object—that is, the aperture function—is described by the field strength distribution  $a(x)$ , which then leads to an intensity distribution  $I_S$  (S-slit) and  $I_D$  (D-wire).

The RCL *Diffraction and interference II* allows the quantitative confirmation of the intensity function (Fig. 9.5c), the resolution of a grating (Fig. 9.6c) and the Babinet principle using the example of a slit and a wire (see measurement results).

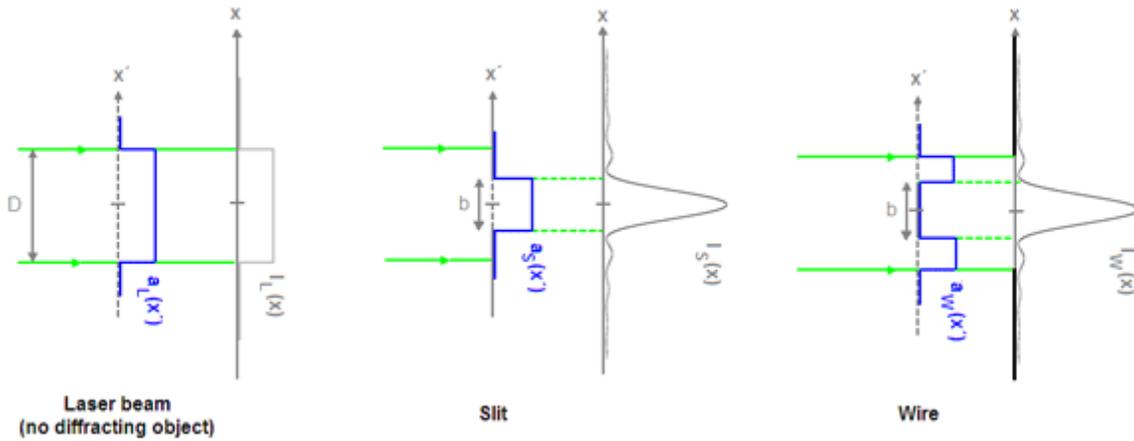


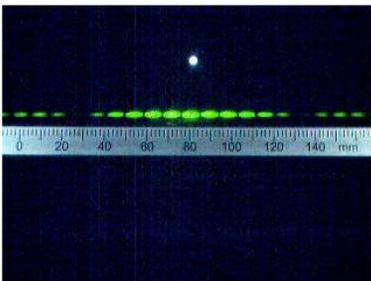
Figure 9.7: Babinet's principle using the example of a slit (S) illuminated by a laser beam (L) of width  $D$  and wire (W) of width  $b$ . Beam of the laser (green). Common geometric shadow area (black). Field strength distributions  $a_L(x)$ ,  $a_S(x)$ ,  $a_W(x)$  in the diffraction object plane over coordinate axis  $x$  (blue). Intensity distributions  $I_L(x)$ ,  $I_S(x)$  and  $I_W(x)$  in the diffraction pattern plane over coordinate axis  $x$  (grey).

## 9.2.4 Operating the experiment

Figure 9.8 shows the lab page after the experimenter calls up the experiment. In the left part, the user sees the webcam image of the diffraction pattern. Immediately below that one can see three buttons concerning the recording measurement technique: For semi-quantitative measurements one can switch the illumination of the centimetre scale on (off) in order to read off positions of maxima / minima. If the *Sensor position* option is selected, one will see a bright spot moving from left to right as an indicator of the sensor movement during an intensity measurement. If one wants to evaluate the diffraction pattern one self, one can create a screenshot of it. The lower webcam image allows observe the movement of the components in real time: selection of the laser, then an aluminium block with imprinted information on the selected wavelength of the laser moves horizontally; according to the selected wavelength one can see the corresponding colour reflections (green, red) of the laser diode. If one looks closely, one can see in the middle of the webcam image that a plate moves (in  $x$ - $y$  plane) if one has selected a specific diffraction object.

**Diffraction and Interference II**

- Introduction
- Setup
- Theory
- Tasks
- Laboratory
- Analysis
- Discussion
- Material
- Support



Scale illumination on/off    Sensor position on/off

Diffraction pattern - Screenshot



Distance diffracting object - screen:  $e = 1.005 \text{ m}$ .

### Diffraction and Interference II

Remaining time to perform experiment: 207 s

**Laser**

Wavelength:

**Diffracting objects**

Slit	Number	Width	Distance
Standard objects:	<input type="text" value="2"/>	<input type="text" value="10 μm"/>	<input type="text" value="60 μm"/>
Resolving power:	<input type="text" value="-"/>	<input type="text" value="5 μm"/>	<input type="text" value="60 μm"/>
Special objects:	<input type="text" value="-"/>		<input type="button" value="Adjust"/>

**Intensity measurement**

Step size (Duration):

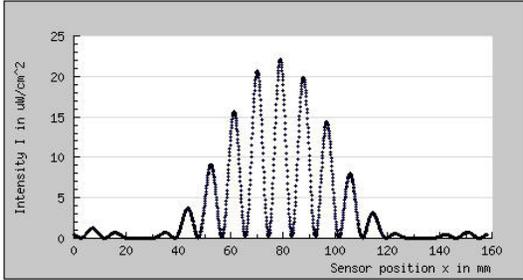


Figure 9.8: From the RCL website, menu point *Laboratory*: View of both webcams (left) and control panel (right). The intensity graph appears only if this option was selected by the user.

The right-hand panel has three blocks: choice of laser wavelength, choice of diffraction object (all parameters  $N$ ,  $b$ ,  $d$  must be specified, as well as special objects - see Tab. 9.1).

During the intensity measurement, the diffraction pattern can be sampled in different step sizes depending on the quality requirements, which are accordingly accompanied by different selectable time intervals. Subsequently, the intensity measurement runs automatically, whereby the scanning movement of the light sensor can be traced on the basis of the moving light spot as an indicator. For further analysis, the experimenter can download his measured data as a table.

This RCL comprises a total of 15 interactions; while all control elements are self-explanatory; All interactions are experiment-specific:

- Select an object (diffraction object of 150 offers),
- Store measurement results (screenshot of diffraction pattern, light intensity versus position of light sensor  $I(x)$ ),
- Set measuring instrument (increment of the moving horizontally light sensor),
- Select measuring instrument (screenshot, ruler or light sensor),
- Record a series of measurements:
  - wavelength versus position of maxima / minima,
  - slit width versus light intensity of the central maximum,
  - slit width versus width of the central maximum,
  - slit distance versus light intensity of the central maximum,
  - slit distance versus position of maxima / minima,
  - number of slits versus number of secondary maxima,
  - number of slits versus minimum order when studying the resolving power,
  - position light sensor versus light intensity,
- Prepare the beam (wavelength),
- Adjust experiment (reset of moving experimental components).

### 9.2.5 Measurement result

As with the RCL radioactivity, we also assume here, that this RCL diffraction and interference II is mostly used in self-study or group work. Therefore we present our measurement results for each of the approximately 15 different measurement types / series, so that the experimenter can compare his own measured data.

At the single slit, there is only one series of measurements possible, the dependence of the diffraction pattern on the slit width  $b$  (Fig. 9.9). This observation can be quantitatively evaluated: With the centimetre scale we can read the distance of the first minimum  $n = 1$  from the

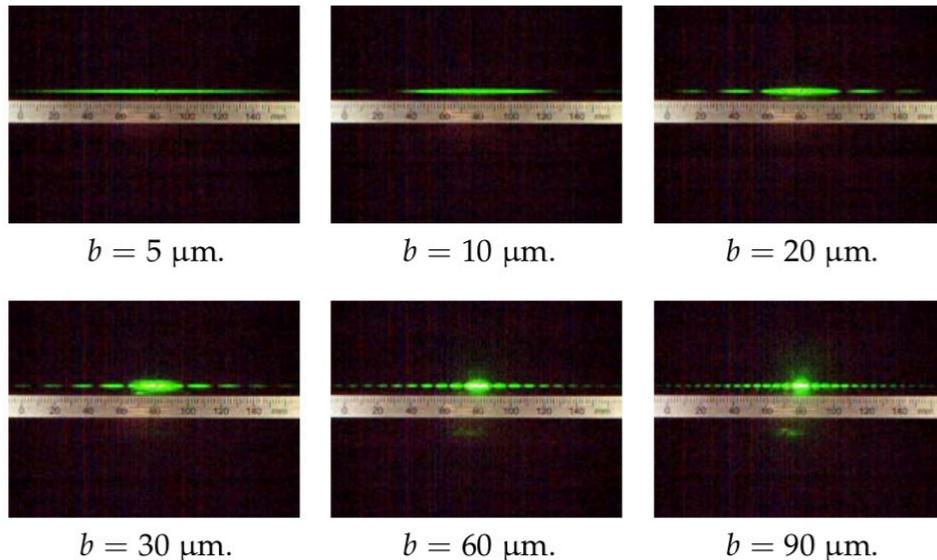


Figure 9.9:  $N = 1$ ,  $\lambda = 532 \text{ nm}$ . Diffraction pattern as a function of increasing slit width.

central maximum  $n = 0$  (see Fig. 9.4). Theoretically one expects (see theory, section 2.2, position of maxima / minima):

$$\sin \alpha_1 = \lambda/b \sim \tan \alpha_1 = a_1/e \quad \text{therefore} \quad a_1 = e \lambda/b$$

The result of the measurement agrees very well with the theoretical expectations (Fig. 9.10a).

Furthermore, we use the light sensor to measure the intensity of the central maximum  $I_0$  for different slits widths  $b$ . For a rectangular aperture of area  $A = c b$  (with  $c = \text{const}$ ) one expects  $I_0 \propto A^2 \propto b^2$  (Fig. 9.10b).

For the grating here is a selection of measurements: Fig. 9.11 shows diffraction patterns for different number of slits  $N$ .

For a grating with  $N$  illuminated slits, the number of sub-maxima is  $N - 2$ ; very easy to recognize.

In general, the grating properties are used to determine an unknown wavelength  $\lambda$ .

$$\sin \alpha = n \lambda/d \sim \tan \alpha = a_n/e \quad \text{therefore} \quad a_n \propto n \lambda$$

Figure 9.12 shows the positions  $a_n$  of the main maxima for different orders  $n$  with the wavelength  $\lambda$  as a parameter.

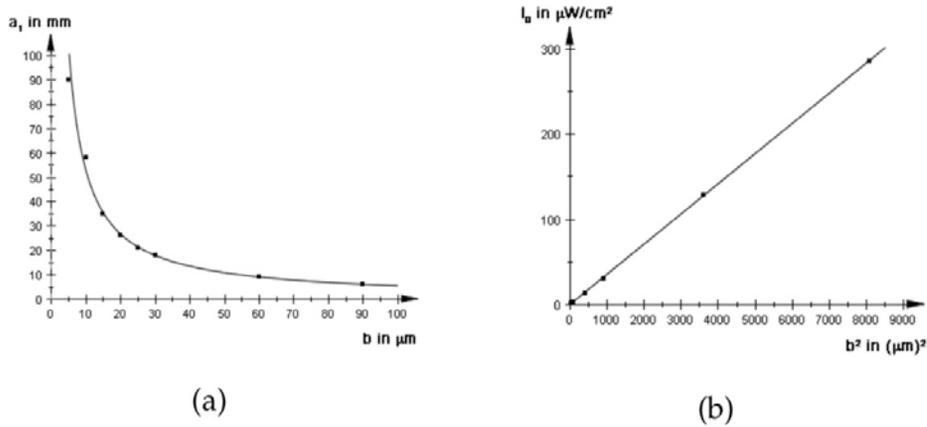


Figure 9.10: (a)  $N = 1$ ,  $\lambda = 532$  nm. Distance  $a_1$  between the minimum 1st order  $n = 1$  and the central maximum  $n = 0$  as a function of the slit width  $b$ . Comparison of measured values (squares) and theoretical data (line). (b)  $N = 1$ ,  $\lambda = 532$  nm. Intensity of the central maximum  $I_0$  versus slit width  $b$ . Measured values (squares), regression line  $I_0 \propto b^2$ .

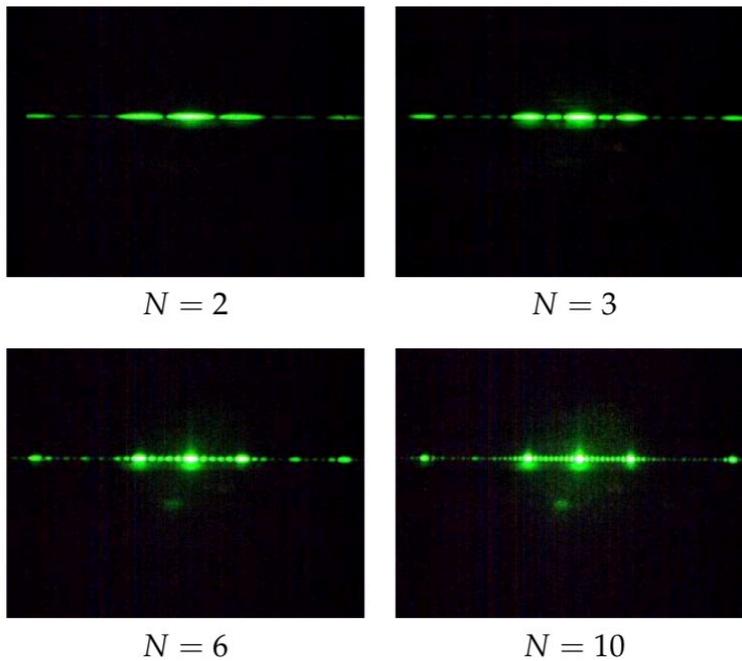


Figure 9.11: Diffraction pattern of gratings ( $\lambda = 532$  nm,  $b = 10$   $\mu\text{m}$ ,  $d = 20$   $\mu\text{m}$ ) with the number  $N$  of slits as a parameter.

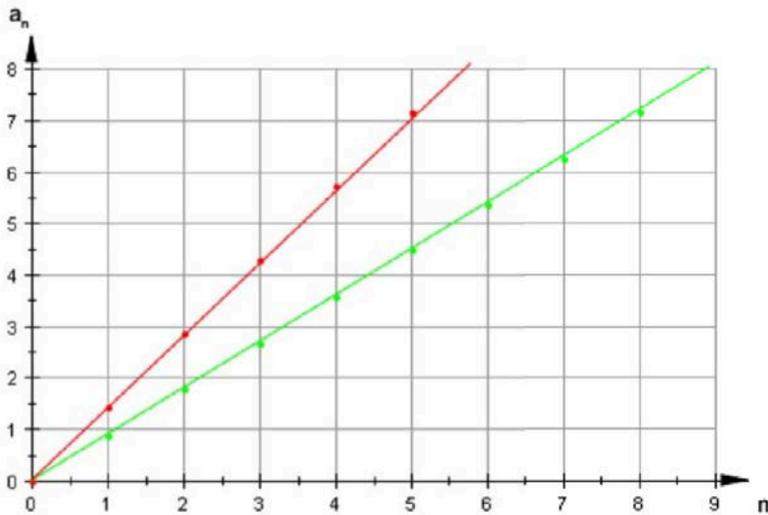


Figure 9.12: Positions of the main maxima for different orders  $n$  with the wavelength  $\lambda$  as parameter (red and green line).

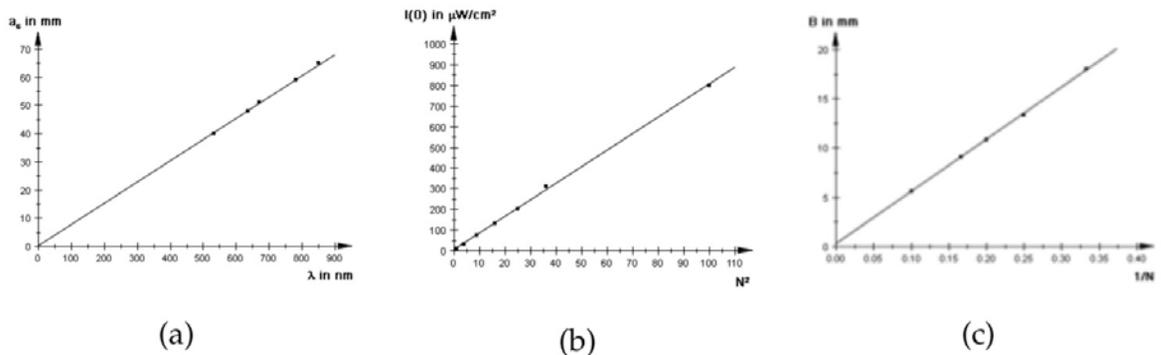


Figure 9.13: (a)  $N = 10$ ,  $b = 20 \mu\text{m}$ ,  $d = 80 \mu\text{m}$ . Distance  $a_6$  between the main maximum  $n = 6$  and the central maximum  $n = 0$  as a function of the wavelength. Comparison between measured (squares) and theoretical values (lines). (b)  $\lambda = 532 \text{ nm}$ ,  $b = 20 \mu\text{m}$ ,  $d = 80 \mu\text{m}$ . Intensity of the central maximum  $I(0)$  as a function of the number of slits  $N$ . Measured values (squares) and regression lines  $I(0) \propto N^2$ . (c)  $\lambda = 532 \text{ nm}$ ,  $b = 10 \mu\text{m}$ ,  $d = 20 \mu\text{m}$ . Width of the central maximum  $B$  as a function of the number of slits  $N$ ; Measured values (squares) and regression line  $B \propto 1/N$

An evaluation of measurement series with the grating ( $N = 12$ ,  $b = 5 \mu\text{m}$ ,  $d = 60 \mu\text{m}$ ) for determining the wavelength yields the values  $\lambda = 533 \text{ nm}$  (manufacturer's data  $\lambda = 532 \text{ nm}$ ) and  $\lambda = 855 \text{ nm}$  from the slopes in Fig. 9.12 ( $\lambda = 850 \text{ nm}$ ).

Figure 9.13 contains three different measured relationships.

Fig. 9.13a shows the distance  $a_n$  from the central maximum as a function of the wavelength  $\lambda$ :

$$\sin \alpha = n\lambda/d \sim \tan \alpha = a_n/e \quad \text{therefore} \quad a_n \propto n\lambda$$

Fig. 9.13b shows the intensity of the central maximum  $I_0$  as a function of the number of slits  $N$ . According to the formula for the intensity distribution  $I(\alpha)/I_0$  (see Fig. 9.4) one expects  $I(0) \propto N^2$ .

Fig. 9.13c shows the width of the central maximum  $B$  as a function of the number of slits  $N$ . In the menu point *Theory*, section 2.3, the relationship itself can be quickly understood  $B \propto 1/N$ .

If one observes a series of diffraction patterns in connection with the characteristics of the diffraction object ( $N$ ,  $b$ ,  $d$ ), one immediately notices: As the slit distance  $d$  is increased, the distance of the main maxima in the diffraction pattern decreases to the same extent (scale law of the Fourier transform). Fig. 9.14 shows the intensity distribution for two cases:  $N = 4$ ,  $b = 15 \mu\text{m}$  and  $d = 30 \mu\text{m}$  or  $d = 90 \mu\text{m}$ .

In the diffraction pattern we measure the distance of secondary maximum to central maximum  $a = 10 \text{ mm}$  (left) and  $a = 3, 5 \text{ mm}$  (right). According to the law of scale, the product  $a \cdot d$  must be constant. What is well fulfilled here.

In the next example we study the transition from the real to the ideal grating: i.d. for this transition see Figure 9.5c to 9.5b. As can be seen from the formula for the general intensity distribution  $I(\alpha)$  (see Fig. 9.5), this can be realized technically by passing the number of slits  $N \rightarrow \infty$  and the slit width  $b \rightarrow 0$ . Figure 9.15 shows the result for  $N = 2, 4$  and  $6$  and for  $b = 20 \mu\text{m}$  to  $5 \mu\text{m}$ .

In the limiting case of an ideal grating, we obtain a diffraction pattern consisting of equidistant "points" of zero intensity, where the mathematical representation of the intensity distribution corresponds to a function with equidistant delta-like maxima (see lattice function in the intensity distribution, and Fig. 9.5b).

The resolution of a grating is shown convincingly in Fig. 9.16.

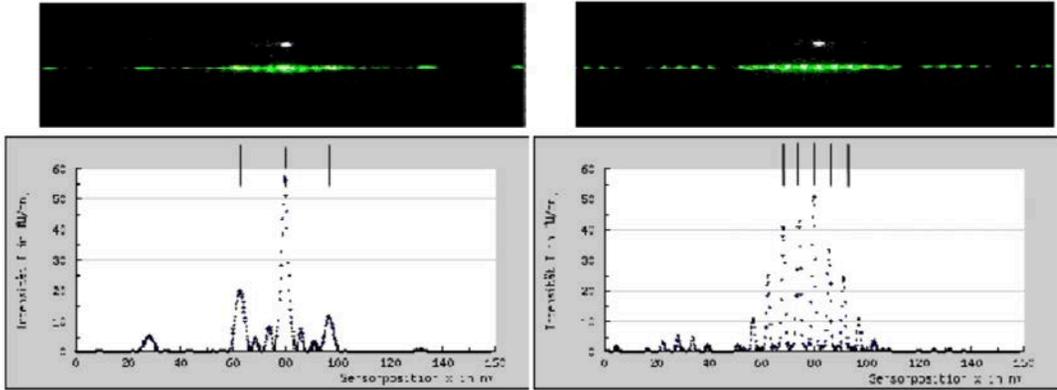


Figure 9.14: Screenshots (top) of the diffraction patterns and measured (below) intensity distribution during diffraction on objects:  $N = 4$ ,  $b = 15\mu\text{m}$  and  $d = 30\mu\text{m}$  (left) and  $d = 90\mu\text{m}$  (right). Vertical lines mark the position of the secondary maxima at  $a = 10\text{ mm}$  (left) and  $a = 3, 5\text{ mm}$  (right).

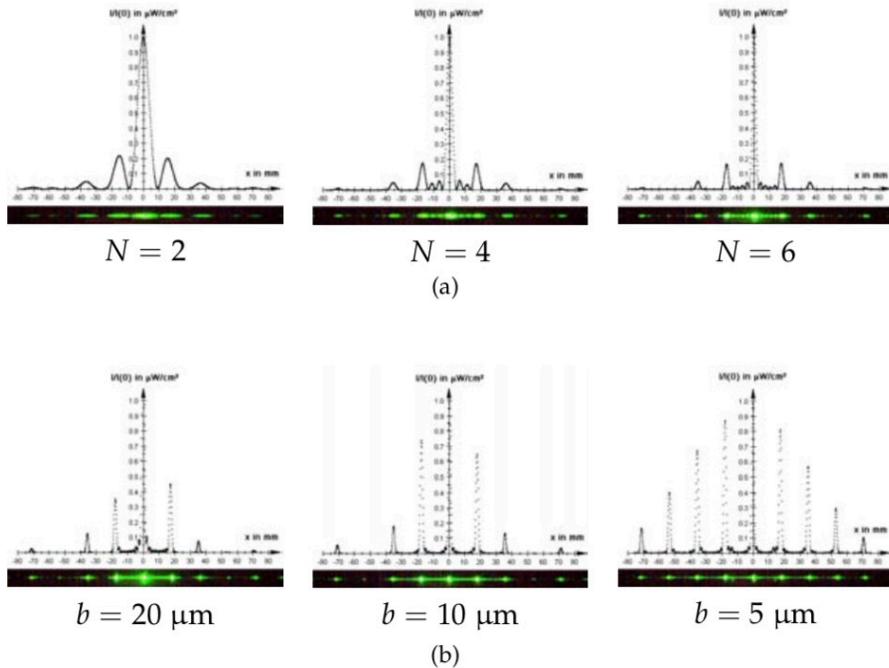


Figure 9.15: (a)  $\lambda = 532\text{nm}$ ,  $b = 20\mu\text{m}$ ,  $d = 30\mu\text{m}$ . Change of relative intensity distribution  $I/I(0)$  and diffraction pattern for increasing number of slits  $N$ . (b)  $\lambda = 532\text{ nm}$ ,  $N = 10$ ,  $d = 30\mu\text{m}$ . Change of relative intensity distribution  $I/I(0)$  and diffraction pattern for decreasing slit width  $b$ .

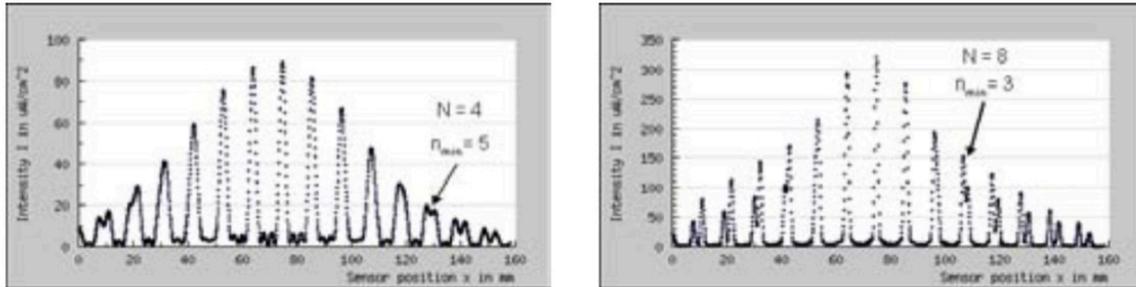


Figure 9.16:  $\lambda_1 = 635\text{nm}$ ,  $\lambda_2 = 670\text{nm}$ ,  $b = 5\mu\text{m}$ ,  $d = 60\mu\text{m}$ . Intensity  $I$  versus light sensor position  $x$  for two different numbers of slits  $N = 4$  and  $N = 8$ . Decreasing order  $n_{\min}$  (arrow) for the resolved wavelengths.

We use a pair of laser diodes ( $\lambda_1 = 635\text{ nm}$ ,  $\lambda_2 = 670\text{ nm}$ ) stacked in a vertical plane and fully illuminating one and the same grating. According to section theory for the resolving power we find  $A_{\text{theo}} = \lambda / \Delta\lambda = 635\text{ nm} / 35\text{ nm} = 19$ . This resolution can be represented by a product  $A = n_{\min} N$  ( $N$  - number of slits,  $n_{\min}$  is the minimum order, where one can separate the two main maxima to different wavelengths). Consequently, this minimum order  $n_{\min}$  must decrease as we increase the number of slits  $N$ : In the experiment shown in Fig. 9.16, we find  $n_{\min} = 5$  at  $N = 4$  and  $n_{\min} = 3$  at  $N = 8$ .

In the theoretical part we have derived Babinet's principle for the case slit-wire with the same width. Fig. 9.17 shows the measurement result. Both intensity distributions match perfectly. In our experiment, the laser beam  $D$  is about 1 mm; the width of both diffraction objects  $b = 90\text{ }\mu\text{m}$  is much smaller; the range of the observed intensity distribution  $x$  is about 10 cm. According to theory, the intensity distribution of slit and wire differ only slightly in the entire observation space, due to the favourably chosen parameters ( $D$ ,  $b$ ,  $x$ ).

Finally, a comparison of theoretically to be expected intensity distribution  $I(x)$  to experimentally self-determined distribution. Fig. 9.18 shows this with the example of a single slit and a grating.

Both - theory / experiment - match perfectly. How does it matter if one wants to appreciate the quality? Starting from the general formula of the intensity distribution  $I(\alpha)$  (see Fig. 9.5) and its discussion (see menu item *Theory* Section 2.3), the following criteria must be paid attention: Position of the main maxima / minima, relative intensities of

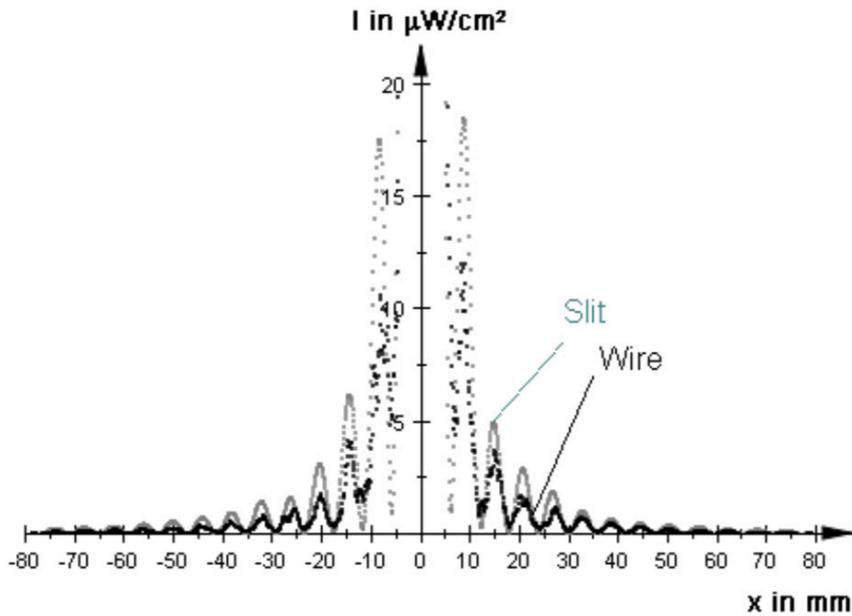


Figure 9.17: Comparison of the measured intensity distributions of slit (gray) and wire (black) of equal width  $b = 90 \mu\text{m}$ . (Height of the central maximum is not shown here.)

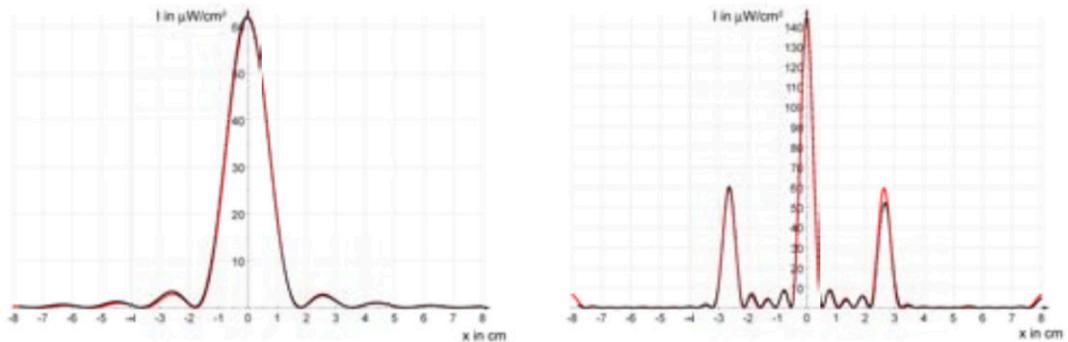


Figure 9.18: Intensity distribution  $I(x)$  at the single slit ( $\lambda = 532 \text{ nm}$ ,  $N = 1$ ,  $b = 10 \mu\text{m}$ ) and the grating ( $\lambda = 532 \text{ nm}$ ,  $N = 5$ ,  $b = 10 \mu\text{m}$ ,  $d = 20 \mu\text{m}$ ). Measurement (black), Theory (red).

main and secondary maxima to central maximum, line width of all maxima, number of main maxima (here  $N - 2 = 3$ ), match of the pattern for  $x > 0$  to  $x < 0$ , etc.

Two further suggestions:

1. If one wants to study the slit function – i.e. the envelope in the entire intensity distribution - the following measurement is recommended: comparison of both diffraction patterns for a single slit  $b$  ( $b = 1\ \mu\text{m}, 10\ \mu\text{m}, 15\ \mu\text{m}, 20\ \mu\text{m}, 25\ \mu\text{m}$  and  $30\ \mu\text{m}$ ) and a double slit with  $d = 60\ \mu\text{m}$  and equal slit widths like before.

2. Comparison of the quality of diffraction objects produced photo lithographically to electron beam lithographic. Measure the diffraction patterns of the same objects e.g. single slits  $b = 30\ \mu\text{m}, 60\ \mu\text{m}, 100\ \mu\text{m}$  and grating  $N = 4$  with slit width  $b = 30\ \mu\text{m}$ , slit distance  $d = 60\ \mu\text{m}$ , by selecting, measuring and evaluating the respective diffraction objects of the two different RCL variants: *Diffraction and Interference I* – photo lithographic objects, *Diffraction and interference II* - electron-beam lithographic objects.

### 9.3 Evaluation and experience

The quality of the measured data is very good. All quantities in the intensity distribution and their properties can be precisely measured to a few percent: position of maxima / minima, their width, relative intensities, etc. The experimentally obtained course of the intensity - even for more complex diffraction objects - agrees well with the theoretically expected ones.

If one only wants to get a qualitative picture of a diffraction pattern – e.g. influence of the slit width – a few 10 seconds of experimentation are sufficient. If one wants to quantitatively measure an object exactly by the light sensor, one needs a few minutes. For measurement series, as we have described in detail in the previous section, it takes about 30 minutes.

Our RCLs provide - here too - pure measured data in form of screenshots or downloadable table values; the further data analysis lies with the experimenter and is not included in the mentioned measuring time.

The added value of realizing this experiment as an RCL is as follows:

- Due to the approximately 150 diffraction objects (variation in  $N, b, d$ ) a variety of measurements and questions at different research levels are possible.

- The diffraction objects produced by electron beam lithography provide high-contrast diffraction patterns, which allow the evaluation towards higher diffraction orders; as well as finer details in the range of secondary maxima.
- The experimenter can gain relatively accurate own measured data in a relatively short time for further analysis and theoretical modelling.
- The experimental setup is superior to a typical demonstration experiment in many ways: 5 laser diodes, compact optical setup, 150 objects on a glass plate, reproducible selection of an object, 3 different recording techniques of diffraction patterns.
- In this setup, a continuous transition from qualitative, to semi-quantitative and finally to quantitative observation is possible, depending on the planned measurement time.
- The experimenter can either experimentally verify the given theory ( $I(\alpha)$ ); or he can practice making hypotheses, checking them, etc; can pursue his own research questions.
- Individual users or groups of users can organize themselves and complete a rich measurement program and exchange measured data in a short time.

The RCL has been online since 2009 and is called up on average five times a day and used for metrological purposes. In the summer of 2012, we retrofitted the x, y displacement elements of the glass plate with the diffraction objects with high-quality commercial stages (see Fig. 9.3, diffraction slide 4).

## 9.4 Didactic material

Possible scenarios for teaching are experimental homework (individually or in groups), a lesson for the teacher or self-study.

Table 9.6 contains a possible worksheet for single-slit measurements.

Table 9.6: Worksheet.

## 1) Questions:

- We will only study the single slit as an object. How is slit width  $b$  and slit height  $c$  defined?
- Familiarize yourself with the scattering geometry.
- The slit is arranged vertically, the intensity pattern horizontally. Why?
- Why is the intensity pattern symmetric to the central maximum  $n = 0$ ?

2) Measure the intensity pattern by taking screen shots for different slit widths  $b$  (green laser at 532nm)

1	25 $\mu\text{m}$	Group 1
5	30 $\mu\text{m}$	Group 2
10	60 $\mu\text{m}$	Group 3
15	90 $\mu\text{m}$	Group 4
20	800 $\mu\text{m}$	Group 5

## 3) Create two diagrams to check theory:

- $a_1 \sim 1/b$  with slit width  $b$ ,  $a_1$  distance from the central maximum  $n = 0$  to the first minimum  $n = 1$ . See theory:  $\sin \alpha_1 = \lambda/b$ ,  $\tan \alpha_1 = a_1/e$ , thus  $a_1 \sim 1/b$ .
- $I_0 \sim b^2$  with  $I_0$  intensity of the central maximum. See theory: intensity  $\sim (\text{area})^2$ , area of the slit  $b \cdot c$ .

## 4) Discussion:

- Look up the formula for the intensity distribution of a single slit in the theory section.
- Compare theory and measured values. Light must therefore be a wave to explain these phenomena of diffraction and interference. Which experiments are required to interpret light as a particle?

We formulate the following learning objectives for the lesson unit "Diffraction on the grating", which we have prepared below:

The students should

- Investigate qualitative and quantitative relationships between wavelength / diffraction object geometry and the intensity distribution of the diffraction pattern.
- Develop interest in the explanation and mathematical description of diffraction in general through independent hypothesis-led experimenting.
- Understand the mathematical description of diffraction by a grating using the pointer diagram model.
- Recognize the modulation of the diffraction pattern by the intensity distribution of a single slit.
- Compare experimental and theoretical data with a computer algebra system or spreadsheet program.

The following learning prerequisites are desirable:

- Description of the superposition of oscillations in the pointer diagram model,
- Interference of mechanical waves (interference of two circular waves in the wave trough, difference in the optical path length and phase difference between waves, conditions for maxima and minima),
- Intensity of mechanical waves (intensity proportional to the amplitude squared),
- Practiced handling of a spreadsheet program or computer algebra system for the comparison of experimental and theoretical data.

Structure of the lesson (Table 9.7)

- Analogy / comparison between double-slit experiment with light and interference of two circular water waves.

- Qualitative and quantitative investigation of the relationship between wavelength / diffraction object geometry and maxima / minima of the diffraction pattern.
- Qualitative and quantitative investigation of the relationship between wavelength / diffraction object geometry and intensity distribution of the diffraction pattern.
- Test to determine the geometry of unknown diffraction objects and classical mathematical tasks.

As part of self-study or project work, the following systematic series of measurements can be used (for measurement results, see section 9.2.5 Measurement result):

- At the single slit, the relationship between the diffraction pattern and the slit width (Fig. 9.9, 9.10).
- At the grating, the correlation between the diffraction pattern and the number of slits (Fig. 9.11).
- Measurement of an unknown wavelength by a grating (Fig. 9.12).
- Measurement of the grating properties as a function of the wavelength, number of slits (Fig. 9.13).
- Correlation of the geometry at the diffraction object (here slit distance) and the distances in the diffraction pattern (here distance  $a_l$ , main maximum  $n = 1$  to central maximum  $n = 0$ ) (Fig. 9.14).
- Transition from the real grating to the ideal grating for the limiting case  $N \rightarrow \infty$  and  $b \rightarrow 0$  (Fig. 9.15).
- Resolving power of a grating (Fig. 9.16).
- Compare diffraction patterns of a slit and a wire of equal width (Fig. 9.17).
- Modelling of experimentally measured intensity distributions at the single slit and grating (Fig. 9.18) with suitable simulation programs.

- Study of the slit function by comparing the diffraction patterns at the single slit with several slit widths and at the multiple slit with equal slit widths.
- For metrology: comparison of the quality of diffraction objects produced by photolithographic / electron beam lithography; comparison of the quality of measurement results, which were obtained by screenshot / centimetre scale and light sensor.

Finally, we refer to a series of simulation programs that can round off and deepen the use of this RCL

- Interference with water waves,
- Interference distribution and pointer diagram model,
- Interference figures,
- Interference at the double and multiple slits,
- Fraunhofer diffraction,
- Young double-slit experiment, etc.

(See didactic material at this RCL, teaching unit at Lehrer Online, there literature and links on the subject).

Table 9.7: Lesson.

**Teaching Unit "Diffraction by a Grating" with RCL "Diffraction and Interference"**

Phase	Contents and forms of work
<b>Analogy / Comparison Double-slit experiment with light (real experiment from the collection) and interference of circular waves (Simulations from RCL / Theory / Section 1.2)</b>	
<b>Introduction</b>	<p>Failure of the ray model of geometric optics. Light as a wave.</p> <p>Model: Exciter in the slits, one exciter per slit, term "diffraction" and correlation with wave interference, qualitative explanation of maxima and minima in the pointer diagram model, correlation between amplitude and intensity.</p> <p>Geometrically based hypotheses on the dependence of the diffraction pattern on the excitation frequency or light wavelength, on the exciter or slit distance and the screen distance</p> <p>Differences between both experiments (e.g. missing maxima, size of the wavelength)</p>
<b>Correlation between wavelength and geometry of diffraction object and maxima / minima of the diffraction patterns</b>	
<b>Experiment (RCL)</b>	<p>RCL as a demonstration experiment:</p> <p>Introduction to the RCL</p> <p>Discuss / demonstrate the dependence of the diffraction pattern on the number of slits</p> <p>Introduce quantities to describe the diffraction pattern (main and secondary maxima, minima, order, distance from the central maximum)</p> <p>RCL as a home experiment:</p> <p>Each group varies one size from the sizes of wavelength, number of slits, slit width and slit distance</p> <p>Qualitative: Recognize relationships and document them with image sequences (observing the diffraction pattern).</p> <p>Quantitative: hypotheses on the mathematical relationship between sizes. Plan, execute, evaluate measuring series and present results (measure with centimeter scale).</p>
<b>Theory</b>	<p>Derive formulas for maxima / minima (see RCL / Theory / Section 2.2 / Tab. 2 or RCL / Material / 3d or 3e).</p> <p>For high-performance courses, the students (or in groups) fill in Tab.2 from RCL / Theory / Section 2.2 drawing, text and derivation of the formula.</p>

<b>Experiment and theory</b>	Control of the derived formulas with RCL. Measurement series on the wavelength dependence of diffraction. Determination of wavelengths. Classical mathematical tasks (see RCL / Material / 3d or 3e).
<b>Correlation between wavelength and geometry of diffraction object and intensity profile of the diffraction patterns</b>	
<b>Experiment (RCL)</b>	RCL as a home experiment: Introduction to intensity measurement. Qualitative: drawing the intensity curve after the image of a diffraction pattern, Dependence of the width and height of the maxima on the number of slits; possibly recognition of the single-slit modulation of the diffraction pattern. Quantitative: Relationship between width and height of the maxima and number of slits (see RCL / Theory / Section 2.3 / Table 3). Series of intensity curves with constant wavelength, slit width and slit distance and variable number of slits for single-slit modulation of the diffraction pattern.
<b>Theory</b>	Derivation of the formula for the intensity profile of the diffraction pattern of a grating (see RCL / Theory / Section 2.3 and RCL / Material / 3d). Alternatively for lack of time or not teach formulas in the pointer diagram model.
<b>Experiment and Theory</b>	Qualitative: Comparison of the diffraction pattern and theoretical intensity pattern, varying only one parameter Quantitative: Comparison experimental and theoretical data applying computer algebra programs
<b>Test</b>	
<b>Close up</b>	Experimental determination of the geometry of unknown objects using the RCL. Theory: Classical tasks about diffraction.

## 9.5 Literature

- [1] Altherr, S., Vetter, M., Eckert, B. und Jodl, H.-J. »Experimentieren aus der Ferne: Ferngesteuertes Labor im Internet (Remotely Controlled Laboratory - RCL)«. In: Praxis der Naturwissenschaften - Physik in der Schule 54.6 (2005), S. 40–46.
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# 10 World Pendulum

## 10.1 Introduction

In this RCL experiment, the weak latitude dependence of the gravitational acceleration  $g(\varphi)$  is to be measured with the help of approximate mathematical pendulums, which are positioned at different places of the earth (location:  $\varphi$ -latitude). Where *remotely controlled* is not so much a question of elaborate experimenting, but that the experimenter can measure with pendulums in different places without having to travel there. Global experimenting in the 21<sup>st</sup> century. Modern means of communication and technologies, such as smartphones, GPS, broadband networks, influence all areas of our lives today. Thus it is imperative that this approach –global experimenting–also contributes to education, such as:

- Weather stations at schools in Europe. Students measure the quantities (wind force and direction, barometric pressure, temperature, rainfall, sunshine duration etc.), communicate the data with each other and present their measured data in a similar way as the professional weather services.
- Network of world pendulums.

In physics lessons, the measurement of the gravitational acceleration ( $g \sim 9,81 \text{ m/s}^2$ ) is usually carried out qualitatively with different methods. Usually very simple experiments such as string pendulum, freefall, inclined plane, spring balance, which are usually carried out as pupil experiments in groups at lower secondary level. The added value of making these simple pendulum experiment remotely controlled lies in the remote operability and the high measuring accuracy ( $\Delta g$  better than  $0,01 \text{ m/s}^2$ ). On the other hand, it can be used to address the latitude dependence of gravitational acceleration. In most curricula, the measurement of gravitational acceleration is presented in various places, such as gravitational field, oscillations, math./phys./real pendulum, basic principles of mechanics; but the latitude dependence is rarely discussed.

The importance of this measurement  $g(\varphi)$  lies in the border area physics - geophysics - geodesy. As recent measurements show, our earth is, to a first approximation, a rotational ellipsoid, but in the model of the deviating local field strength, the earth appears more as a "potato" [1]. Databases of relevant institutes (e.g. Phys. Bundesanstalt Braunschweig, Potsdam Geo Research Centre) contain worldwide values of local gravitational acceleration with an accuracy of 0,00001 m/s<sup>2</sup>. Today, measurements of the gravitational field in on the earth's surface are carried out continuously with a dense network of stationary measuring stations by telemetry. With satellite-supported, movable measuring instruments, the earth's gravitational field can be measured all over the earth since about 2000 [2- 4].

It is not easy to measure the latitude dependence of earth acceleration within the framework of teaching: In the local factor project [5] at the end of the 1990s, values of gravitational acceleration were measured with pendulums in schools in Germany and Switzerland, sent by e-mail and sent to the Website and published together. The latitude dependence of the gravitational acceleration could not be detected because of the size of the measurement errors and too small latitude differences. Another suggestion is to prove the latitude dependence of earth acceleration with a self-made fall equipment transportable for school trips within Germany [6]. Experience has shown that these simple devices with school supplies do not provide reliable results. Therefore, we have developed an RCL world pendulum that can be used to measure the latitude dependence of gravitational acceleration in real time in several places around the world with sufficient accuracy via the internet and without travelling. Participants in our teacher training courses on the use of RCLs rated this RCL very well.

One of our partners, who host one of our world pendulums, Prof. H. Fernandes in Lisbon (Portugal) initiated recently a worldwide pendulum project with many pendulums at different positions in South America; for interested reader have a look at those two websites: [http://groups.ist.utl.pt/wwwelab/wiki/index.php?title=Content\\_Management](http://groups.ist.utl.pt/wwwelab/wiki/index.php?title=Content_Management) and [http://groups.ist.utl.pt/wwwelab/wiki/index.php?title=World\\_Pendulum](http://groups.ist.utl.pt/wwwelab/wiki/index.php?title=World_Pendulum).

Finally, a report, with which the importance of the experiment -  $g(\varphi)$  to determine - is addressed in everyday life.

In 1671, the astronomer Jean Richer (1630 - 1696) travelled from Paris to Cayenne in French Guiana on the east coast of South America. Together with the left behind Jean Picard in Paris he wanted to

determine the distance between the sun and earth by parallax measurements in the upcoming Mars opposition. Richer was known, however, by his discovery that the entrained pendulum clock in Cayenne was late (be retarded) by about 2 minutes / day [7].

Today we know for sure that this observation is due to the latitude dependence of the gravitational acceleration  $g$ . The acceleration of gravity in Cayenne with  $g_{Ca}$  (4,9 degree) = 9,781 m/s<sup>2</sup> is 0,03 m/s<sup>2</sup> less than that in Paris with  $g_{Pa}$  (48,8 degree) = 9,811 m/s<sup>2</sup>. Therefore, with constant pendulum mass in Cayenne, the clock pendulum has a smaller restoring force than in Paris. The lower acceleration in Cayenne results in a longer oscillation period. Since the second hand always indicates one second after a complete oscillation, the pendulum clock in Cayenne is retarded. For a mathematical pendulum the oscillation period is

$$T = 2\pi \sqrt{\frac{l}{g}}, \quad \frac{T_{Ca}}{T_{Pa}} = \sqrt{\frac{g_{Pa}}{g_{Ca}}} = 1.00133.$$

This results in an error of 115 s per day  $\sim$  2 min per day in accordance with Richer's observation.

## 10.2 Experiment and RCL variant

### 10.2.1 Experimental setup and function

For relative measurements of gravitational acceleration, precision mechanical devices known as gravimeters are used. According to the spring balance principle, gravity is compensated by a linear spring force or to increase the measuring sensitivity by a nonlinear lever spring force arrangement. For absolute measurements, the dependence of the falling motion on the gravitational acceleration is used in the pendulum, vertical throw and free fall methods [8].

Here we use a string pendulum, whereby, as is well known, the oscillation period  $T$  and the known linear length  $l$  can be used to deduce the gravitational acceleration  $g$ :  $T = 2\pi\sqrt{l/g}$ . Since the gravitational acceleration  $g$  between the equator and the two poles changes by 0,034 m/s<sup>2</sup> (see later section theory), we demand an accuracy for the measurement of  $g$  of about  $\Delta g = 0,01$  m/s<sup>2</sup>. The accuracy of our time measurement is  $\Delta t = 0,1$  ms. The length  $l$  of the pendulum (about 3 m) is known with an uncertainty  $\Delta l = 55$  microns. If the room temperature

changes by about 10°C in the laboratory, this results in a change in length, which in turn causes a  $\Delta g = 0,002 \text{ m/s}^2$ . Therefore we provide a temperature measurement.

Another requirement for the string pendulum in the RCL is the process of catching the pendulum ball, bringing it into a specific deflection angle (< 10 degree) and releasing it; then measure. So far we have built 5 world pendulums for general use:

- Aden (Yemen);  $\varphi = 12, 80$  degree
- Munich, Germany);  $\varphi = 48, 07$  degree
- Naples (Italy);  $\varphi = 40, 83$  degree
- Lisbon (Portugal);  $\varphi = 38, 74$  degree
- Riga (Latvia);  $\varphi = 56, 93$  degree

In the following we describe the experimental setup and the function of all components. It has to be considered - see theory - that the theoretical model of a pendulum (mathematical, physical, real pendulum) contains many parameters; some of them are fixed given, others are freely selectable within certain limits. Therefore, at the end of this subchapter, some remarks on the design of our pendulum, how it might interest the reader here. (For those who are more deeply interested, we provide bibliography at the appropriate places.)

The pendulums (Fig. 10.1) consist of a suspension (1a - 1d), a wire (2) and a ball (3) made of steel. The wire is fastened with a clamp (1a). A triangular-shaped prismatic cutting edge (1b) and a cutting edge bearing (1c) allow almost frictionless pendulum movement about a stable pivot point D. A tube (1d) serves as a guide for the wire and reduces tilting of the cutting edge. The suspension is horizontal on a wall bracket (4).

The accuracy of the length measurement of each wire has a significant influence on the accuracy of the determination of the gravitational acceleration. Therefore, the wire length of approx. 2.7 m was determined with a specially designed mechanical measuring device. A thermal change in length of the wire can be taken into account by a room

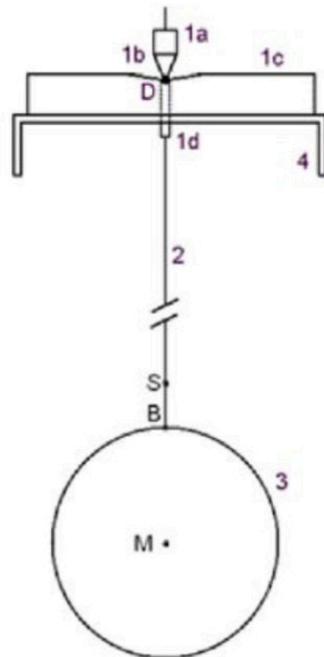


Figure 10.1: Schematic representation of the pendulum: Suspension (1a-1d), wire (2), ball (3) and wall bracket (4), point of rotation D, wire attachment point B, centre of gravity S and ball centre M.

temperature measurement in the RCL. The total error of the length determination of the wire is approx. 0,055 mm (more detailed information on the length determination of the wire as a link under menu point *Experimental set up*).

With the elongation mechanism (Fig. 10.2), the pendulum can be deflected from any state of motion to a selectable starting angle between 1 degree and 10 degree. The mechanical components are located on a base board (1) aligned horizontally with four legs (2) and adjusted to the height of the ball (3) above ground. When deflecting, an electromagnet (4) approaches the ball, which moves in a carriage (5) on rails (6). The carriage is moved by a stepper motor (7) with shaft (8) via a cable pull (9) and a deflection roller (10). A tension spring (11) generates the necessary cable tension for a non-slip movement of the cable over the shaft of the stepper motor and absorbs in addition the shock when catching the ball.

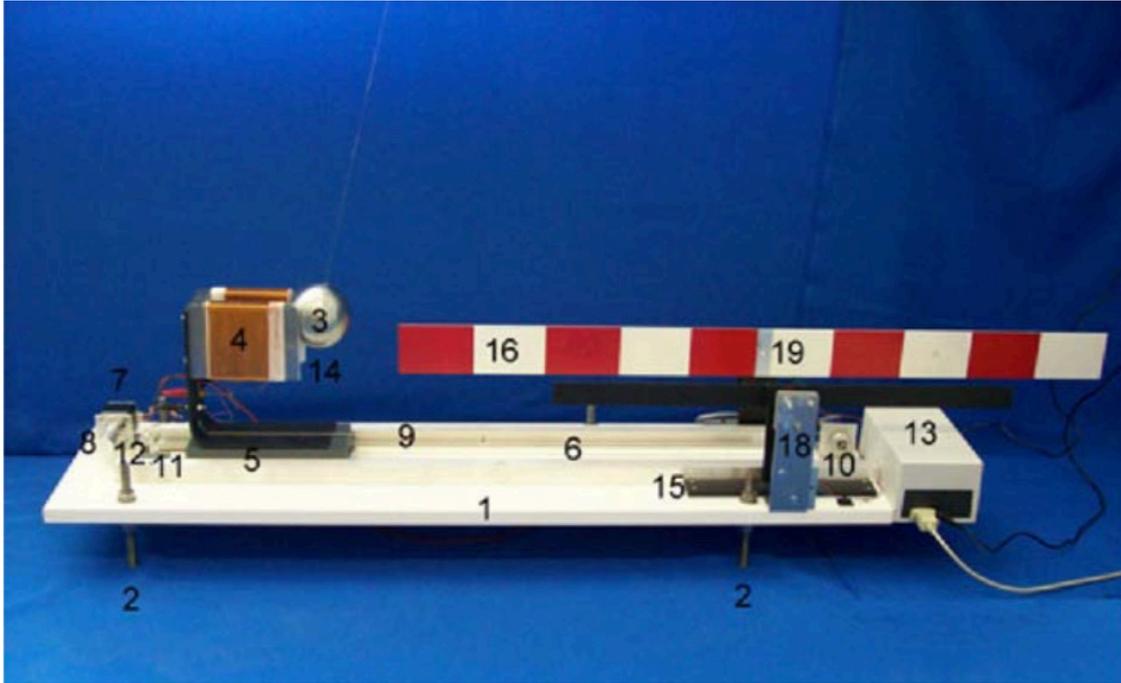


Figure 10.2: Experimental setup. Base board (1), legs (2), ball (3), electromagnet (4), carriage (5), rails (6), stepper motor (7) with shaft (8), cable pull (9), pulley (10), tension spring (11), limit end switch (12), interface (13), Teflon foil (14), iron band (15), ruler (16), laser holder (18) and pinhole (19).

After the electromagnet has caught and tightened the ball, the carriage first moves to the left stop to actuate the limit switch (12). As a result, in the interface (13), which controls the elongation mechanism via a catch routine programmed in a microcontroller, the carriage position is set to zero. This ensures the long-term stability of the deflection accuracy of the pendulum. Then the carriage moves to the desired initial elongation angle, then the ball is released by switching off the electromagnet and the carriage moves back to the left stop.

The geometry of the poles of the electromagnet is adapted to the spherical shape of the ball, so that a sufficiently large magnetic force is generated by the smallest possible electric current. A Teflon foil (14) on the poles minimizes the friction of the ball moving up or down on the poles during pendulum elongation. This minimizes disturbing wobbling of the ball when releasing.

A front and rear iron band (15) prevent the ball from moving out of the plane of vibration in an uncontrolled manner after any unsuccessful attempts to catch it and being caught at the end by the electromagnet at the latest in the rest position. A ruler (16) with 10 cm wide white and red fields allows a visual control of the momentary elongation of the pendulum.

The most important component of the experimental set-up is a photocell for time measurement (Fig. 10.3). On the one hand, it measures the time required for the positioning of the deflection / catch mechanism to pass the rest position (dark time) and, on the other hand, the oscillation period of the pendulum to determine the acceleration due to gravity.

The light barrier consists of a laser diode (17) on a laser holder (18), a pinhole (19) and a light sensor (20) with adapted measuring electronics (21). The laser beam is aligned to the light sensor located behind the aperture using the adjustment screws (22). The pinhole improves the accuracy of the time measurement by reducing the laser beam diameter. It is about 0,1 ms.

In the menu point *Experimental set up*, the reader / experimenter finds all the necessary details about the 5 world pendulums such as latitude, height  $h$  above normal zero, mass and volume of the pendulum, spherical radius, pendulum length, moment of inertia, etc., which are slightly different depending on the respective pendulum.

On the design of the pendulum: We can model the string pendulum in the RCL experiment by a mathematical pendulum (see later section *Theory*); i. e. point like pendulum mass, massless string, neither friction nor buoyancy; In the physical pendulum model, friction and buoyancy are also zero, while the pendulum and wire are viewed in real terms. In the real pendulum, where these approximations made so far are all cancelled, we still have to distinguish the harmonic and an-harmonic case (elongation angle  $\alpha > 5^\circ$ ); wherein the period  $T(\alpha)$  is to be considered again with and without damping (decaying amplitude).

For the use of this RCL in school, a string pendulum was dimensioned such that the determination of the gravitational acceleration in the mathematical and physical pendulum model leads to the same value of gravitational acceleration: The relative error  $f = (g_m - g_p) / g_p$  for the gravitational acceleration  $g_m$  determined in the mathematical

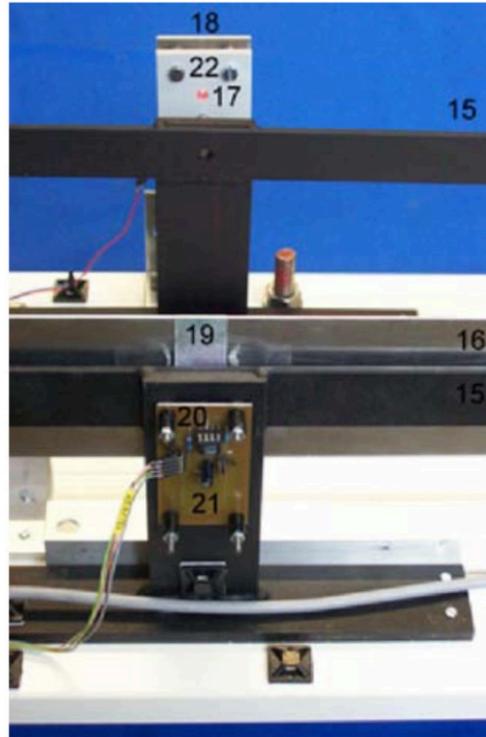


Figure 10.3: Components of the light barrier. Laser diode (17), laser holder (18), pinhole (19), light sensor (20), measuring electronics (21) and adjusting screws (22).

pendulum model with respect to the gravitational acceleration  $g_p$  determined in the physical pendulum model is given by the spherical radius  $r_K$ , ball density  $\rho_K$ , wire radius  $r_D$ , wire length  $l_D$ , wire density  $\rho_D$  and moment of inertia  $J_A$  and mass  $m_A$  of the suspension by [9]:

$$f = \frac{g^m - g_p}{g_p}$$

$$f = \frac{(l_D + r_K) \left[ m_A l_{SA} + \frac{1}{2} \rho_D \pi r_D^2 l_D^2 + \frac{4}{3} \rho_K \pi r_K^3 (l_D + r_K) \right]}{J_A + \frac{1}{3} \rho_D \pi r_D^2 l_D^3 + \frac{8}{15} \rho_K \pi r_K^5 + \frac{4}{3} \rho_K \pi r_K^3 (l_D + r_K)^2} - 1$$

In Fig. 10.4, the relative error  $f$  independent of the elongation angle  $\alpha$  is plotted versus the radius of the sphere  $r_K$  for approximately the same data of wire and sphere of the five pendulums.



Figure 10.4: Relative error  $f$  of the determination of the gravitational acceleration in the mathematical pendulum model as a function of the spherical radius  $r_K$  of the pendulum mass (steel)

The spherical radius  $r_K$  was chosen as an independent variable because other parameters could not be chosen freely: The wire length  $l_D$  had to be as large as possible for a small error of the length measurement, but the pendulum should be even smaller than a room height of about 3 m. The wire radius  $r_D$  must be at least so large that the tensile strength of the wire is not exceeded by the weight of the ball. As a ball material no lead could be chosen, otherwise the deflection mechanism of the pendulum with an electro-magnet does not work. As radius  $r_K$  of the pendulum balls, a value of 4.274 cm was chosen for a vanishing error  $f$  according to Fig. 10.4.

For the interested reader, we first refer to the websites of these RCLs. The menu point *Theory*, -see section pendulum models - also provide “information on the dimensioning of the pendulum”. There the formula for  $f(r_K)$  is derived. Secondly, all data on 5 pendulums such as mass, volume, radius of the pendulum and the pendulum wire can be found in a table in the menu point *Experimental set up*. Third, tips and tricks for building a pendulum and preliminary measurements can be found in [9, 10].

## 10.2.2 Navigation menu

In the menu point *Experimental set up* the principle of the pendulum is described, the necessary details to the 5 existing world pendulums as well as a detailed description of how the pendulum length of nearly 3 m to  $\Delta l = 55 \mu\text{m}$  was measured exactly by a special measuring apparatus.

The menu point *Theory* contains two sections: on the one hand, the latitude dependence of the gravitational acceleration, which is derived step by step; from the constant size  $g_0 = 9,8 \text{ m/s}^2$  to the finest modeling of  $g(\varphi)$ , the so-called WELMEC formula [11]. On the other hand, the pendulum, which we chose as a world pendulum to measure  $g(\varphi)$ , is also described step by step: Definition of geometry / estimate of possible forces / mathematical pendulum / physical pendulum / real pendulum / including restoring force for large elongation and damping.

The menu point *Tasks* contains suggestions for measuring and comprehension questions (Table 10.1).

In the menu point *Laboratories*, the experimenter first selects one of the 5 world pendulums (locations Aden, Munich, Naples, Lisbon, Riga); then he starts the experiment. At the top left, the experimenter sees a webcam image of the experimental setup - similar to Fig. 10.2. Below are the pendulum data. Right next to it the control panel; kept relatively simple here: select elongation angle and start pendulum; after a few seconds, measure the oscillation period and measure the room temperature to correct the pendulum length  $l(T)$ .

In the menu point *Evaluation* two examples: once the measurement of the world pendulum in Kaisersesch (from summer 2013 on positioned in Lisbon) in the mathematical pendulum model with a small deflection angle; the simplest case for pupils, but with a detailed error estimation and a comparison to the theoretical value according to the WELMEC formula. As a second example for students a comparative determination of the gravitational acceleration in the mathematical, physical and real pendulum model with large deflection angles - a comparison. In the menu point *Discussion* we ask comprehension questions about the experimental set up, the theory, the experiment and evaluation (Tab. 10.2)

Table 10.1: Tasks.

- 1) Latitude dependence of gravitational acceleration
  - a) The astronomer Richer discovered in 1671 on his journey from Paris to Cayenne in French Guiana, that his carried along with him pendulum clock was late in Cayenne: Recreate his experience with the world pendulum and explain the effect.
  - b) Measure the gravitational acceleration in the mathematical pendulum model with small deflection at the pendulum locations Riga, Naples, Aden, Hermannsburg and Kaisersesch. Compare the measured results with the theoretical course according to the WELMEC formula. Estimate the absolute and relative measurement error for  $g$  assuming that the pendulums behave like mathematical pendulums.
  - c) Perform for larger elongation angles and b) explain the difference.
  
- 2) Pendulum as a  $g$ -measurement device
  - a) Measure the gravitational acceleration at a pendulum location in the physical pendulum model at small elongation. Does buoyancy really has to be considered?
  - b) Show experimentally that the pendulums at these sites are not harmonic oscillators. Determine the relationship between the oscillation period  $T$  and the deflection angle  $\alpha$ . Compare this with the theoretical course of  $k(\alpha)$  (compare Theory, 2.2).
  - c) Measure the gravitational acceleration at one pendulum location in the mathematical and physical pendulum model without consideration of the buoyancy force. Explain the agreement of the results.
  - d) Check for one of the pendulums, if the damping constant  $\delta$  of the pendulum is constant. Compare the measured damping constant with the theoretically calculated one (see Theory, 2.1 and 2.2) and explain the difference. Determine  $g$  in the real pendulum model.

The menu point *Material* describes everything necessary about the experimental material, if one wants to build another pendulum by oneself. The didactic material (see later) includes:

- Lessons,
- Task collection with model solutions,
- Tips and tricks as well as a construction manual for the RCL world pendulum in case of a replica,
- Pendulum data of the 5 locations, automated evaluation of measurement results in different pendulum models.

Table 10.2: Discussion.

- 1) Setup
  - a) How works a light barrier?
  - b) Inform yourself about methods of length measurement: Why was the length measurement of the pendulum by the user omitted in the experiment?
  - c) When the sphere of the pendulum is caught by the magnet, there is no crash between the sphere and the magnet: how does the magnet "know" the amplitude of the pendulum?
  - d) Discuss whether a determination of the gravitational acceleration by vertically falling of a body can not be performed more accurately than a pendulum.
  
- 2) Theory
  - a) Richer discovered on his trip from Paris to Cayenne that his pendulum clock in Cayenne was about 2 min/day late: Is this effect explainable in a different form than the latitude dependence of the earth acceleration?
  - b) Derive the elevation term  $g_0 \cdot 0.000003085 \cdot h$  in the WELMEC formula from the gravitational law. Is the height dependence of the gravitational acceleration measurable by our world pendulum? Compare height dependency with latitude dependency at your location.
  - c) Research or calculate whether the influence by the sun, by the moon or by the tides does not have to be taken into account when measuring the latitude dependency of the earth's acceleration by our RCL.
  - d) Show that the formula for the oscillation period in the mathematical pendulum model is a special case of the formula concerned in the physical pendulum model, and this on the other side is a special case of that in the real pendulum model.
  - e) Justify whether the consideration of buoyancy or friction results in a greater or lesser oscillation period of the pendulum.
  - f) Up to which elongation angle can the anharmonicity of the pendulum ignored for a  $g$ -determination at  $0.005 \text{ m/s}^2$ ?
  - g) In March 2002, the double satellite GRACE was put into orbit around the earth: what does the abbreviation GRACE stand for? What are the goals of the GRACE project? What is SST and which functional principle is SST based on?
  
- 3) Laboratory
  - a) Why does a more realistic pendulum model not necessarily lead to an increase in the accuracy of the  $g$ -determination?
  - b) Why does the length of the pendulum changes during the oscillation movement?
  
- 4) Evaluation
  - a) Discuss qualitatively the influence of sources of error on the  $g$ -determination.

### 10.2.3 Theoretical Basics

Here we merely list the formulas underlying the different approaches for describing gravitational acceleration.

- Latitude dependence of gravitational acceleration:
  - Earth as a homogeneous sphere at rest:

$$g_0(\varphi) = G m_E / r_E^2 = 9.798 \text{ m/s}^2$$

(with  $G$  - gravitational constant,  $m_E$  - mass of the earth,  $r_E$  - constant distance).  $g_0$  as a constant size (Fig. 10.6).

- Earth as a rotating homogeneous sphere

$$g_{\text{eff}} = g_0 - g_{\text{cr}} = G m_E / r_E^2 - \omega^2 r_E \cos^2 \varphi$$

with  $\omega$  - angular velocity of a rotating homogeneous sphere,  $\varphi$  - latitude to point P (location of the pendulum) (see Fig. 10.6) In this model, the acceleration by gravity varies between the equator ( $\varphi = 0$  degree) and the poles ( $\varphi = \pm 90^\circ$ ) by  $0.035 \text{ m/s}^2$  (Figure 10.6).

- Earth as a rotating inhomogeneous ellipsoid

The radius at the equator ( $r_A = 6378.137 \text{ km}$ ) is slightly larger than at the poles ( $r_P = 6356.752 \text{ km}$ ). This flattening as well as the anisotropy of the density distribution provides the international gravity formula ( $g_n$  see Fig. 10.6).

$$g_n(\varphi) = 9.780327 \cdot [1 + 0.0053024 \sin^2(\varphi) - 0.0000058 \sin^2(2\varphi)] \text{ m/s}^2$$

For points that are higher in height  $h$  than the reference ellipsoid, for  $h \ll r_A$  the acceleration of gravity can be calculated using the WEL-MEC formula ( $h$  in meters) [11]:

$$g_n(\varphi, h) = 9.780327 \cdot [1 + 0.0053024 \sin^2(\varphi) - 0.0000058 \sin^2(2\varphi) - 0.000003] \text{ m/s}^2$$

This height correction can be quickly made clear:

$$g_0(h) = G \frac{m_E}{(r_E + h)^2} \sim G \frac{m_E}{r_E^2} \left(1 - \frac{2h}{r_E}\right) = g_0 - \frac{\Delta g}{\Delta h} \cdot h$$

At the equator ( $r_E = r_A$ ) we get  $\Delta g / \Delta h \approx 3 \mu\text{m/s}^2/\text{m}$ ; if the height  $h$  is about  $2000 \text{ m}$ ,  $g$  becomes smaller at  $0.006 \text{ m/s}^2$ .

Figure 10.6 shows  $g(\varphi)$  for these 3 cases and the latitudes of the world pendulum in 2011.

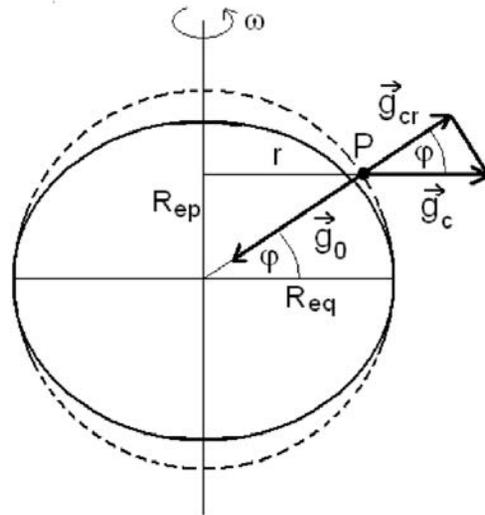


Figure 10.5: Geometry of the rotating sphere. Dynamic contribution to the gravitational acceleration  $g_{eff} = g_0 - g_{cr}$  [10].

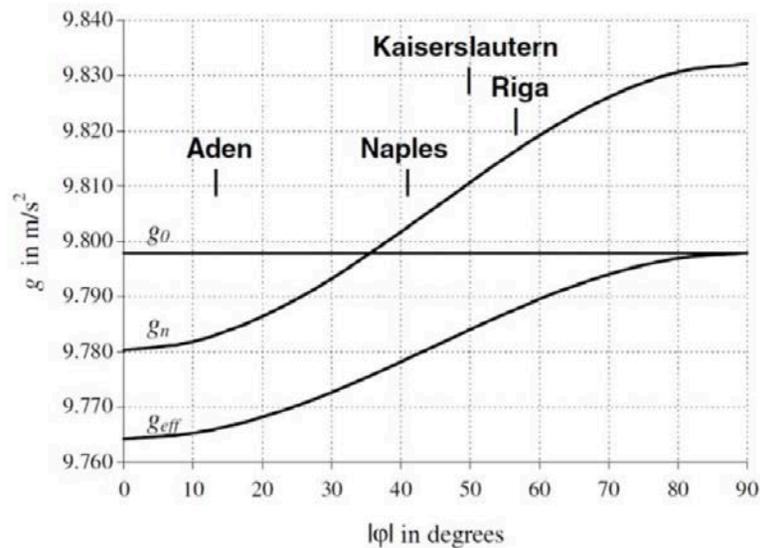


Figure 10.6: Graphical representation of the gravitational acceleration  $g(\varphi)$  as a result of the 3 models: Earth at rest ( $g_0$ ), rotating homogeneous sphere ( $g_{eff}$ ) and rotating ellipsoid ( $g_n$ ). Also marked are the latitudes of these institutes cooperating in the world pendulum project [9, 10].

- Pendulum models

As already noted, the derivations can be found step by step for the following pendulum models in the menu point *Theory*. The procedure is well-known: take model assumptions (e.g. point-like pendulum mass), balance effective forces (e.g. in addition to weight force buoyancy force and frictional force), solve the equations of motion,  $g(\varphi)$  can be calculated from the oscillation period  $T$ .

Figure 10.7 shows the string pendulum with sizes used. Due to the mass of the wire, the centre of gravity  $S$  of the pendulum is not in the centre of the sphere  $M$ ; the distance  $l_S$  is smaller than the distance  $l_M$ .

Since the pendulum participates in the rotational motion of the earth, the centrifugal force acts on the pendulum mass in addition to the gravitational force in the accelerated reference frame. The buoyancy force of the pendulum mass in air is  $F_A = m_L g = \rho_L V g$  (with  $\rho_L$  density of the air,  $V$  - volume of the pendulum). Friction is approximated by Stokes frictional force:  $F_R = 6\pi\eta_L r_K v_S$  (with  $\eta_L$  air viscosity,  $r_K$  - sphere radius,  $v_S$  - velocity of the centre of gravity of the pendulum).

The harmonic mathematical pendulum requires a point like mass, massless suspension and small elongation:

$$g_m = 4\pi^2 l_M / T^2$$

The harmonic physical pendulum takes into account expansions of the objects; instead of masses moment of inertia  $J$  must be considered and a buoyancy force has to be added:

$$g_p = 4\pi^2 J / [T^2(m - \rho_L V) l_S]$$

In the real pendulum, the frictional force  $F_R$  and thus the damping  $\delta$  of the pendulum are additionally to be considered,

$$g_r = [4\pi^2 / (T^2 + \delta^2)] J / [T^2(m - \rho_L V) l_S]$$

If the deflection angle is no longer small ( $\alpha$  larger than  $5^\circ$ ), then the oscillation period of the pendulum must be corrected by a factor that takes into account anharmonicity. It is known that in the harmonic case the small angle approximation applies (see Fig. 10.8).

$$F_G = m g \sin \alpha \approx m g \alpha$$

For larger elongation angles, the oscillation period is no longer independent of this deflection angle. Theoretically, it is found that the oscillation period is greater by a factor  $k$  dependent on the elongation angle than the oscillation period  $T_0$  in the harmonic case

$$T(\alpha) = k(\alpha) \cdot T_0$$

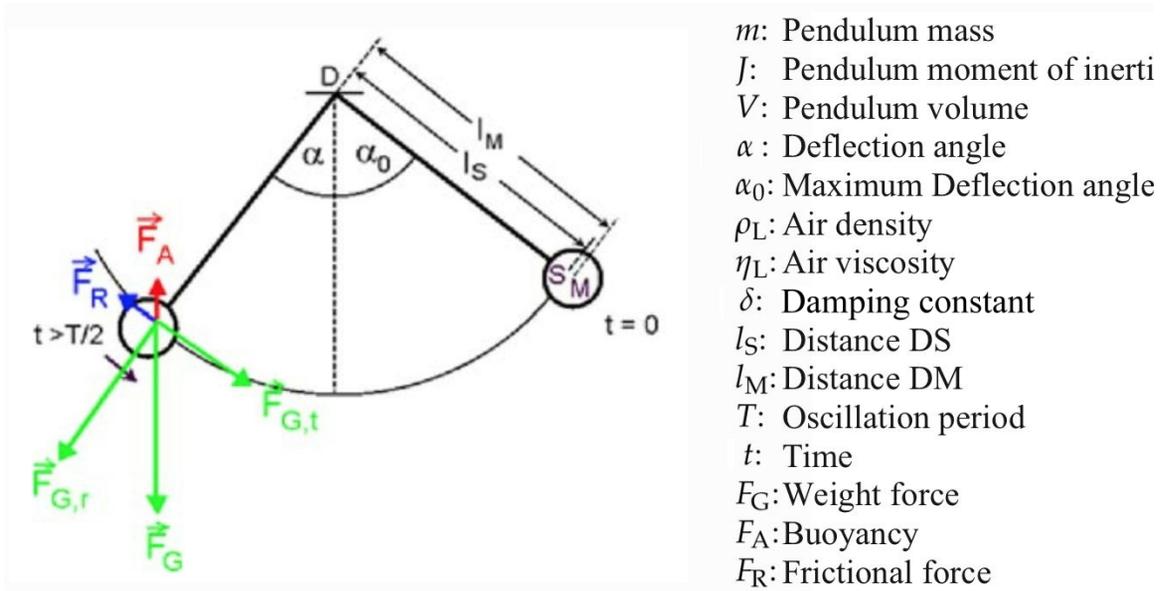


Figure 10.7: Schematic representation of a pendulum and of used parameters.

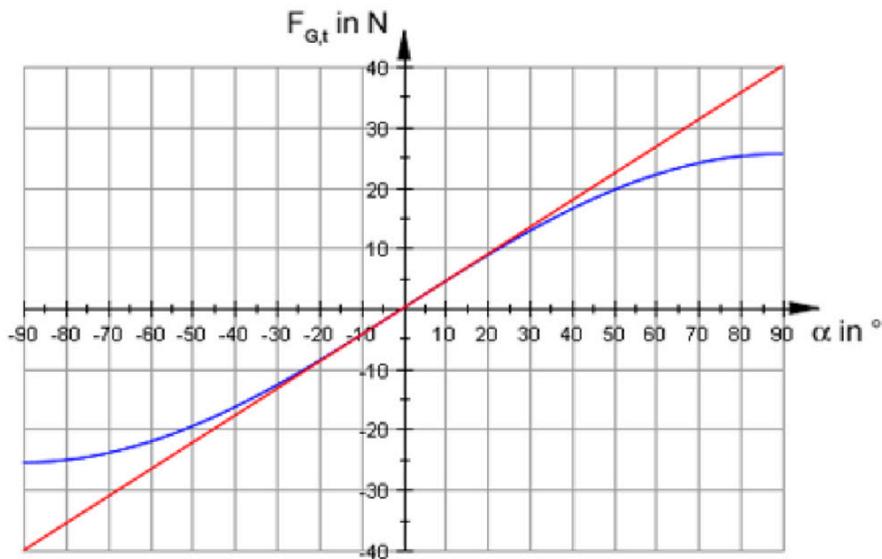


Figure 10.8: Actual restoring force (blue curve, anharmonic) and approximate restoring force (red curve, harmonic) for  $m = 2.6$  kg and  $g = 9.81$  m/s<sup>2</sup> as a function of the elongation angle

The calculation of  $k$  up to the fourth summand is sufficient for the required accuracy of approximately  $\Delta g = 0.003 \text{ m/s}^2$ . (For the derivation of the  $k$ -factor see the menu point *Theory* - Derivation of the formula for  $g$  in the math model with anharmonic approximation.)

Thus:

$$g_m = \frac{4\pi^2 l_M}{T^2} \cdot k^2$$

$$g_P = \frac{4\pi^2 J}{T^2(m - \rho_L V)l_S} \cdot k^2$$

$$g_r = \frac{\left(\frac{4\pi^2}{T^2} + \delta^2\right) J}{T^2(m - \rho_L V)l_S} \cdot k^2$$

Finally, according to theory, the damping  $\delta$  causes an exponentially decreasing elongation angle ( $\alpha(t) = \alpha_0 e^{-\delta t}$ ). It is therefore necessary to measure only two consecutive amplitudes in order to be able to determine the damping constant  $\delta$ . The following applies:

$$\delta = \frac{\ln\left(\frac{\alpha(t_2)}{\alpha(t_1)}\right)}{t_1 - t_2}$$

In the subchapter - *Measurement results* - we will use these formulas, briefly listed here, to interpret the measurement data.

### 10.2.4 Operating the experiment

Figure 10.9 shows the menu point *Laboratory* for the World Pendulum in Lisbon.

On the left you can see the image of the webcam from the pendulum seen from the point of view of the pendulum suspension downward; right is the control panel. If one has selected an angle and start the experiment, one can observe how the carriage with electromagnet moves from right to left, takes the ball, than moves with the ball to the right corner to calibrate its position. Then the carriage with the ball goes back as far as the selected angle is reached, there to let go of the ball; then the carriage moves away from the swinging ball by moving back to the right end position.

After a few oscillations, the measurement of the oscillation period can be started; After several periods one can already see the slightly

## Remotely Controlled Laboratories - RCLs

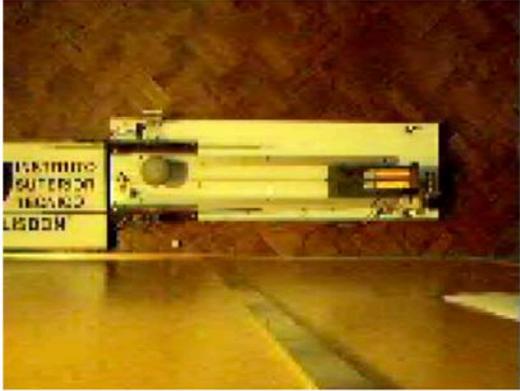
experimenting from a distance

Home	RCL-Project	RCLs	Technical Notes
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### World Pendulum

- Introduction
- Setup
- Theory
- Tasks
- Laboratories
- Analysis
- Discussion
- Material
- Support



Data of pendulum	
Location:	Lisbon (Portugal)
Latitude:	$\varphi = 38.74^\circ$
Height above sea level:	$h = 15 \text{ m}$
Length of wire ( $\vartheta = 20^\circ\text{C}$ ):	$l_{w,0} = 2.6515 \text{ m}$
Radius of sphere:	$r_s = 0.04274 \text{ m}$
Coefficient of thermal expansion of wire material :	$\alpha_w = 1.7 \cdot 10^{-5} \text{ }^\circ\text{C}^{-1}$

Figure 10.9: Lab side of the pendulum in Lisbon.

decreasing oscillation period because of damping. The measurement of the room temperature  $\vartheta$  is necessary in order to be able to correct the pendulum length  $l(\vartheta)$  appropriately.

The operation of the RCL experiment is comparatively easy. "Press buttons" means here:

- select parameter (elongation angle),
- take a series of measurements (latitude - oscillation period),
- measure different quantities (oscillation period, number of periods, elongation angle, total time, room temperature).

In our opinion, the focus here is more on the data analysis (which pendulum model, which approximations), the calculation of  $g(\varphi)$  compared to the theoretically expected value as well as in the communication of the measurement results (global experimentation).

### 10.2.5 Measurement result

Until 2011 we had 5 pendulum sites with the following measurement result; see Tab. 10.3 [12].

In Fig. 10.10, the values  $g_{p,a}$  of the gravitational acceleration determined experimentally in the physical, anharmonic pendulum model are compared with the graph of the WELMEC formula for  $h = 0$  m.

As a further test, Fig. 10.11 shows a comparison between those measured on the pendulum in Kaisersesch and that of the PTB for the pendulum location Kaisersesch provided value (difference of both values).

Finally, two interesting measurements for interested student groups as a project.

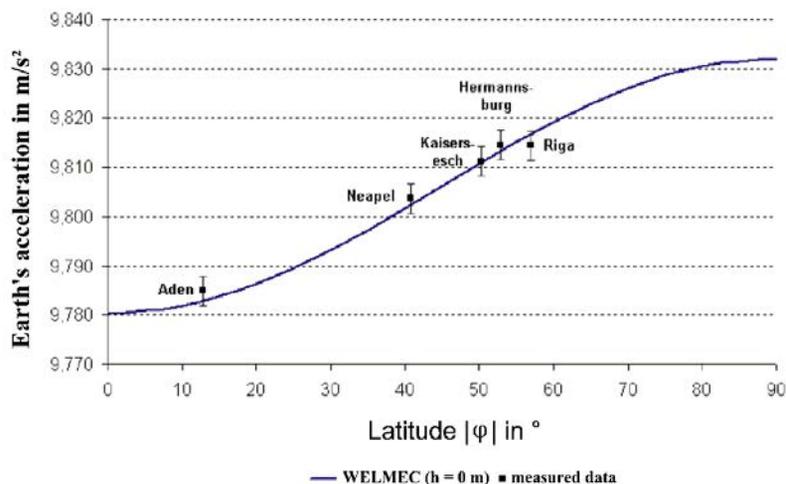


Figure 10.10: Comparison of theory and experiment of latitude dependence of gravitational acceleration.

Table 10.3: Measurements at the locations of the RCL World Pendulum [12]

	Location	Aden (Yemen)		Naples (Italy)		Kaisersesch (Germany)		Hermannsburg (Germany)		Riga (Lithuania)	
Data	Geographical latitude $\varphi$ in $^\circ$	12.818		40.839		50.231		52.832		56.930	
	Geographical length $\lambda$ in $^\circ$	45.032		14.186		7.151		10.100		24.121	
	Height $h$ over NN in m	3		6		458		57		11	
	PTB gravitational acceleration $g_{PTB}$ in $m/s^2$	9.7829		9.8026		9.8099		9.8130		9.8164	
	Welmec gravitational acceleration $g_w(\varphi, h)$ in $m/s^2$	9.7829		9.8024		9.8095		9.8130		9.8167	
	Room temperature $\theta$ in $^\circ C$	24.50		19.75		22.25		18.75		20.50	
Mmeasurements	Deflection angle $\alpha$ in $^\circ$	0.82	9.49	1.25	9.75	0.85	9.85	0.81	9.85	0.83	9.90
	Oscillation period $T$ in s	3.29937	3.30447	3.29639	3.30244	3.29511	3.30114	3.29489	3.30163	3.29223	3.29883
		3.29924	3.30467	3.29813	3.30236	3.29554	3.30111	3.29492	3.30157	3.29226	3.29875
		3.29986	3.30475	3.29584	3.30228	3.29512	3.30112	3.29498	3.30152	3.29244	3.29875
		3.29927	3.30486	3.29587	3.30230	3.29492	3.30105	3.29491	3.30154	3.29224	3.29875
Mean $T$ in s	3.29942	3.30508	3.29573	3.30223	3.29492	3.30105	3.29479	3.30143	3.29245	3.29872	
$g$ in model with buoyancy	Harmonic, mathematical $g_{m,h}$ in $m/s^2$	9.7838	9.7522	9.8034	9.7683	9.8091	9.7739	9.8159	9.7759	9.8150	9.7768
	$g_{m,h} = g_{m,h} - g_{PTB}$ in $m/s^2$	+0.0010	-0.031	0.0008	-0.0343	-0.0011	-0.0360	+0.0029	-0.0371	-0.0014	-0.0396
	Anharmonic, mathematical $g_{m,a}$ in $m/s^2$	9.784034	9.785744	9.804066	9.803756	9.809446	9.810169	9.816200	9.812664	9.815329	9.813370
	Anharmonic, physical $g_{p,a}$ in $m/s^2$	9.784100	9.785781	9.804105	9.803793	9.809404	9.810126	9.816240	9.812703	9.815376	9.813416
	$g_{p,a} - g_{m,a}$ in $m/s^2$	0.000034	0.000037	0.000039	0.000037	0.000042	0.000043	0.000040	0.000039	0.000047	0.000046
	$\Delta g_{p,a} = g_{p,a} - g_{PTB}$ in $m/s^2$	+0.0012	+0.0029	+0.0016	+0.0013	-0.0005	+0.0002	+0.0032	-0.0003	-0.0010	-0.0030

### Anharmonicity

The oscillation period  $T_{theo}$  increases due to the anharmonicity of the pendulum

$$T_{theo}(\alpha) = 2\pi \sqrt{\frac{J}{(m - \rho_L V)g_L S}} \cdot \left[ 1 + \left(\frac{1}{2}\right)^2 \sin^2\left(\frac{\alpha}{2}\right) + \left(\frac{1 \cdot 3}{2 \cdot 4}\right)^2 \sin^4\left(\frac{\alpha}{2}\right) + \left(\frac{1 \cdot 3 \cdot 5}{2 \cdot 4 \cdot 6}\right)^2 \sin^6\left(\frac{\alpha}{2}\right) + \dots \right]$$

$$= T_0 \cdot k(\alpha)$$

with increasing elongation angle. The oscillation period  $T_0$  in the harmonic case for negligible deflection angle ( $\alpha$  towards zero degree) was determined from the pendulum data. For the anharmonicity factor  $k$ , the development terms up to the fourth order have been taken

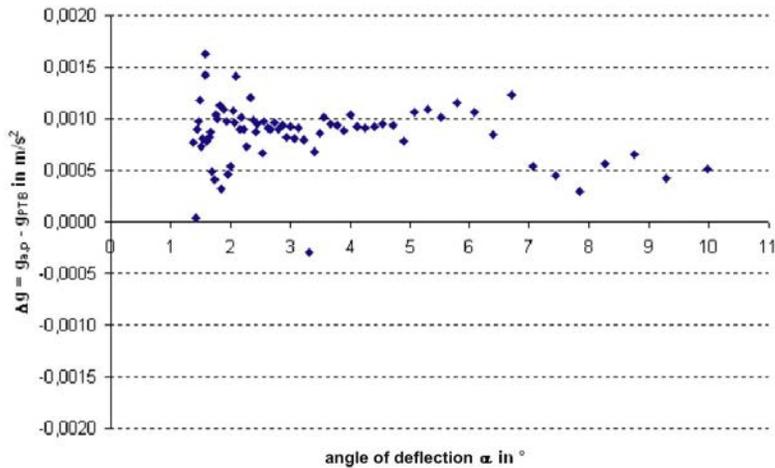


Figure 10.11: Deviation of the gravitational acceleration of the RCL pendulum in Kaisersesch (at different elongation angles) from the value specified by the PTB.

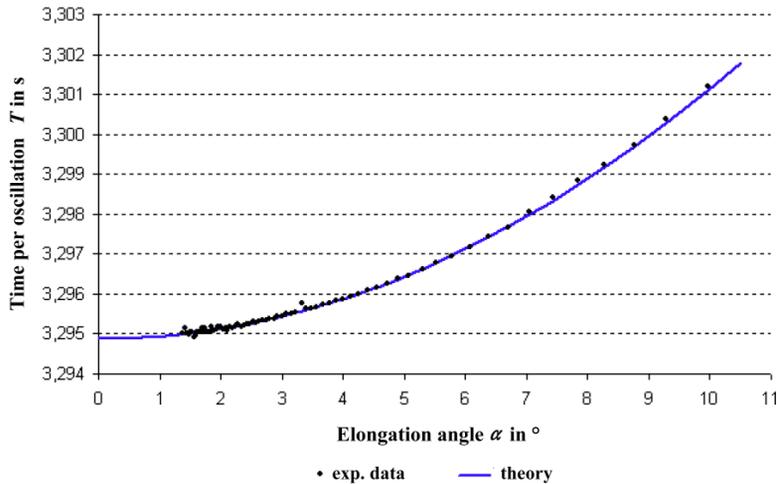


Figure 10.12: Anharmonicity of the RCL world pendulum in Kaisersesch.

into account. Fig. 10.12 shows that the measured values of the oscillation period  $T$  as a function of the elongation angle agree very well with the theoretical curve of the oscillation period  $T_{\text{theo}}$ .

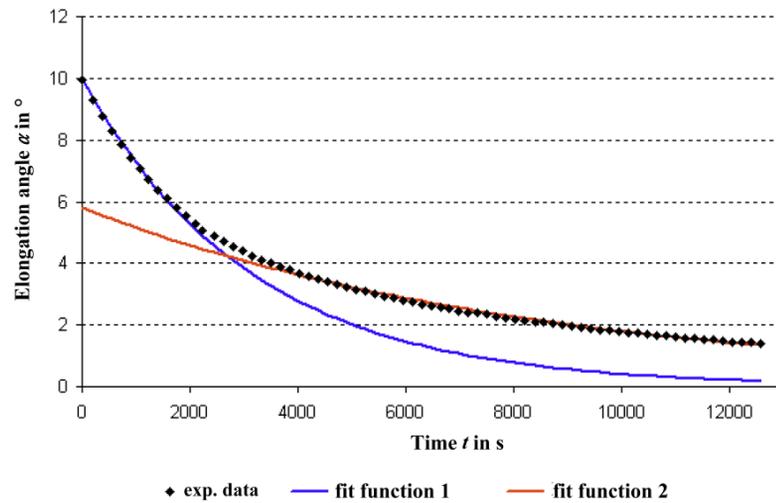


Figure 10.13: Damping of the pendulum; two exponential fit functions are applied to reproduce experimental data.

### Damping of the pendulum

As Fig. 10.13 shows, that the elongation angle  $\alpha$  decreases from 10 degrees to approximately 1.5 degree within approximately 3.5 hours. The damping can not be described by a uniform exponential function. At low deflection angles, the damping is probably dominated by a velocity-proportional sliding frictional force of the pendulum suspension, which is theoretically described by an exponential function. With large deflection angles and higher velocities of the pendulum mass, Newton's frictional force in air, which is proportional to the square of the velocity, dominates, in which there is theoretically no exponential decrease in the deflection angle.

Meanwhile, since summer 2013, two world pendulums have moved:

- Herrmannsburg ( $\varphi = 52, 83$ ) to Munich ( $\varphi = 48, 07$ )
- Kaisersesch ( $\varphi = 50, 23$ ) to Lisbon ( $\varphi = 38, 74$ )

### 10.3 Evaluation and experience

If we take into account all measurements of the 7 pendulum places then we have the following picture. The deviation of the measured value of the gravitational acceleration from the value according to the WELMEC formula is about 0.01% in the physical anharmonic pendulum model; the relative error in the measurement is  $\Delta g/g = 0.01\%$ ; modelling the raw data in the mathematical, harmonic as well as in the physical, anharmonic pendulum model there is a difference of  $\Delta g = 0.001 \text{ m/s}^2$ . A very good result, if we consider that professional gravimeters provide about  $10^{-5} - 10^{-6} \text{ m/s}^2$  accurate values, and school devices and accelerometers in smartphones usually  $10^{-1} - 10^{-2} \text{ m/s}^2$ .

The measuring time for about 10 oscillations takes about 1 minute; more complex measurement such as the determination of damping will take about 4 hours.

Since 2008 the project is online; without any problems. We limited ourselves to 5 world pendulums in 5 places in Europe. However, the number of pendulums by replica is easily expandable.

One of our partners, who host one of our world pendulums, Prof.H.Fernandes in Lisbon (Portugal) initiated recently a worldwide pendulum project with many pendulums at different positions in South America; for interested reader have a look at those two web-sites: [http://groups.ist.utl.pt/wwwelab/wiki/index.php?title=Content\\_Management](http://groups.ist.utl.pt/wwwelab/wiki/index.php?title=Content_Management) and [http://groups.ist.utl.pt/wwwelab/wiki/index.php?title=World\\_Pendulum](http://groups.ist.utl.pt/wwwelab/wiki/index.php?title=World_Pendulum).

The added value of the world pendulum as an RCL consists in the following:

- New experiment to measure the global effect of latitude dependence of gravitational acceleration.
- Measure the oscillation period of the pendulum at 5 locations in approximately 30 minutes.
- At  $0.001 \text{ m/s}^2$  accurate determination of the gravitational acceleration and thus by a factor of about 50 more accurate determination than with traditional school experiments.

The world pendulum has been used typically 9 times a day in recent years, with a significantly increasing number of users (about 2 visitors / day per year more). We have not studied the way of experimenting

by a visitor; the control panel is not very versatile - choose an angle and start the experiment; and measuring the oscillation period. Much more interesting here is how the experimenter further processes these raw data (oscillation period  $T$ , period number  $n$ ); i.e. measurement value analysis, evaluation and comparison e.g. with values from the internet database of the PTB Braunschweig.

## 10.4 Didactic material

This world pendulum project is mainly suitable for group work, for project work, and in cooperation of student groups from different countries. The expected measurement results ( $g(\varphi)$ ,  $T(\alpha)$ ,  $\delta$ ) have been described in detail.

The following learning objectives are formulated in close accordance with the material canon for the upper level at gymnasium (age 17-19 years old).

The students should

- Investigate experimentally the latitude dependence of gravitational acceleration with the RCL world pendulum.
- Explain qualitatively and semi-quantitatively the latitude dependence of gravitational acceleration as the cause of the interaction of earth rotation and earth flattening.
- Determine the gravitational acceleration with a pendulum in the mathematical and optionally in the physical or real pendulum model.
- Apply and deepen knowledge of mechanics such as circular motion, gravitation, centrifugal force, oscillation of pendulum and determination of gravitational acceleration to measure and explain latitude dependence, or expand their knowledge.

We have roughly designed three very different lessons:

### 1. Latitude dependence of gravitational acceleration

- Objective and methodology

In this lesson, students will be introduced to the study and explanation of a complex phenomenon, such as the latitude dependence of earth acceleration. Methodologically, this goal is to be achieved by a

narrative approach that stimulates hypothesis formation, the experimental investigation of the phenomenon with the RCL and the possibility to use acquired knowledge from mechanics to explain the phenomenon.

- Overview of the lesson

a) Narrative introduction with the story of how Richer came to this observation

b) Hypothesis formation and initial hypothesis tests

c) Measuring the latitude dependence of  $g$  with the RCL world pendulum

d) Latitude dependence of  $g$  due to the earth rotation and due to earth flattening

e) Compare experimental  $g(\varphi)$  values with the WELMEC formula

## 2. From the simple earth accelerometer to the world pendulum

- Objective and methodology

The students should learn what it means to accurately measure a quantity such as the gravitational acceleration. They should recognize that the measurement accuracy of such a size depends on many factors, such as the internal research question, the measuring apparatus, the measuring method and also the carefulness of the experimenter. Methodologically, this goal is to be achieved through a clearly structured lesson in its phases and a learning process based essentially on student activities.

- Overview of the lesson

a) Question, experiments for  $g$ -determination

b) Organization of group and learning process

c) Open student experiments

d) Presentation of measurement results, systemisation of experiences

e) Application of the learned to the RCL "world pendulum"

## 3. Building a pendulum to measure the acceleration of earth

- Objectives and Methodology

A pendulum is planned, dimensioned and installed in a physics class room, with which the earth's acceleration can be determined as accurately as possible in the classroom. This task can either be awarded as specialist work or carried out within the framework of a school working group.

- Overview of the lesson
  - a) Planning the experimental setup
  - b) Material acquisition, installation of the pendulum
  - c) Test measurements
  - d) Publication of the pendulum as another RCL on the internet

These lessons are available for download (see menu point *Material* section 2a for teacher online). A detailed collection of exercises with sample solutions contains 10 exercises on theory, 5 on experimental setup, 3 on measurement and evaluation. Of these, 6 sub-tasks at school level, 19 sub-tasks can only be used at university level. Table 10.4 contains 3 examples with model solution as an example.

To conclude, for a long-term project - building your own world pendulum - we can try to give out workshop aids. An assembly instruction for such a string pendulum and the associated RCL is stored under Didactic Material (Section 2f).

Table 10.4: Collection of tasks for the world pendulum.

### Task on causes and models of latitude dependence of gravitational acceleration

- a) Explain qualitatively the causes of the latitude dependence of gravitational acceleration.
- b) In the model of the earth as a homogeneous resting sphere of radius  $r = r_p$ , calculate the amount  $a_G(r, \vartheta, \varphi)$  and the direction of the gravitational acceleration and the gravitational potential  $V_G(r, \vartheta, \varphi)$  inside and outside the earth. Show  $a_G$  and  $V$  in graphical form. What are the values on the earth's surface?
- c) For the calculation of the latitude dependence of the gravitational acceleration, a point mass model of the earth ellipsoid with the mass  $M$  in the center and the masses  $m_1$  and  $m_2$  at  $r_p$  is used: How to get to the model? Calculate the masses  $M$ ,  $m_1$  and  $m_2$  assuming a constant density of the earth. Determine the direction and magnitude of the gravitational acceleration and the gravitational potential for the equator and the poles.
- d) How well does the model from c) describe the latitude dependence of the earth acceleration? What are the differences between the experimental g-values at the equator and the poles? How can the gravitational field strength of extended bodies be calculated in principle?
- e) Which part of the centrifugal acceleration  $a_Z$  is relevant to the latitude dependence of the gravitational acceleration? Calculate this fraction for a spherical earth with radius  $r = r_A$ . How short must an earth day be, so that a person on the 50th latitude is weightless?
- f) Perform the calculation of centrifugal acceleration in a more realistic model of the earth as an ellipsoid of revolution. What is the conclusion of the comparison with the result from e)?

### Solution to causes and models of latitude dependence of gravitational acceleration

a) The latitude dependence of gravitational acceleration has two causes:

Since the earth is not a sphere, but rather a flattened ellipsoid, the gravitational acceleration along a longitude is not constant. The gravitational acceleration increases with increasing latitude.

As the earth revolves around the earth's axis, centrifugal force acts as an inertial force on each body in the rotating reference system, in addition to gravitational force or centrifugal acceleration as inertial acceleration. These depend on the distance of the body from the axis of earth rotation and therefore decrease from a maximum value at the equator with increasing latitude to zero at the poles. Both causes work in the same direction, so that the gravitational acceleration at the equator is smaller than that at the poles.

b) Due to the spherically symmetric mass distribution,  $a_G$  and  $V$  depend only on the position on an  $r$ -axis passing through the center of the sphere. By integration over mass elements (see VII.2, pp. 71-73) or with Gauss's theorem you get  $a_G$ .  $V$  is obtained by integrating  $a_G$  with the boundary conditions  $V(\infty) = 0$  and the continuity of  $V$  at  $r = r_P$ :

$$a_G(r) = \begin{cases} \frac{Gm_E}{r^2} & \text{für } r < -r_P \\ -\frac{Gm_E}{r_P^3}r & \text{für } |r| \leq r_P \\ -\frac{Gm_E}{r^2} & \text{für } r > r_P \end{cases} \quad V(r) = \begin{cases} -\frac{Gm_E}{2r_P^3}(r^2 - 3r_P^2) & \text{für } |r| \leq r_P \\ -\frac{Gm_E}{r} & \text{für } |r| > r_P \end{cases}$$

It is  $a_G(r_P) = -9.857 \text{ m/s}^2$  and  $V(r_P) = -6.266 \cdot 10^7 \text{ J/kg}$ .

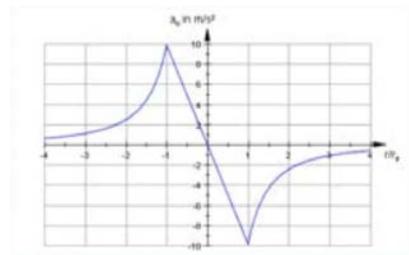


Fig. 10.14 Gravitational field strength of the earth

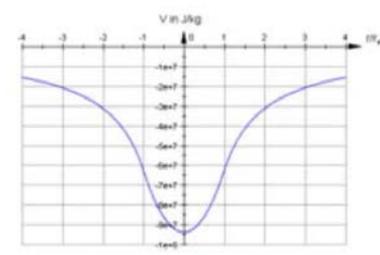


Fig 10.15 Gravitational potential of the earth

Due to the spherically symmetric mass distribution, the gravitational acceleration in each spatial point points to the center of the sphere. A latitude dependence is not available.

c) According to Newton, the mass  $M$  replaces the gravitational effect of the globe with radius  $r = r_p$ . The masses  $m_1$  and  $m_2$  should replace the gravitational effect of the beads. Since the beads are the same,  $m_1 = m_2 = m$ . The ellipsoid volume  $V_{\text{ellipsoid}}$ , the volume  $V_{\text{sphere}}$  of the sphere with radius  $r_p$  and the volume  $V_{\text{bead}}$  of a bead.

$$V_{\text{ellipsoid}} = (4/3) \pi r_A^2 r_p = 1.08324 \cdot 10^{21} \text{ m}^3$$

$$V_{\text{sphere}} = (4/3) \pi r_p^3 = 1.07598 \cdot 10^{21} \text{ m}^3$$

$$V_{\text{bead}} = (1/2) (V_{\text{ellipsoid}} - V_{\text{sphere}}) = 3.62993 \cdot 10^{18} \text{ m}^3$$

With the density  $\rho_E = m_E/V_{\text{ellipsoid}} = 5514.58 \text{ kg/m}^3$ , the masses  $M = 5.93358 \cdot 10^{24} \text{ kg}$  and  $m = 2.00175 \cdot 10^{19} \text{ kg}$  are obtained.

$$|a_{G,A}| = G \left( \frac{M}{r_A^2} + \frac{m}{(r_A - r_p)^2} + \frac{m}{(r_A + r_p)^2} \right) = 12,64 \frac{\text{m}}{\text{s}^2}$$

$$|a_{G,P}| = G \left( \frac{M}{r_p^2} + \sqrt{2} \frac{m}{(\sqrt{2}r_p)^2} \right) = \frac{G}{r_p^2} \left( M + \frac{m}{\sqrt{2}} \right) = 9,79 \frac{\text{m}}{\text{s}^2}$$

The acceleration directions point to the point mass  $M$ . The potentials result from summation of the individual potentials:

$$V_A = -G \left( \frac{M}{r_A} + \frac{m}{(r_A - r_p)} + \frac{m}{(r_A + r_p)} \right) = -6,234 \cdot 10^7 \frac{\text{J}}{\text{kg}}$$

$$V_P = -G \left( \frac{M}{r_p} + \frac{m}{\sqrt{2}r_p} + \frac{m}{\sqrt{2}r_p} \right) = -\frac{G}{r_p} (M + \sqrt{2}m) = -6,227 \cdot 10^7 \frac{\text{J}}{\text{kg}}$$

d) The model gives a constant  $a_G$  value along a widening circle due to the rotational symmetry about the Earth axis in accordance with the experiment. According to c),  $a_{G,A} > a_{G,P}$  is in contradiction to the experimental data for two reasons: The distance of the masses  $m$  from the mass  $M$  is chosen arbitrarily. The value  $a_{G,A}$  is too large, because, the earth density is not constant. The earth crust density of about  $2 - 3 \text{ g/cm}^3$  is only about half of the average earth density of  $5.5 \text{ g/cm}^3$ . Therefore, the mass and gravitational effect of the beads was calculated too large.

As in Fig. 6, the body is decomposed into infinitesimal mass elements  $dm = \rho(r) dV$  and sums up the contributions

$$d\vec{a}_G = G \frac{\vec{r} - \vec{r}'}{|\vec{r} - \vec{r}'|^3} dm$$

vectorially in point P

$$\vec{a}_G = G \int_V \frac{\rho(\vec{r})(\vec{r} - \vec{r}')}{|\vec{r} - \vec{r}'|^3} dV$$

Another way is the summation of the potentials with subsequent gradient formation.

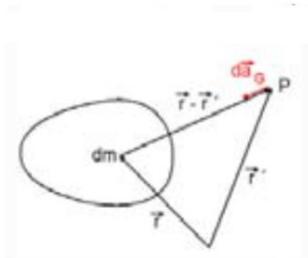


Fig. 10.16: Determination of gravitational acceleration

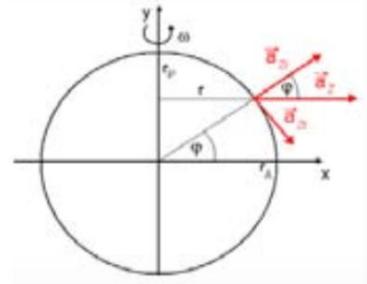


Fig. 10.17: Sketch for the calculation of  $a_{zr}$  for spherical earth.

e) The direction of the centrifugal acceleration  $a_z$  is always axial or perpendicular to the axis of rotation (Fig. 10.17). Only the proportion  $a_{zr}$  in the opposite direction to the gravitational acceleration contributes to the gravitational acceleration:

$$a_{zr} = \omega^2 r \cos \varphi = \omega^2 r_A \cos^2 \varphi$$

The maximum value  $\omega^2 r_A = 0.0337 \text{ m/s}^2$  is reached at the equator, and because of  $r = 0$   $a_{zr} = 0$  at the poles (Fig. 10.18).

For weightlessness,  $a_{zr} = g$ . This gives you:

$$\omega^2 = \frac{g}{r_A \cos^2 \varphi} \Leftrightarrow T = 2\pi \sqrt{\frac{r_A \cos^2 \varphi}{g}}$$

$$= 3256 \text{ s} = 54 \text{ min } 16 \text{ s} \approx 1 \text{ h}$$

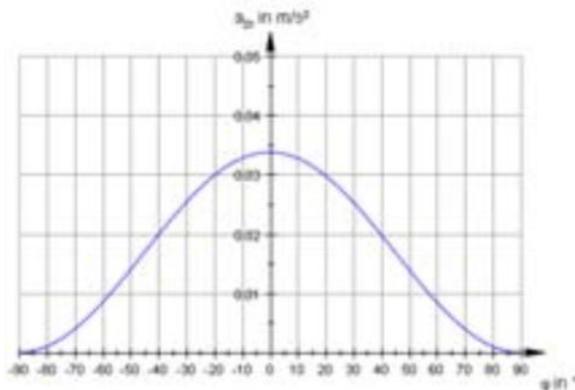


Fig. 10.18:  $a_{zr}(\varphi)$  for spherical earth.

f) In comparison to the model from a), the distance  $r$  of a point from the axis of rotation of the earth changes (Fig. 10.19). This can be calculated from the equation of function of an ellipse with the semiaxes  $a$  and  $b$ :

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = \frac{r^2}{r_A^2} + \frac{r^2 \tan^2 \varphi}{r_P^2} = 1 \Leftrightarrow r(\varphi) = \frac{r_P}{\sqrt{\left(\frac{r_P}{r_A}\right)^2 + \tan^2 \varphi}} \Leftrightarrow \left(\frac{r_A}{r}\right)^2 = 1 + \left(\frac{r_A}{r_P}\right)^2 \tan^2 \varphi$$

Assuming that the gravitational acceleration of the earth ellipsoid points to the midpoint  $M$  of the ellipsoid,  $a_{zr}$  can be calculated. However, radial and tangential components of the centrifuge acceleration  $a_z$  are no longer perpendicular to each other. The angle is obtained from the slope of the ellipse:

$$y'(x) = \frac{d}{dx} \left( b \sqrt{1 - \frac{x^2}{a^2}} \right) = -\frac{b}{a^2} \frac{x}{\sqrt{1 - \frac{x^2}{a^2}}} = \tan \alpha$$

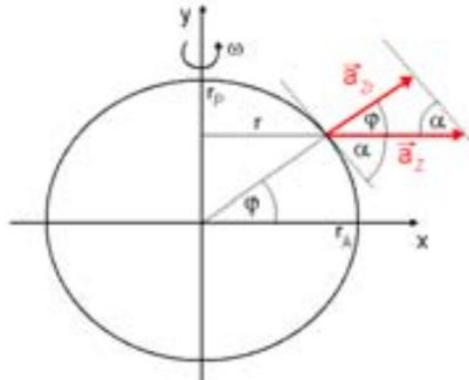


Fig.9: Sketch for the calculation of  $a_{zr}$  for an ellipsoidal Earth.

According to Fig. 10.19, one obtains in a triangle with the inner angles and:

$$\frac{a_{zr}}{\sin \alpha} = \frac{a_z}{\sin[180 - (\alpha + \varphi)]} \Rightarrow a_{zr}(\varphi) = \omega^2 r(\varphi) \frac{\sin \alpha(\varphi)}{\sin[\alpha(\varphi) + \varphi]}$$

The difference  $\Delta a_{zr}(\varphi) = a_{zr}(\text{spherical earth}) - a_{zr}(\text{ellipsoidal earth})$  is shown in Fig. 10.10. For the poles this is zero because of  $r = 0$  and for the equator because of  $r = r_p$  in the case of the spherical earth. Since  $\Delta a_{zr} < 0.0001 \text{ m/s}^2$ , the influence of the earth flattening on the centrifugal acceleration is negligible compared to that on the gravitational acceleration of about  $0.02 \text{ m/s}^2$ .

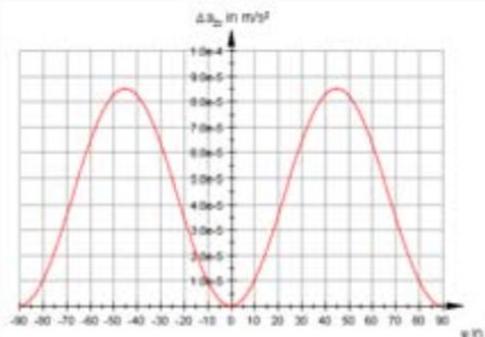


Fig. 10.20: Sketch for the calculation of  $a_{zr}$  for an ellipsoidal earth.

### Task for the deflection mechanism of the pendulum

To bring the pendulum with an electromagnet to an initial deflection angle desired by the experimenter, the current horizontal deflection  $a_K$  of the ball of the pendulum must be known. This is determined from the dark time  $t_D$  during passage of the ball center through the laser beam of the light barrier:

- 1.1. Derive a formula for the calculation of  $a_K$  from  $t_D$ . Calculate the deflection angle, the speed of the center of the sphere at zero angle and the dark time for  $a_{K, \min} = 5 \text{ cm}$  and  $a_{K, \max} = 50 \text{ cm}$ .
- 1.2. Match the formula so that  $a_K$  becomes  $\sim 1/t_D$  and check if the deviation is less than 5 mm.

### Solution to the deflection mechanism of the pendulum

a) The horizontal deflection  $a_K$  (Fig. 10.21) is calculated in the physical pendulum model from the dark time  $t_D$  with the law of conservation of energy (transformation of potential energy into rotational energy):

$$E_{\text{pot}} = E_{\text{rot}} \quad \Leftrightarrow \quad m g h = \left(\frac{1}{2}\right) J \omega^2$$

Taking into account that the velocity of the center of the sphere does not coincide with that of the center of gravity of the pendulum, Fig. 10.21 uses the theorem of Pythagoras, the set of rays and the conversion between orbit and angular velocity, to extract

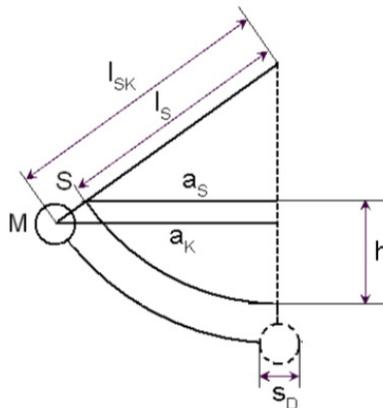


Fig. 10.21 Sketch for the calculation of the relationship between the horizontal deflection  $a_K$  and the dark time  $t_D$

$$h = l_s - \sqrt{l_s^2 - a_s^2} \quad \frac{a_s}{a_K} = \frac{l_s}{l_{SK}} \quad \omega = \frac{l_s}{v_s} = \frac{l_{SK}}{v_K}.$$

Inserting the formulas into the energy approach and solving the root equation for  $v_K$  yields:

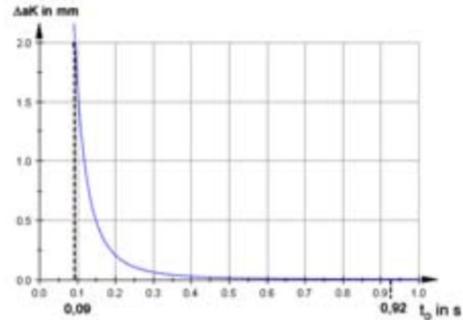


Fig. 10.22: Difference  $\Delta a_K$  between approximate and approximate calculation of  $a_K(t_D)$ .

$$v_K = \sqrt{\frac{2mgl_s^2}{J} \left( l_s - \sqrt{l_s^2 - a_K^2 \frac{l_s^2}{l_{SK}^2}} \right)} = \sqrt{\frac{2mgl_s^3}{J} \left( 1 - \sqrt{1 - \frac{a_K^2}{l_{SK}^2}} \right)}$$

The approximate calculation of the instantaneous velocity  $v_K$  from the average velocity yields  $a_K(t_D)$ :

$$v_K \approx \frac{s_D}{t_D} \quad a_K(t_D) = l_{SK} \sqrt{\frac{Js_D^2}{mgl_s^3 t_D^2} - \left( \frac{Js_D^2}{2mgl_s^3 t_D^2} \right)^2}$$

With  $s_D = 2 r_K$  and  $\alpha = \arctan(a_K/l_{SK})$  one obtains the following table:

Horizontal initial deflection $a$	Angle of deflection $\alpha$	Speed $v_K$	Dark time $t_D$
$a_{K,\min} = 5 \text{ cm}$	$\alpha_{0,\min} = 1.06^\circ$	$v_{K,\min} = 9.3 \text{ cm/s}$	$t_{D,\max} = 0.92 \text{ s}$
$a_{K,\max} = 50 \text{ cm}$	$\alpha_{0,\max} = 10.67^\circ$	$v_{K,\max} = 95.8 \text{ cm/s}$	$t_{D,\min} = 0.09 \text{ s}$

b) With  $s_D = 2 r_K$  and  $e = (4J r_K^2) / (m g l_s^3)$  one gets

$$a_K(t_D) = l_{SK} \sqrt{\frac{e}{t_D^2} - \left( \frac{e}{2t_D^2} \right)^2} \approx l_{SK} \frac{\sqrt{e}}{t_D}$$

Fig. 10.22 shows that the deviation  $\Delta a_K$  for  $t_D \in [0.09 \text{ s}; 0.92 \text{ s}]$  is less than 2 mm.

### Task to change the length of the wire during the pendulum motion

- a) Using the assumption of a rigid wire, derive a formula  $v_s(\alpha, \alpha_0, g, l_s)$  for the calculation of the velocity of the center of gravity of the pendulum as it passes through the position of angle  $\alpha$  equal zero.
- b) Which forces can lead to a change in length of the elastic wire during the pendulum movement? Calculate the forces as a function of the parameters  $\alpha_0, m$  and  $g$  assuming the ball mass  $m_K \approx$  pendulum mass  $m$ .
- c) Calculate the change in length  $\Delta l_D = l - l_D$ , where  $l_D$  is the wire length of the suspended and stationary pendulum. Plot  $\Delta l_D(\alpha)$  for  $\alpha = 10^\circ$  and explain the result qualitatively.

### Solution for changing the length of the wire during oscillation

- a) The center-of-mass velocity  $v_s$  is determined by the energy conservation law (decrease of the potential energy equal to increase of the rotational energy) neglecting the friction:

$$m g h_0 - m g h = \left(\frac{1}{2}\right) J \omega^2$$

With the relation to the conversion from angular to center-of-mass velocity, the approximation that the pendulum mass is concentrated in the center of gravity and geometrical relations (Fig. 10.23) we obtain:

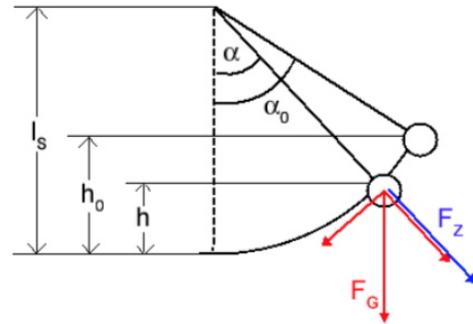
$$\omega = \frac{v_s}{l_s} \quad J \approx m l_s^2 \quad h = l_s(1 - \cos \alpha) \quad h_0 = l_s(1 - \cos \alpha_0)$$

This gives you

$$v^2 = 2 g l_s (\cos \alpha - \cos \alpha_0).$$

b) The radial component  $F_{G,r}$  of the static weight force  $F_G$  and the centripetal force  $F_Z$  result in a change in length  $\Delta l$  of the wire due to the finite elastic modulus  $E_D$ .

Neglecting the weight of the wire and the fact that the weight of the suspension is supported by the wall bracket, Fig. 10.23 shows



**Fig. 10.23: Sketch for calculating the speed of the center of gravity**

$$F_{G,r} = m_K g \cos \alpha \quad \text{for } |\alpha| \leq 90^\circ.$$

$F_Z$ : Substituting the result from a) in the formula for the centrifugal force shows that the centrifugal force is independent of  $l_S$ :

$$F_Z = m v_S^2 = 2 m g (\cos \alpha - \cos \alpha_0)$$

The total force  $F$  is calculated using the approximation  $m_K \approx m$

$$F = F_{G,r} + F_Z \approx m g \cos \alpha + 2 m g (\cos \alpha - \cos \alpha_0) = 3 m g \cos \alpha - 2 m g \cos \alpha_0.$$

c) The length  $l$  and length change  $\Delta l$  of a wire under load can be calculated according to Hooke's law from the length  $l_0$  of the unloaded wire:

$$\sigma = \varepsilon E_D \Leftrightarrow \frac{F}{A_D} = \frac{l - l_0}{l_0} E_D \Leftrightarrow l = l_0 \left( 1 + \frac{F}{E_D A_D} \right) \Leftrightarrow \Delta l = l - l_0 = l_0 \frac{F}{E_D A_D}$$

In our case, the length  $l$  of the wire is, when applying the force  $F$  with  $b = m g / E_D A_D$

$$l = l_0 \left( 1 + \frac{3 m g \cos \alpha - 2 m g \cos \alpha_0}{E_D A_D} \right) = l_0 (1 + 3 b \cos \alpha - 2 b \cos \alpha_0).$$

The length  $l_0$  of the unloaded wire can be calculated from the length  $l_D$  of the wire measured under load:

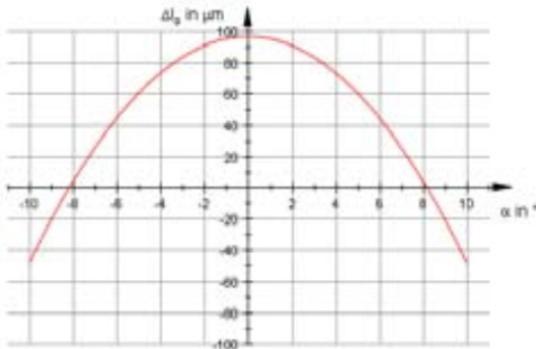
$$l_D - l_0 = l_0 \cdot \frac{mg}{E_D A_D} \Leftrightarrow l_0 = \frac{l_D}{1+b}.$$

The change in length  $\Delta l_D$  of the wire relative to the measured under load length  $l_D$  of the wire

$$\Delta l_D(\alpha, \alpha_0) = l - l_D = \frac{l_D}{1+b} (1 + 3b \cos \alpha - 2b \cos \alpha_0) - l_D = l_D \frac{b}{1+b} (3 \cos \alpha - 2 \cos \alpha_0 - 1).$$

According to the diagram (Fig. 10.24), the length of the pendulum fluctuates by approx.  $150 \mu\text{m} = 0.15 \text{ mm}$  during the oscillation movement for  $\alpha = 10^\circ$ . The existence of a  $l = l_D$  at  $\alpha_0 = \pm 8^\circ$  can be qualitatively explained:

If  $\alpha = 0^\circ$ , the change in length  $\Delta l_D = l - l_D > 0$ , in addition to the force  $F_{G,r} = mg$ , which stretches the wire to  $l = l_D$ , also affects the maximum force  $F_Z$  ( $v_S$  maximum). If  $\alpha = \pm \alpha_0$ , the change in length is  $\Delta l_D = l - l_D < 0$ , where  $F_Z = 0$  ( $v_S = 0$ ) and  $F_{G,r} < mg$ .



**Fig. 10.24:** Length change of the wire as a function of the deflection angle for  $\alpha_0 = 10^\circ$

## 10.5 Literature

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# 11 Semiconductor characteristics and oscilloscope

When designing, building, testing and using the RCL's semiconductor characteristics, we realized that this RCL can only be meaningfully used experimentally if one masters the handling of the oscilloscope instrument, such as voltage and time measurement. For this reason, we have designed and built a self-contained RCL oscilloscope that closes this gap. In the following chapter, both RCLs are linked or displayed serially.

## 11.1 Introduction

The significance of the oscilloscope in physics teaching as a basic measuring device or during student lab is well known and indisputable. Characteristics of semiconductors are only exemplarily demonstrated in physics lessons, if at all. The importance of this topic in everyday life can be seen in typical technical applications, but more than a black box method without wanting to / have to understand details.

The semiconductor components we use here are typical for everyday use:

- Rectifier of AC voltage in power supplies and controllable rectifiers,
- Switch and protection against overvoltage e.g. in high-frequency engineering,
- Protection against incorrect polarity,
- Voltage limiters,
- Signal generator and receiver, e.g. in the case of light barriers and remote controls,
- Voltage stabilizers,
- Protective diodes,

- Amplifiers,
- Control and switching in integrated circuits especially with minimal power consumption,
- Lossless current regulator,
- and many more.

As the current physics classes are still not integrated with enough technical and everyday applications and the basics of solid state physics are hardly provided, we see the use of both RCLs more in self-study, in the completion of an electronics student lab and in dealing with an oscilloscope. Alternatives in physics lessons are the well-known electronic kits of the teaching materials industry [1] as well as tutorials with simulation programs for learning the mode of operation and the fields of application of an oscilloscope [2, 3].

Why both topics are hardly implemented in real class?

- Mostly only 1-2 oscilloscopes are in a collection of physics apparatus; student lab is not possible.
- Learning to operate an oscilloscope is not an essential learning objective, since one can do without this knowledge except for a few professions.
- In order to understand the mode of action of these semiconductor components used here, the basics of semiconductor physics and solid state physics are needed; which is usually not or only optionally taught in the upper classes at gymnasium level.
- The handling of an oscilloscope today is so user-friendly prepared by the manufacturer, therefore one comes to the margins of the few uses.
- If one actually need a characteristic curve of an electronic component, one will now find it quickly on the internet (see also RCL menu item Materials).
- Measuring semiconductor characteristics with a multi meter is lengthy because it takes many readings to detect or qualitatively analyze these characteristics (e.g. working point).

From this perspective, it is not surprising that the majority of physics teachers in postgraduate training courses on RCLs consider it a very good idea to realize both the oscilloscope and the semiconductor characteristics as RCL, in parallel to possible on-site real-world experiments.

## 11.2 Experiment and RCL variant

### 11.2.1 RCL Oscilloscope (in short)

The experimental setup of the RCLs oscilloscope (Fig. 11.1, 11.2) consists of the two components:

- Oscilloscope (digital, because of the control via the interface),
- Frequency generator (integrated in the interface).

The frequency generator supplies three periodic voltages  $U_1(t)$ ,  $U_2(t)$ ,  $U_3(t)$  of different frequencies, which can be determined and evaluated. The oscilloscope makes the time dependence of these voltages  $U(t)$  visible. The screen of the oscilloscope is displayed to the experimenter using a webcam in the browser.

The menu point *Theory* describes the experimental set up and operation of a Braun tube and the experimental set up and function of an oscilloscope such e.g. the deflection and trigger function. The controls of the oscilloscope are described in detail: the front view of the oscilloscope used here is shown and all the buttons required here are displayed and their function explained (power, x position, y position, y amplification, time base, triggering). In addition, the oscilloscope screen and its displays are discussed. The menu point *Tasks* contains a proposal for several measurements. The menu point *Laboratory* shows on the left the webcam image of the oscilloscope screen and on the right the control panel (Fig. 11.3).

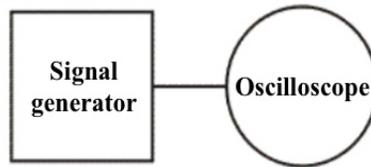


Figure 11.1: Basic experimental setup of the RCL oscilloscope.

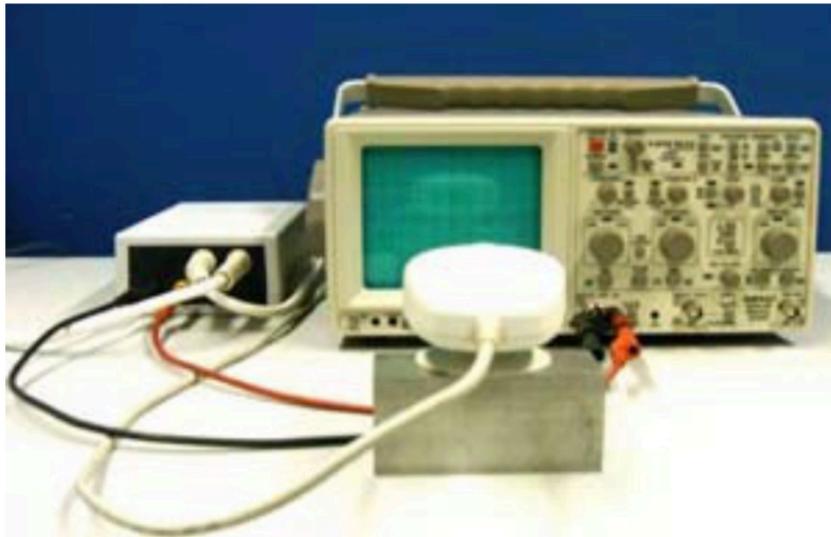
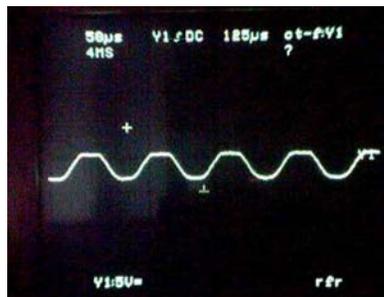


Figure 11.2: Experimental setup of the RCL.



Oscilloscope is switched on automatically. It needs a few seconds for booting.

Oscilloscope screenshot



Operation of oscilloscope: move mouse pointer on active control element (mouse pointer changes into a hand). Click on upper/lower part of control element.

Selection of signal



Figure 11.3: Laboratory webpage.

In the menu point *Analysis*, the task (see menu point) is executed as an example for signal 2.

### 1. Amplitude of the AC voltage

The amplitude here is called the maximum deflection of an oscillation or here the maximum voltage difference of the periodic voltage. To determine the amplitude  $A$ , one measures the peak-to-peak value in the time course of the voltage, i.e. the vertical distance between minimum and maximum of the curve. By measuring the distance we obtain  $2 \cdot A = 3.6 \text{ V}$  (Fig. 11.4).

It should be noted that in this example the scale (volts / div.) is 1 volt / unit and one unit is the box size of  $1 \times 1 \text{ cm}^2$ . For the amplitude  $A = 1.8 \text{ V}$  is obtained. The measurement inaccuracy of approximately 1 mm and the device error of 3% contribute to the inaccuracy of the measurement (see data sheet under Material). Thus,  $\Delta A = 2 \cdot (1.8 \text{ V} \cdot 0.03 + 0.1 \text{ V}) = 0.3 \text{ V}$ . Factor 2 takes into account that both reading at the minimum and reading at the maximum will cause an error. Overall, one can specify the amplitude of the periodic voltage with  $A = (1.8 \pm 0.3) \text{ V}$ . It indicates the peak value of the AC voltage, i.e.  $U = (1.8 \pm 0.3) \text{ V}$ .

### 2. Duration of a period and frequency of the AC voltage

The period of an oscillation is the minimum time interval in which the oscillation - here the voltage curve  $U(t)$  - is again in the same state of the oscillation; in other words in the same phase. To determine the duration of the period, one first measures the length of a period on the horizontal time axis (Fig. 11.5).

One reads  $L_T = 5.4 \text{ cm}$ . The time/div display on the screen shows that one unit corresponds to  $20 \mu\text{s}$ . This yields for the period  $T = 5.4 \text{ cm} \cdot 20 \mu\text{s}/\text{cm} = 108 \text{ microseconds}$ . For the accuracy of the measurement, the reading inaccuracy of approximately 1 mm and the measuring error of 2% of the oscilloscope (see data sheet under Material) contribute both. Thus,  $\Delta T = 2 (108 \mu\text{s} \cdot 0.02 + 0.1 \text{ cm} \cdot 20 \mu\text{s}/\text{cm}) = 8 \mu\text{s}$ . Again, the factor 2 takes into account that one makes an error when reading on both sides. Overall, the period of the voltage  $T = (108 \pm 8) \mu\text{s}$  and  $\Delta T/T = 7\%$ .

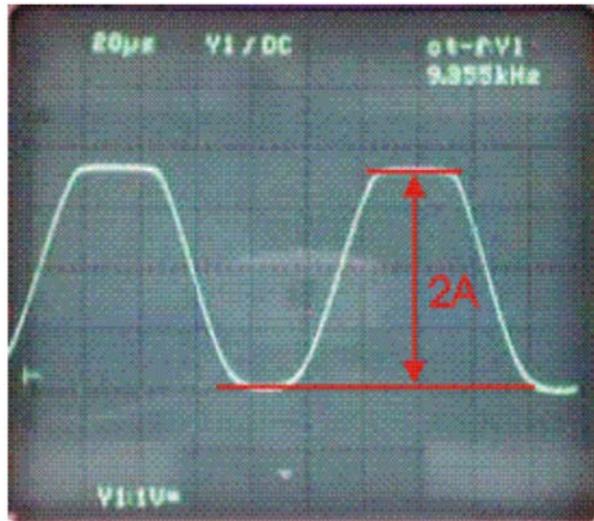


Figure 11.4: Determination of the amplitude

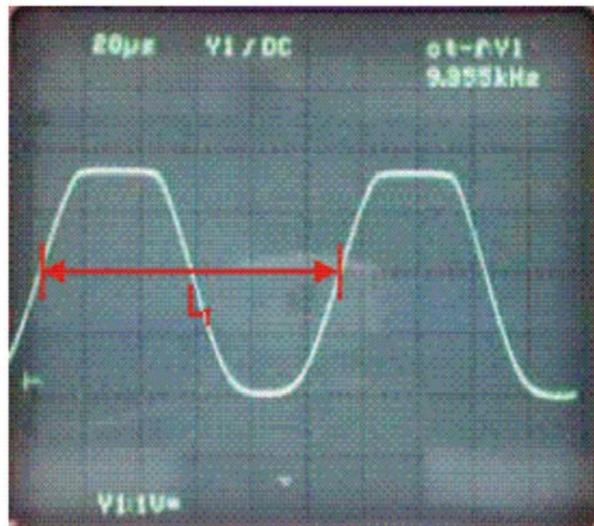


Figure 11.5: Determination of the period.

The frequency  $f$  of the voltage is  $f = 1/T = 9.3$  kHz. The error of the frequency can be calculated with the relative error of the period to  $\Delta f = 9.3$  kHz  $\cdot$  0.07 = 0.7 kHz. Thus, the frequency runs up to  $f = (9.3 \pm 0.7)$  kHz. The frequency calculated from the measured period deviates

by approximately 1% from the frequency indicated on the top right of the oscilloscope screen.

### 3. Offset of the AC voltage

To determine the offset, the symbol  generated by the oscilloscope must be visible at the bottom of the screen. This symbol indicates the position of the voltage value 0 V (see theory). First, one measures vertically the distance between this symbol and the minimum of the voltage (see Figure 11.6). It is  $U_0 = (2.0 \pm 0.3) \text{ V}$ . The procedure is analogous to the amplitude determination. Add to  $U_0$  the amplitude, i.e. the peak value of the AC voltage, we obtain the offset voltage  $U_{\text{Offset}} = U_0 + U = 2\text{V} + 1.8\text{V} = 3.8\text{V}$ . To calculate the error of  $U_{\text{Offset}}$ , the errors of  $U_0$  and  $U$  are added. This gives  $\Delta U_{\text{Offset}} = \Delta U_0 + \Delta U = 0.3 \text{ V} + 0.3 \text{ V} = 0.6 \text{ V}$ . Thus, the offset of the indicated voltage  $U_{\text{Offset}} = (3.8 \pm 0.6) \text{ V}$ . This offset is in the AC mode of the Oscilloscope (see theory) not shown.

The menu point *Discussion* provides comprehension questions about the experimental set up, the theory, the laboratory and the analysis. The menu point *Material* refers to manuals of the oscilloscope and to the frequency generator in the interface; a didactic analysis completes this RCL with hints for physics teachers.

## 11.2.2 RCL Semiconductor Characteristics

### Experimental setup and function

The experimental setup for the RCL U-I characteristics of semiconductor devices consist of the following components (Fig. 11.7, 11.8):

- Modules with the semiconductor components for selection on a rotatable disk,
- Oscilloscope for displaying the characteristic curves,
- Multi meter for indicating voltages and currents with various characteristics,
- Voltage source (integrated in the interface).

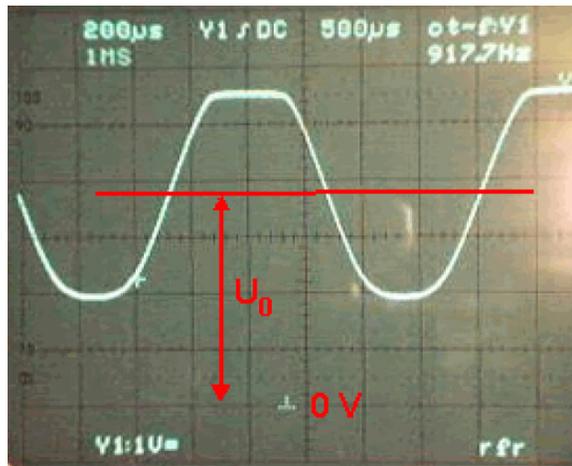


Figure 11.6: Determination of the off-set of voltage.

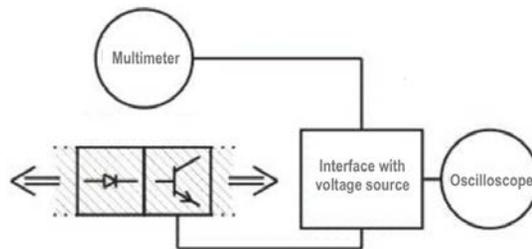


Figure 11.7: Sketch of the experimental setup.

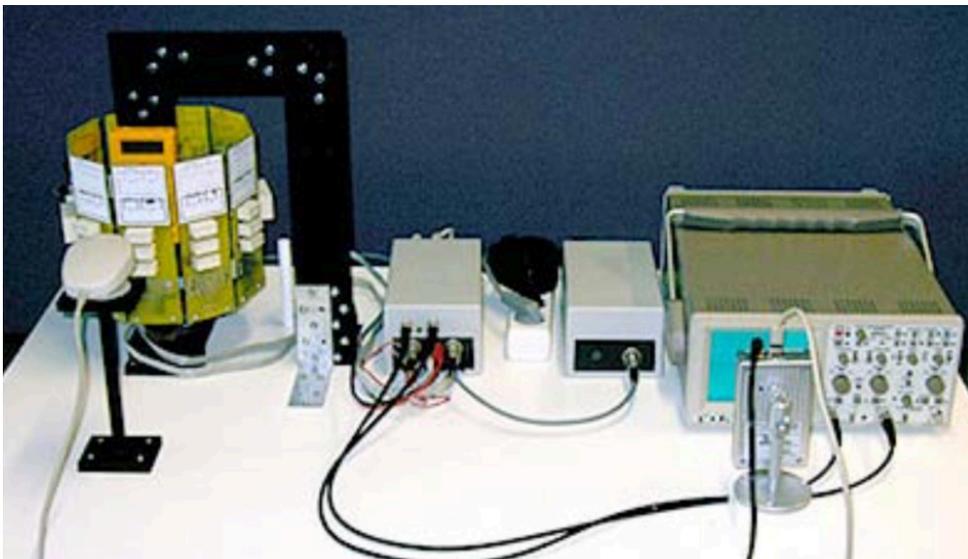


Figure 11.8: Photo of the experimental setup (arranged as in Fig. 11.7).

For observation by the user two webcams are needed; one to display the oscilloscope screen and a second to view the selected circuit and transmit the multi meter display. The following semiconductor components are available for measuring characteristic curves:

- Diode (1N4448),
- LED (TLLR4400),
- Schottky diode (SB340),
- Zener diode (ZPD2,7),
- Transistor (npn) (BC546):
  - input characteristic  $I_B (U_{BE})$ ,
  - output characteristic  $I_C (U_{CE})$ ,
  - current control characteristic  $I_C (I_B)$ ,
- MOSFET (n-channel enhancement type) (BUZ21):
  - Transfer characteristic  $I_D (U_{GS})$ ,
  - Output characteristic  $I_D (U_{DS})$ ,
- Thyristor (cathode-side controlled p-gate thyristor) (TIC106M).

In the menu point *Material* one will find further details about these components including data sheets.

### Navigation menu

The menu point *Experimental set up* is followed by *Theory*. Under fundamentals we describe the formation of energy bands in solids, especially in semiconductors; then the n-type doping and the p-type doping are explained; finally the p-n transition is explained for the case of the reverse direction and forward direction. Below is a brief description of the 7 components used here.

**Diode** A diode consists of a p-n junction (Figure 11.9).



Figure 11.9: Circuit diagram and structure of a diode.

If the diode is switched in the reverse direction (plus pole to n-layer and minus pole to p-layer), it will not conduct, as long as a certain voltage is not exceeded (destruction of the diode). If the plus pole is connected to the p-layer and the minus pole to the n-layer (forward direction), the diode becomes conductive from a certain voltage (forward voltage  $U_{DI}$ ) (Fig. 11.10).

Because of this behaviour, diodes find application in almost every electronic device (e.g. power supply units, alternator in the car).

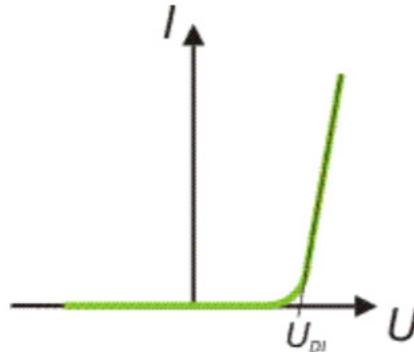


Figure 11.10: Characteristic of a diode.

They will be used as rectifier of AC voltages (Graetz circuit), switch, protection against reverse polarity and voltage limiter.

**Light-emitting diode** Like the diode, a light-emitting diode consists of a p-n junction (Fig. 11.11).



Figure 11.11: Circuit diagram and structure of a light-emitting diode.

The recombination of the electrons with the holes in the p-region releases energy. This is emitted, inter alia, in the form of light of a specific wavelength. Since the p-layer is very thin here, this light can penetrate to the outside. The LED lights up. An example of using LEDs is a display of some digital alarm clocks. Further LEDs are used as signal transmitter of light barriers and infrared LEDs as signal transmitter in remote controls units.

**Schottky diode** The Schottky diode consists of a metal-semiconductor junction (here: metal-n junction, Fig. 11.12).



Figure 11.12: Circuit diagram and structure of a Schottky diode.

The behaviour of electrons corresponds to that in a diode. They diffuse at the boundary region from the n-layer into the metal. As a result, the metal is locally negatively charged and the n-layer locally positively charged. A depletion zone (Schottky barrier) forms in the n-layer. The behaviour, when applying a voltage, corresponds to that of a diode. The current flow takes place in the Schottky diode only by electrons. Therefore, no electric fields are formed as in the diode between electrons and holes, which would first have to be removed. This has the consequence that a Schottky diode has a lower forward voltage  $U_{D1}$  and shorter switching times than a diode. It is therefore used mainly as a rectifier and protection against overvoltage in high-frequency technology, as well as a rectifier in power supplies with low voltage.

**Zener diode** The Zener diode is named after the American physicist Clarence Melvin Zener (Figure 11.13).



Figure 11.13: Circuit diagram of a Zener diode (Z- diode).

To understand how a Zener diode works, one need to be more specific about the diode's barrier region. Previously, it was said that a reverse-connected diode would not conduct a current. However, by thermal excitation, electrons from the space-charge zone of the p-region return to the n-region, where they are accelerated towards the plus-pole (reverse direction: plus-pole at n-layer). So it always flows a very small current in the reverse direction (reverse current  $I_S$ ). If the reverse voltage  $U_S$  is increased and reaches a certain value (breakdown voltage  $U_{Db}$ ), the reverse current grows abruptly (Fig. 11.14).

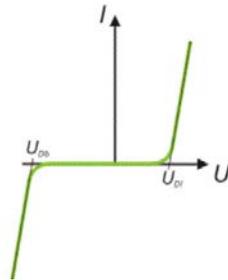


Figure 11.14: Characteristic of a Z-diode.

This is described by two effects.

#### 1. Zener effect

The barrier voltage  $U_S$  also increases the electric field strength in the barrier layer. In the band model, this means that the valence and conduction band are shifted against each other. If the upper edge of the valence band in the p-region is higher than the lower edge of the conduction band in the n-region, electrons can pass from the valence band of the p-region through the now very narrow forbidden zone into the conduction band of the n-region (Tunnel effect). There, the electrons are accelerated to the plus pole (see Fig.11.15).

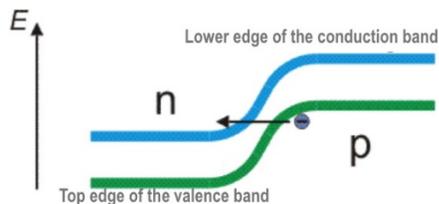


Figure 11.15: Zener effect in the band model.

#### 2. Avalanche effect

Raising the barrier voltage  $U_S$  increases the kinetic energy of the electrons, which are responsible for the reverse current  $I_S$ . If the energy of the electrons is sufficiently large, they eject bound electrons from the valence band and lift them into the conduction band, where they are accelerated to the plus pole. These electrons, which are lifted into the conduction band, in turn reach again high kinetic energies, so that they can lift further electrons from the valence into the conduction band (avalanche effect). These two effects cause a diode to become conductive even in the reverse direction after a certain voltage.

The size of the breakdown voltage, that is to say the voltage from which the Zener effect and avalanche effect cause a current in reverse direction, depends on the doping. For a normal diode, the breakdown voltage is about 50 to well over 1000 volts. A Zener diode is doped so high that the breakdown voltage is less than 5 volts depending on the amount of doping. Z-diodes are used primarily as voltage stabilizers. Here, Zener diodes are operated in the reverse direction and it is exploited the steep increase in current with hardly changing voltage in the breakdown point. As such, they are built into power supplies of any electrical device. Furthermore, Zener diodes are used as protection diodes in measuring circuits and as voltage limiters.

**Transistor** The first functioning bipolar transistor was introduced by Bell Laboratories in 1947 (Fig. 11.16).

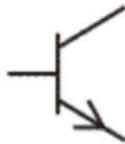


Figure 11.16: Circuit diagram of an npn transistor.

A transistor consists of three semiconductor layers. Here the npn type used in the RCL experiment is described. The description of the pnp transistor is phenomenologically analogous. An n-layer is followed by a p-layer and again by an n-layer. Because both n- and p-layers occur here, this element is called a bipolar transistor (Figure 11.17).

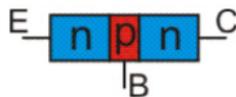


Figure 11.17: Structure of an npn transistor.

Each layer has an electrode. These are called emitter (E), base (B) and collector (C). If a voltage is applied between the emitter and the collector, then regardless of the polarity, one of the two p-n junctions is always switched in the reverse direction so that no current flows. By applying a voltage to the base, the emitter-collector path can be

brought into a conducting state. A transistor thus represents an electronic switch.

If at the emitter the negative and at the collector the positive pole of a voltage is applied, then blocks the p-n junction between base and collector. If in addition, a voltage is applied between emitter and base in such a way, that the positive pole is at the base, a current flows between emitter and base. Since the p-region here is very thin and poorly doped, only a few electrons can recombine with holes in the p-region. They diffuse through the p-region and are attracted by the collector, which is at positive potential. Thus, a current flows between emitter and collector, although base and collector are reverse-connected (Fig. 11.18 and 11.19).

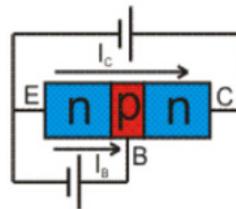


Figure 11.18: Emitter circuit of an npn transistor.

For a given voltage between emitter and collector, the collector current  $I_C$  (current through emitter-collector path) can thus be regulated by a much lower base current  $I_B$  (current through emitter-base path). With this property, a transistor is used as a switch, for example, in logic circuits (computer chips), for feedback coupling in the resonant circuit of a radio and as an amplifier of electrical currents (power of control current less than working current).

The switching characteristic of a transistor can be understood from the input and output characteristics (Figure 11.19):

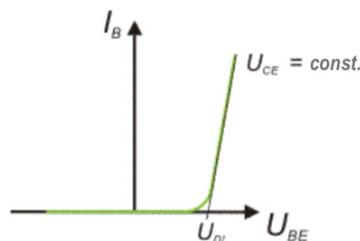


Figure 11.19: Input characteristic of a transistor.

In the input characteristic, the base current  $I_B$  is plotted as a function of  $U_{BE}$  (at constant voltage  $U_{CE}$ ). The characteristic illustrates that the emitter-base region of the transistor represents a diode. Thus, the transistor switches from a certain voltage  $U_{DI}$  between emitter and base.

In the output characteristic, the collector current  $I_C$  is plotted in the direction of  $U_{CE}$  (with constant base current  $I_B$ ) (Fig. 11.20).

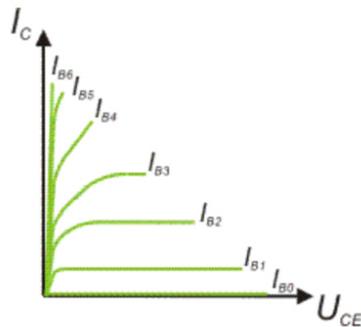


Figure 11.20: Output characteristic of a transistor.

By increasing the base current  $I_B$ , the output characteristic is shifted in the  $+I_C$  direction. If one draws several output characteristics to different  $I_B$  (parameter of the output characteristic) into a coordinate system, a so-called characteristic field results (Fig. 11.21)

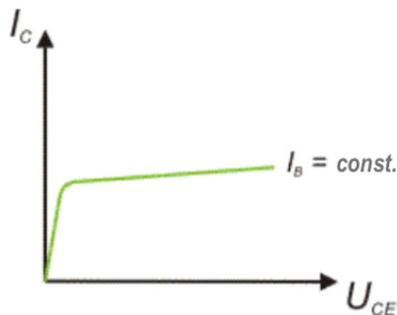


Figure 11.21: Output characteristic field.

If a transistor is in the barrier state ( $U_{BE} = 0$  V or  $I_B = 0$  A), then  $I_C$  is also equal to zero. Thus, almost the entire voltage of the voltage source drops across it, i.e.  $U_{CE}$  will be in a maximum. If a transistor is fully conductive ( $U_{BE} \gg U_{DI}$ ), then the current ( $I_C$ ) flowing through it is

maximum, but the voltage ( $U_{CE}$ ), that drops across it, is almost zero. These two states can also be drawn into the characteristic field and linked together by a straight line (Fig. 11.22).

The straight line is called a working line. The intersections of the working line with the individual characteristics are called working points. The working point of an electronic component is not fixed, but is individually determined by appropriate selection of the remaining components (eg resistances), depending on the requirement or intended use. For example, if a transistor is used to amplify currents, the working point is placed in the linearly increasing range.

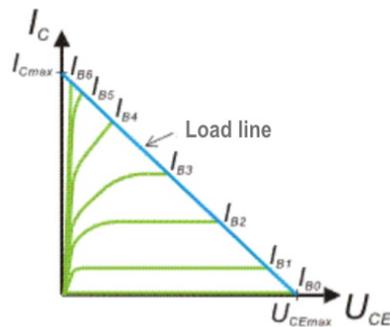


Figure 11.22: Working line in the output characteristic field.

The amplification effect of a transistor can be illustrated by the so-called current control characteristic. The collector current  $I_C$  is plotted as a function of  $I_B$ . It can be seen that a small base current causes a large collector current (Fig. 11.23).

The slope of the current control characteristic gives the current gain factor  $B$  of the transistor.

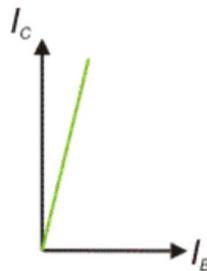


Figure 11.23: Linear gain range of the transistor (current control characteristic).

**MOSFET** MOSFET stands for Metal Oxide Semiconductor Field Effect Transistor. It represents a special variant of the family of field-effect transistors which, in contrast to bipolar transistors, control the flow of current by means of electric fields instead of currents.

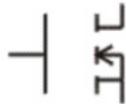


Figure 11.24: Circuit diagram of a MOSFET.

The description of the MOSFET here refers to the used n-channel enhancement type. A MOSFET consists of a p-doped semiconductor crystal (substrate), into which two n-doped regions are integrated. Since the MOSFET (general FETs) has only one (main) semiconductor region (p-region), it is called an unipolar transistors.

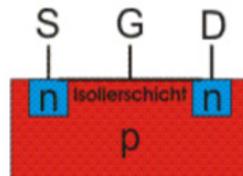


Figure 11.25: Structure of a MOSFET.

Both the n-regions and the p-region are connected to electrodes. These are called source (S), gate (G) and drain (D). Between the gate and the substrate is an insulating layer. No matter which polarity has a voltage between source and drain, the MOSFET is always in a barrier state (self-blocking). It is now possible to apply a voltage between source and drain so that the negative pole is at the source and the plus pole at the drain, and between the source and the gate such that the gate is connected to the plus pole. This attracts the electrons of the p-type region to the gate, where they collect below an insulating layer. The result is a connection of electrons (bridge) between source and drain. Since the drain is at the positive potential, the electrons are attracted to it and a current is flowing between source and drain.

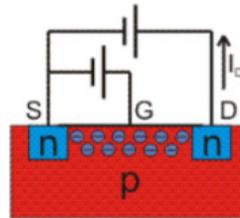


Figure 11.26: How a MOSFET works.

A MOSFET thus controls the drain current  $I_D$  (current through source and drain) by an electric field between the source and gate.

Due to this property, a MOSFET is used as a switch in integrated circuits because it does not require any power to control (no current flow between S and G but only an electric field). Further, MOSFETs are used in DC-DC solid state relays and audio power amplifiers.

The course of the transfer (also called input characteristic) and of the output characteristics of the MOSFETs corresponds to those of a bipolar transistor.

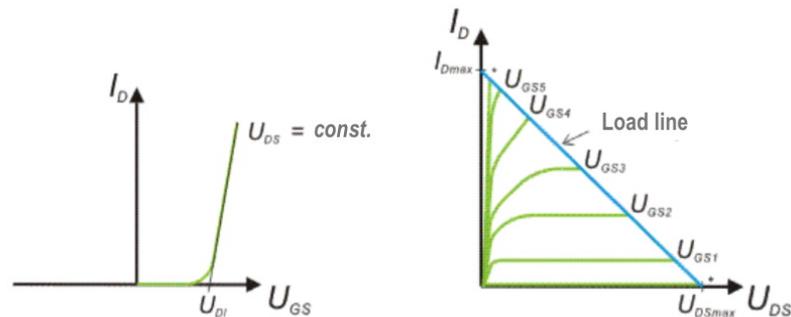


Figure 11.27: Transfer characteristic (left) and output characteristic field (right) of a MOSFET.

In contrast to the bipolar transistor, the transfer characteristic of the MOSFET shows the drain current as a function of  $U_{GS}$ . This results from the fact that no gate current flows in the MOSFET, since field effect transistors—as explained above—are controlled only by an electric field. Therefore, no current-control characteristic can be recorded. With the same reason, the parameter of the characteristic curves in the output characteristic field is  $U_{GS}$ .

**Thyristor** The first thyristors were developed in 1957 by General Electric in the USA.

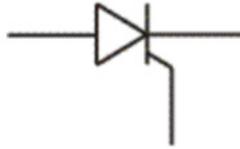


Figure 11.28: Circuit diagram of a thyristor.

A thyristor consists of four semiconductor layers. Here, the cathode-side controlled p-gate thyristor, used in this experiment, will be described. The description of the anode-side controlled n-gate thyristor is phenomenologically analogous. An n-p junction is followed by another n-p junction.

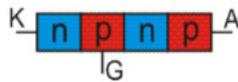


Figure 11.29: Structure of a thyristor.

The electrode on the outer n-layer is referred to as the cathode (K), the middle p-layer as the gate (G), and the one on the outer p-layer as the anode (A). The thyristor distinguishes between two types of poling. In the polarity in forward direction the negative pole of the voltage is located at the cathode and the positive pole at the anode. In this polarity, the middle p-n junction blocks. In the reverse direction, a thyristor is connected in such a way, that the plus pole of the voltage is located at the cathode and the negative pole at the anode. Now the two outer n-p transitions are blocking. The thyristor is now poled in the forward direction. If there is no voltage at the gate, the thyristor ignites, i.e. it conducts only from a very high voltage (breakthrough in the middle p-n junction: see section Z-diode). By applying a gate voltage (positive pole to gate) and a given voltage between cathode and anode, the ignition of the thyristor, i.e. the (zero-tilt) switching voltage  $U_S$  is controlled. As in the case of the transistor, electrons enter the middle p-layer, through which they diffuse, and then are accelerated towards the anode.

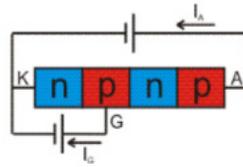


Figure 11.30: Operation of a thyristor in the forward direction.

If the thyristor has ignited, it represents a diode that conducts or blocks depending on the polarity (forward or reverse direction). Only when the anode current  $I_A$  drops below a certain value (the so-called holding current  $I_H$ ) (this happens inter alia when the polarity is reversed) a new barrier layer is formed in the middle p-n junction and the thyristor must be re-ignited.

With this property the thyristor is used as a controllable rectifier in semiconductor relays for AC voltage and as a lossless current regulator (e.g. in drilling machines).

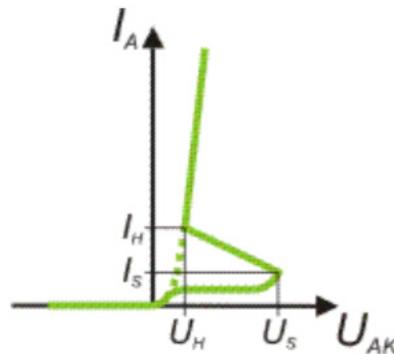


Figure 11.31: Characteristic curves of a thyristor.

If the interested reader wants more information about these 7 components than offered in the menu point *Theory*, we refer to books on semiconductor physics [4].

The next menu point *Tasks* sets out a clear, exemplary measurement program (Table 11.1).

In the menu point *Laboratory* the experimenter logs on. On the left side of the lab page, he sees the webcam image of the selected semiconductor device, below that the web cam image of the oscilloscope screen, and on the right, the control panel for selecting the component to be measured and for operating the oscilloscope.

In the menu point *Analysis* - see next but one section - three components are measured as an example:

- Determination of the forward voltage of the diode,
- Characteristic field of a transistor,
- Evaluation of the thyristor characteristic with respect to switching voltage and holding current.

In the menu point *Discussion*, we ask comprehension questions about the experimental set up, the theory, the laboratory, and the analysis (Table 11.2).

In the menu point *Material*, interested parties will find the datasheets of the semiconductor components used, a handbook on the oscilloscope, as well as a short didactic analysis of the RCL experiment.

Table 11.1: Tasks

1. Diode, Schottky - diode, light emitting diode and Zener diode
  - a) Determine the forward voltage  $U_{DI}$  or the breakdown voltage  $U_{Db}$ .
2. Bipolar transistor
  - a) Determine the forward voltage  $U_{DI}$  from the input characteristic  $I_B (U_{BE})$ .
  - b) Record the output characteristic field  $I_C (U_{CE})$  and draw the working line.
  - c) Determine the current amplification factor  $B$  from the current-control characteristic  $I_C (I_B)$ .  
Using the current-control characteristic and the characteristic curve of the output characteristics, trace the linear amplification range.
3. MOSFET
  - a) Determine the forward voltage from the transfer characteristic  $I_D (U_{GS})$ .
  - b) Record the output characteristic field  $I_D (U_{DS})$  and draw the working line.
4. Thyristor
  - a) Determine the (zero-tilt) switching voltage  $U_S$  as a function of the gate current  $I_G$ .
  - b) Determine the holding current  $I_H$ .
  - c) Compare the characteristic with the output characteristic of the transistor as the control current changes.

Table 11.2: Discussion

1. Experimental set up
  - a) Why does the current have to be determined indirectly by tapping the voltage across a resistor?
2. Theory
  - a) Estimate the number of charge carriers in a metal, in a semiconductor.
  - b) Compare the charge carriers (electrons, holes) in terms of their properties such as charge, mass, mobility, etc.
  - c) What distinguishes a semiconductor from a conductor?
  - d) How does a rectifier, a Graetz circuit work?
  - e) How to make a simple amplifier?
3. Laboratory
  - a) Why does the LED flicker in the webcam image?
  - b) Where does the reading error come from on the oscilloscope screen?
4. Analysis
  - a) Compare a measured characteristic field with that specified in the data sheet of the component.
  - b) Compare real measured characteristics with those in textbooks (idealized).

## Operating the experiment

If the experimenter calls up the laboratory of this RCL, he sees the following picture (Fig. 11.32):

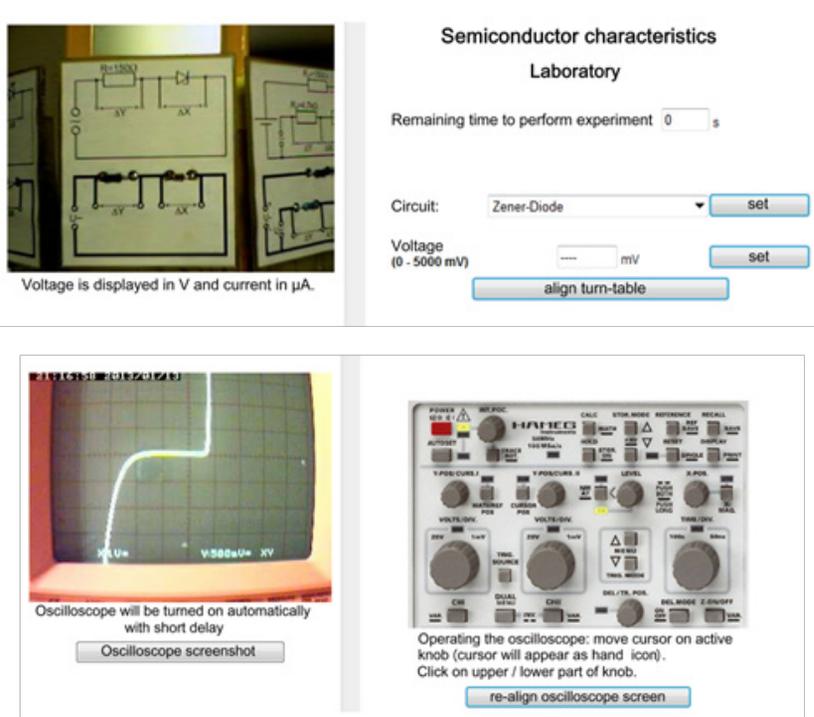


Figure 11.32: Laboratory page.

First, the experimenter selects a component - here the Zener diode - and presses the *Adjust* button. He observes how the cylinder with the 7 components rotates into the corresponding position (see Fig. 11.8). On top of each board we recorded the circuit diagram above and below the measuring circuit. If the selected component is not centrally clean visible, press the button *align* to rotate the cylinder. On the oscilloscope screen's webcam image, the user can manipulate the corresponding characteristic and display it by operating the oscilloscope. If one wants to measure - voltages, moving the signal, etc., operate the oscilloscope. (Moving the cursor over the replica of this oscilloscope reveals four active buttons.) If one selects as a component a transistor, a MOSFET, or a thyristor, the digital multi meter on top will automatically switched on and the experiment will ask for an appropriate input.

What do the corresponding buttons in the control panel mean in the sense of learning goals in a student lab?

- Select an object (one of 7 semiconductor devices),
- Save measurement results (screenshots),
- Operate the oscilloscope(x and y deflection, x and y position, time base, trigger level),
- Select a parameter (voltage in case of transistor or thyristor, current in case of transistor or thyristor),
- Adjust experiment (bring cylinder with circuits and oscilloscope image into initial setting),
- Observe the relationship (oscilloscope setting and its change on the screen).

Parts of it also occur already on the RCL oscilloscope; additionally:

- Select signal source (from 3 different signal types),
- Adjust experiment (reset to standard signal).

All of these activities in both RCLs are experiment-specific and have a sufficient variation for use in class or self-study; although run as remote controllable, the experimenter can fully operate both experiments, as in the real experimental setup in class.

### Measurement result

One way of measuring here is to independently measure the characteristic curve for one component in order to compare it with literature (see material data sheets). Another way is to use a characteristic curve and evaluate by oneself. In the menu point *Analysis*, we have carried out the forward voltage of the diode and the characteristic of a thyristor. Here is the third example.

- Characteristic field of the transistor

To record a characteristic field, characteristic curves are recorded for different base current strengths  $I_B$ : 0, 32, 50, 68, 87, 107, 146, 226,

369, 472, 678 and 885  $\mu\text{A}$ . The images of the characteristic curves are made semi-transparent with an image processing program (see under *Material*) and placed one above the other. This gives the following picture:

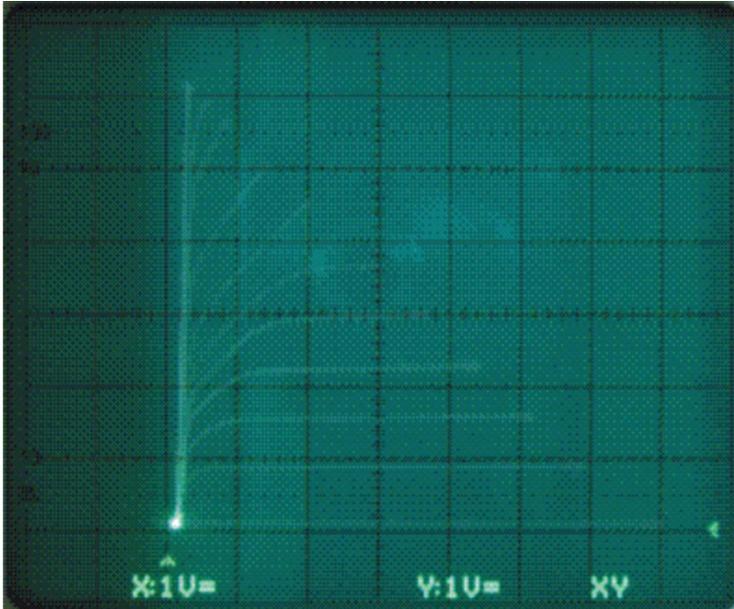


Figure 11.33: Characteristic field of a transistor.

On the characteristic curve for  $I_B = 0 \text{ A}$ , the voltage  $U_{CE\text{max}} = 7 \text{ V}$  is read off. The reading inaccuracy can be assumed with a half scale of 1 mm. The error of the oscilloscope is 2% according to the manufacturer's instructions for horizontal deflection in digital mode. Thus,  $\Delta U_{CE\text{max}} = 2 (7\text{V} \cdot 0.02 + 0.1\text{V}) = 0.5\text{V}$  and thus  $U_{CE\text{max}} = (7.0.0 \pm 0.5) \text{ V}$ .

If the transistor is fully conductive, then the entire 7 V drops at  $R_C$ . Calculated from this results  $I_{C\text{max}} = U_{R_{C\text{max}}} / R_C = 7 \text{ V} / 150 \Omega = 47 \text{ mA}$ . For the calculation of the error of  $I_C$  the above reading inaccuracy applies. The oscilloscope's error in the vertical deflection range is 5 mV / cm to 20 V / cm at  $\pm 3\%$ . The error of resistance is so small that it can be neglected. Thus,  $\Delta I_{C\text{max}} = \Delta U_{R_{C\text{max}}} / R_C = 0.5\text{V} / 150\Omega = 3\text{mA}$  or total  $I_{C\text{max}} = (47 \pm 3) \text{ mA}$ . The points of maximum current  $I_{C\text{max}}$  and maximum voltage  $U_{CE\text{max}}$  determine the working line.

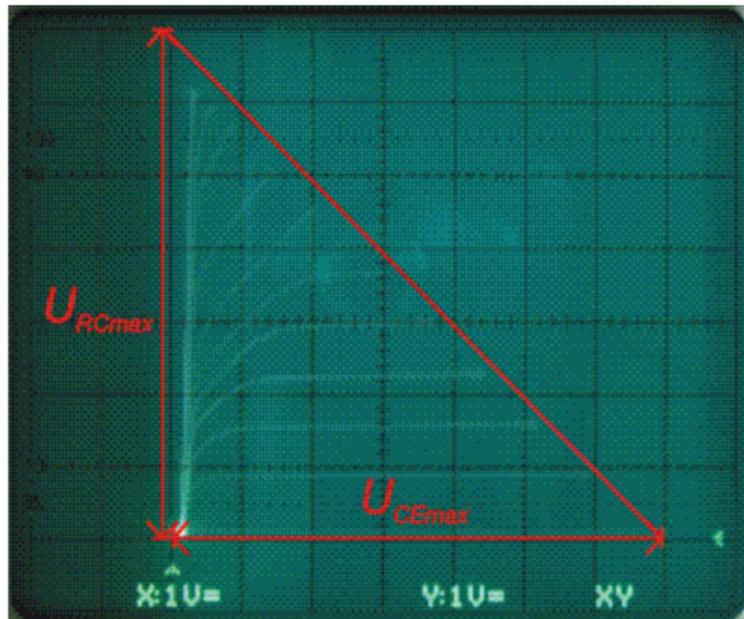


Figure 11.34: Working line in the characteristic field of a transistor.

- Current control characteristic of the transistor

In order to determine the amplification factor  $B$ , first a triangle with the voltages which drop off at the resistors  $R_C$  and  $R_B$  is measured in the linear amplification range of the characteristic curve. The characteristic curve results at a constant voltage  $U_{CE} = 2.83 \text{ V}$ ; while the voltage applied to the collector circuit DC voltage  $U_{dc} = 5 \text{ V}$ .

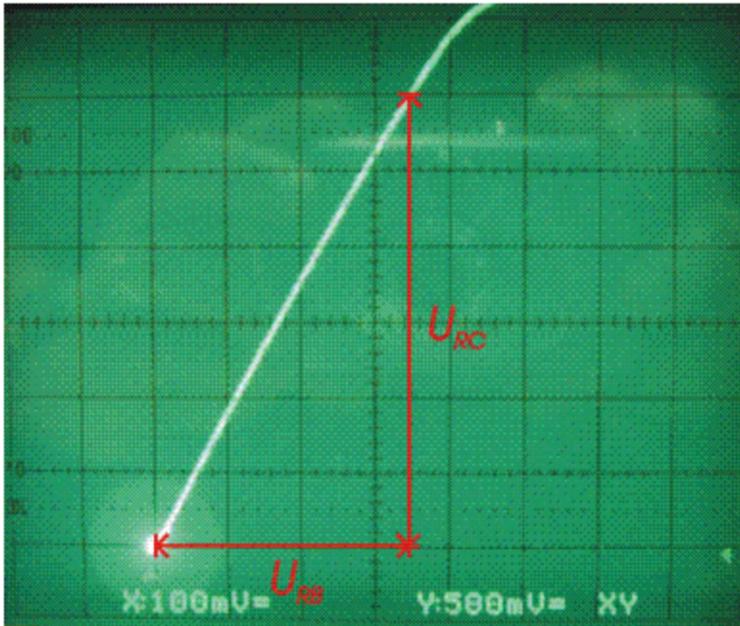


Figure 11.35: Current control characteristic of a transistor.

By measuring results  $U_{RC} = 3 \text{ V}$  and  $U_{RS} = 0,34 \text{ V}$ . The scale (volts / div.) here is  $0,1 \text{ volt / unit}$  in  $x$  and  $0,5 \text{ volts / unit}$  in  $y$ -direction. With  $R_C = 150 \Omega$  and  $R_B = 4,7 \text{ k}\Omega$ , the associated currents are  $I_C = U_{RC}/R_C = 3\text{V} / 150\Omega = 20\text{mA}$  and  $I_B = U_{RB}/R_B = 0,34\text{V} / 4,7\text{k}\Omega = 72\mu\text{A}$ . Thus, the current amplification factor  $B = I_C/I_B = 20 \text{ mA} / 72 \mu\text{A} = 278$ .

To calculate the error of  $B$ , the errors of  $U_{RC}$  and  $U_{RB}$  must first be calculated: The accuracy of the reading is again assumed to be half a scale. The error of the oscilloscope in the case of vertical deflection in the measuring range  $5 \text{ mV / cm}$  to  $20 \text{ V / cm}$  is  $\pm 3\%$ ; with horizontal deflection at  $\pm 2\%$ . Thus,  $\Delta U_{RC} = 2 (3\text{V} \cdot 0,03 + 0,05\text{V}) = 0,3\text{V}$  and  $\Delta U_{RS} = 2 (0,34\text{V} \cdot 0,02 + 0,01\text{V}) = 0,03\text{V}$ . The error of the resistors is negligible. For example, the errors of  $I_C$  and  $I_B$  can be estimated by  $\Delta I_C = \Delta U_{RC}/R_C = 0,3\text{V} / 150\Omega = 2\text{mA}$  and  $\Delta I_B = \Delta U_{RS}/R_B = 0,03\text{V} / 4,7\text{k}\Omega = 6\mu\text{A}$ . This gives the relative errors  $\Delta I_C / I_C = 2 \text{ mA} / 20 \text{ mA} = 0,1$  therefore  $10\%$  and  $\Delta I_B / I_B = 6 \mu\text{A} / 72\mu\text{A} = 0,08$  therefore  $8\%$ . The relative error of the current amplification factor  $B$  is estimated by the addition of the relative errors of  $I_C$  and  $I_B$  and gives  $\Delta B / B = \Delta I_C / I_C + \Delta I_B / I_B = 0,1 + 0,08 = 0,18$  therefore  $18\%$ . With  $B = 278$ ,  $\Delta B = 278 \cdot 0,18 = 50$  and thus  $B = 278 \pm 50$ .

## 11.3 Evaluation and experience

For both types of autonomous measuring - first recording the characteristic itself and comparing it with literature, secondly evaluating the recorded characteristic itself – this RCL provides convincing measured values. It is in no way inferior to the real experiment. Raw data can be recorded very quickly. If one wants to optimize the pictorial representation of a characteristic one needs some time and experience. If one wants to record a characteristic field (image processing program see material), the analysis of own data requires most of the time. Both RCLs can be used during a student lab or as a project.

Both RCLs have been online since 2007, without any problems. We see the added value of offering the respective experiment as RCL in the following:

- Replacement for an expensive oscilloscope or missing device sets for students.
- Motivation for students to use a complicated measuring instrument and prepare for student lab with oscilloscopes.
- Characteristic comparison of several electronic components.
- Due to fast measuring methods in the x-y mode of an oscilloscope (no manual recording of individual measured value pairs), the understanding of the characteristic curve is paramount.

In recent years, the RCL oscilloscope has been called about 14 times a day, the RCL semiconductor characteristic about 7 times a day. The experimenters of the RCL semiconductor characteristics fall into 2 groups: Short visit (10 seconds): qualitative inspection; long visit (1-5 minutes): Measure with variation of parameters.

In order to learn more about the experimental behaviour at both RCLs, one would have to embed both RCLs in a classroom situation and evaluate:

- Independently working on the use with an oscilloscope (how long last experimenting, random or systematic procedure etc.),

- Electronic student lab for vocational preparation at vocational schools.

## 11.4 Didactic material

Since both RCLs are not in the centre of physics education, a lesson makes little sense. Of course, under menu point *Material*, we did a didactical analysis for the teacher as a suggestion. In addition, there is under material a short version for a student lab for vocational students and long distance students.

- Oscilloscope introductory course for vocational students:

We propose a method widely used in industry and economics, such as is used for aircraft pilots (aircraft simulator). In a media-assisted self-learning phase, the operation and use of an oscilloscope is learned with an RCL (duration 2-3 weeks). In a staff-supervised practice phase, the knowledge from the self-learning phase is applied, deepened and extended (one morning and / or one afternoon).

- Preparation for a student lab course:

For a variety of reasons (such as distance learning, existing teach ware, time-cost savings), there are a number of teach ware to learn how to build, operate, and interact with an oscilloscope during student labs. Mostly built as a tutorial for self-study, this teach ware uses well-executed, well-designed, self-explanatory simulation programs (some examples: [2]).

## 11.5 Literature

[1] Students' training boxes from educational equipment manufacturers (eg Leybold, Phywe, Conatex) on electrics for general education schools, as well as special electronics for vocational schools.

[2] Virtual Oscilloscopes (selection):

TU Ilmenau, url: [http://www.schule-bw.de/unterricht/facher/physik/online\\_material/e\\_lehre\\_2/teilchenfeld/oszilloskop.htm...](http://www.schule-bw.de/unterricht/facher/physik/online_material/e_lehre_2/teilchenfeld/oszilloskop.htm...)

- Peter Debik, url: <http://www.virtuelles-oszilloskop.de/index.html>  
Dep. of Electrical and Computer Engineering (ECE), North Carolina State University (NCSU),url: <http://www.ece.ncsu.edu/virtuallab/JAVA/applets/osc.html>...
- Edward Ball, Virtual Oscilloscope Simulation, url: <http://academo.org/demos/virtual-oscilloscope...>
- [3] Virtual Oszilloskop, Landesbildungsserver Baden-Württemberg, url: [http://www.schule-bw.de/unterricht/facher/physik/online-material/e\\_lehre\\_2/teilchenfeld/osziolloskop.htm...](http://www.schule-bw.de/unterricht/facher/physik/online-material/e_lehre_2/teilchenfeld/osziolloskop.htm...)
- Glen A. Williamson, Oscilloscope Tutorial, url: <http://www.williamson-labs.com/Scope1.htm>...
- [4] The literature on semiconductor physics and electronic labs has become confusing today. Semiconductor physics is adequately presented in textbooks of the upper level (eg Metzler Physik). We refer to electronic circuits and labs two older books that still provide a good basis and give examples of experimentation: K. Albrecht, M.-U. Farber, electronics with semiconductor devices, basics - circuits - experiments. Aulis, Koeln 1973.  
S. Wirsum, Elektronik-Selbstbau-Praktikum, Franzis, München 1979.

# 12 Wind Tunnel

## 12.1 Introduction

In industrial society, the automobile is caught between economic growth, the cost factor and the status symbol of individual mobility, environmental pollution and future drive systems. Pupils grow up in this field of tension and receive a great deal of information from parents, classmates, teachers, friends and media on the subject of automobiles. With regard to driving license acquisition, they are increasingly interested in the automobile at the beginning of the upper secondary level (age of 17-19 years old). The topic of "car" has been given due attention in popular textbooks and syllabi since the 1970s. In addition, there are a large number of suitable simulations for schools and videos of car manufacturers (see later didactic material). With the RCL wind tunnel, the air resistance of model automobiles can be quantitatively measured.

Why are no suitable real-life experiments performed?

- A wind tunnel is usually missing to quantitatively measure flow resistance.
- There are numerous qualitative experiments on the inclined plane for rolling friction, for air resistance, but only qualitative experiments for sec. I (age of 10-16 years old) (see later didactic material - teaching unit)
- It is difficult to convincingly measure the flow resistance with school equipment ( $F \propto v$ ,  $F \propto v^2$ ).
- This subject has too little significance in the curriculum, for physics tasks and examinations despite the high motivation potential.

That's why we offer an RCL wind tunnel that allows the experimenter to quantitatively measure the air resistance on the automobile. It therefore makes sense to inform the subject of air resistance on the car and integrate it in a wider context, such as that of fuel consumption. The lesson is structured in such a way that the initial question » Why and what for needs an automobile fuel?« is used to investigate air

resistance with this RCL. Based on the formula for aerodynamic resistance, further questions are addressed: "What is the proportion of air resistance in fuel consumption?", "How can an energy-saving driving style be physically justified?".

Our RCL wind tunnel has its purpose when the (student) experimenter uses the RCL to measure quantitatively, analyse and evaluate his data. As the ultimate long-term goal, we strive for the user's understanding that he prefers cars with a low  $c_w$  value and aligns his driving style at fuel consumption.

## 12.2 Experiment and RCL variant

### 12.2.1 Experimental setup and function

The challenge in the planning of the RCL wind tunnel was, on the one hand, to generate an homogeneous flow of air as possible and, on the other hand, to measure small forces (air friction force in mN).

Fig. 12.1 shows the approximately 2 m long wind tunnel with measuring section:

The components of the wind tunnel are

- an inlet nozzle and a rectifier for the air stream (Fig. 12.2),
- an incoming tube with length of 2m (diameter  $D = 114$  mm),
- a wind anemometer to measure velocities (measuring range 2, 5 to 150 km/h)
- and an adjustable wind generator.

The wind tunnel was designed for the most homogeneous flow possible:

- The inlet nozzle is shaped so that the air is sucked-in as evenly as possible so that the flow is laminar in the channel. Suitable is a radius of curvature  $R$  of the inlet nozzle with  $R/D = 1/4$ .

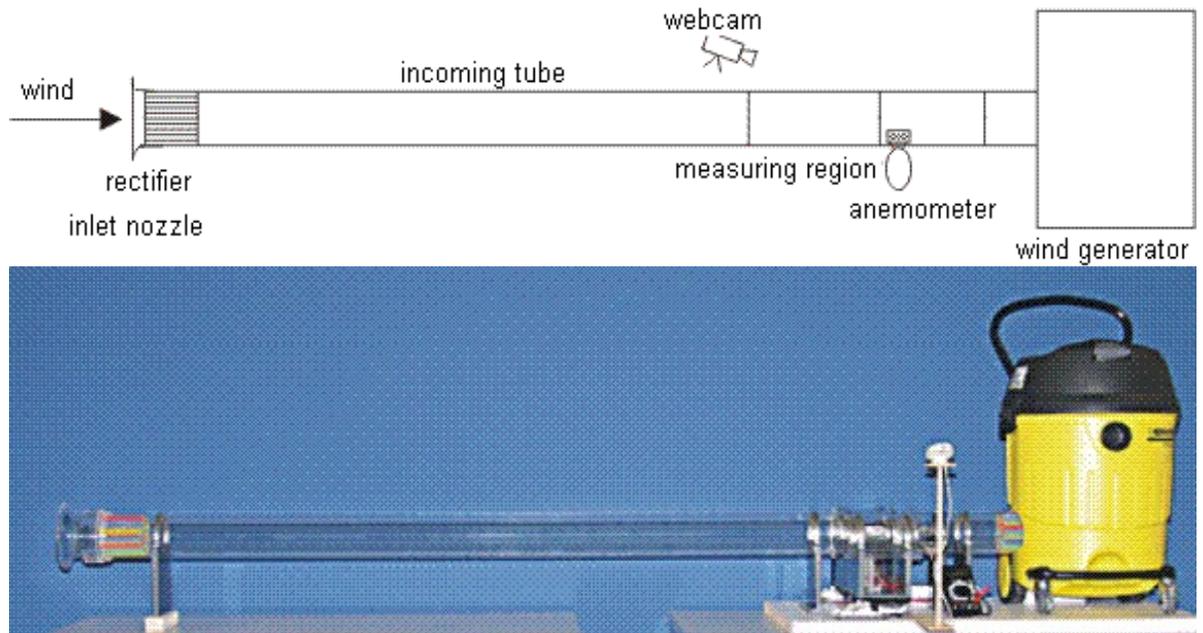


Fig. 12.1: Schematic and figurative representation of the experimental setup.

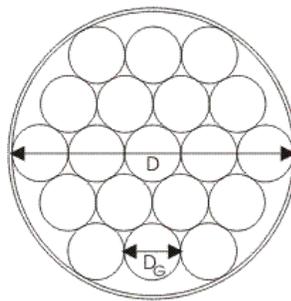


Fig. 12.2: Cross section of the rectifier

The rectifier (Fig.12 2) ensures that the air is streaming twist-free (without vortices) and regular into the wind tunnel. Suitable is a diameter  $D_G$  of the tubes of the rectifier with  $D_G \leq 0.2 \cdot D$  (diameter  $D$  of incoming tube,  $D_G = 4$  mm). The length of the rectifier should be the same as the diameter  $D$  of the incoming tube.

- The incoming tube should have a length  $L \approx 20 \cdot D$

The measuring section includes:

- a linear slide with the three model cars BMW 6 Series Coupe, BMW X5 and a fire engine transversely to the direction of flow (Fig. 12.3),
- bending beam with strain gauges underneath each model car, at the same time holding the model,
- multi meter for reading the voltage for electronic force measurement (strain gauges).

All the details of the electronic force measurement by means of strain gauges, calibration of the force meter, measurement of the cross-sectional area of the cars - all this is described under measurement result.

For this reason, we have described the wind tunnel and the force measurement so precisely because this system is excellently suited for replicating it in a project: technical complexity and costs are low, all components are easily procured, a replica is not too expensive.

### 12.2.2 Navigation menu

The menu point *Experimental set up* is followed by the menu point *Theory*.

The flow resistance for laminar flow ( $F \propto v$ ) and for turbulent flow ( $F \propto v^2$ ) is explained and deduced. The similarity law of fluid mechanics based on the Reynolds number is derived, discussed and evaluated; e.g. if we measure the flow resistance here on small toy cars, what significance does this have for automobiles of everyday life?

The menu point *Tasks* recommends some qualitative as well as quantitative measurements.

After the user has called up the experiment, the menu point *Laboratory* shows the webcam image of the measuring section on the left (see Fig. 12.4) and the control panel on the right: choice of vehicle, choice of power level of wind generator, measurement of wind speed and force (actually a voltage measurement at the strain gauge, see Fig. 12.3).

The menu point *Analysis* contains all measurements on the fire engine as an example: Determination of the  $c_W$  value, checking the hypothesis  $F_R \propto v^2$  (see next section *Measurement result*)

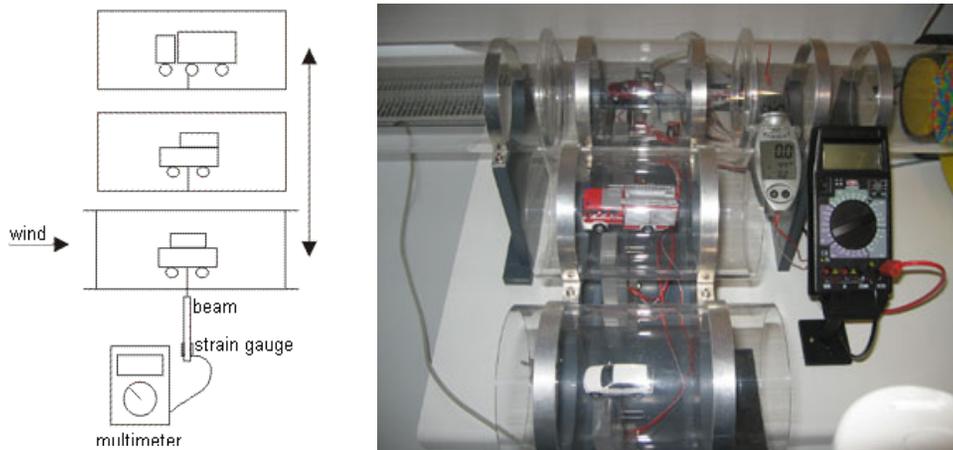


Fig. 12.3: Schematic and figurative representation of the measuring region.

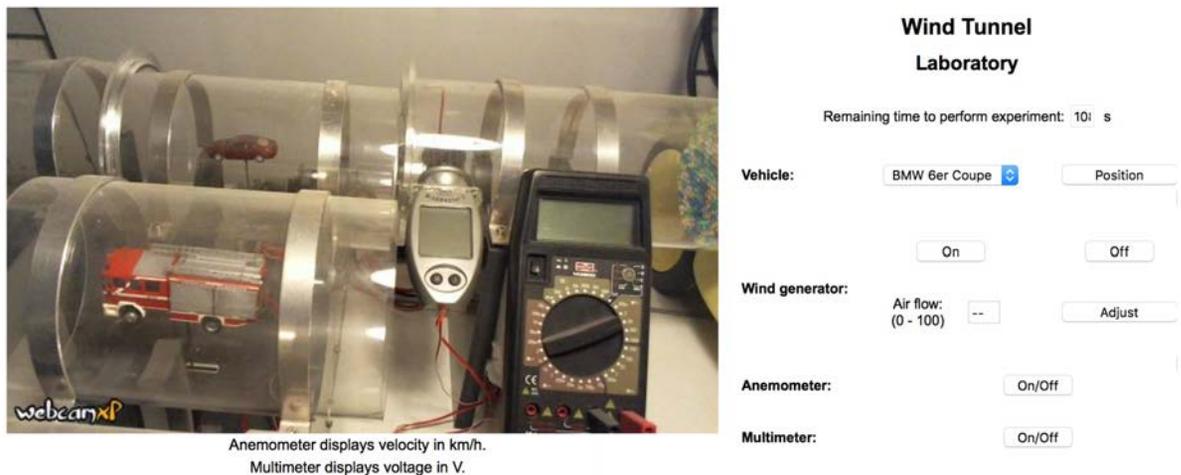


Figure 12.4: Laboratory page.

The menu item *Discussion* examines with quite difficult questions about the experimental setup, the theory, the laboratory, the evaluation, whether the experimenter has understood what he actually measures in the experiment (Table 12.1).

The menu point *Material* contains all information about the wind generator (vacuum cleaner fan), anemometer, the model cars and the strain gauges used. The didactic material includes a didactic analysis on this topic, a possible lesson and a collection of exercises with model solutions (see section didactic material).

Table 12.1: Discussion

1. Experimental set up
  - a) According to which physical principles do anemometers work?
  - b) What other possibilities exist, besides the experiment here, to measure small forces?
  - c) How can the power (number of revolutions) of an electric motor (e.g. in a vacuum cleaner) be regulated?
  
2. Theory
  - a) What does a  $c_W$  value greater than 1 mean?
  - b) Which conditions influence the  $c_W$  value?
  - c) What falls faster to the ground - a feather or a stone? Why and under which conditions?
  - d) Where can you see vortices behind a body flowing around in everyday life?
  - e) In which area are the lowest  $c_W$  values of animals and vehicles? Which is each?
  - f) In order to be able to land on the ground without injury, a parachutist (mass  $m = 80$  kg) may reach a maximum speed of about 5 m/s. How should the parachute ( $c_W = 1.4$ ) be shaped?
  - g) A football player shoots a ball (circumference 90 cm, mass  $m = 600$  g) at a speed of 20 m/s. Compare the aerodynamic resistance of the flying ball with its weight.
  - h) An Airbus A 320 flies at a speed of 1000 km/h at a height of 10 km. Another plane flies half as fast and half as high. Calculate the ratio of air resistances of the two aircraft. The density of air at 5 km altitude is  $0.67 \text{ kg/m}^3$  and at 10 km altitude  $0.38 \text{ kg/m}^3$ . Suppose both aircraft have the same effective cross-sectional area and  $c_W$ .
  
3. Laboratory
  - a) Which size influencing the air resistance force can not be independently varied in the experiment by other parameters? How should a modified experiment look like?
  
4. Analysis
  - a) Find a justification for the different  $c_W$  values of the three vehicles used here.
  - b) How does the wind or the direction of wind influence the gasoline consumption? Why?
  - c) Which conditions influence the gasoline consumption in addition to the air resistance?
  - d) Should you pay attention to the  $c_W$  value when buying a car?

### 12.2.3 Operating the experiment

In Fig. 12.4 we can see the webcam image of the measuring section in the left part of the laboratory page.

Again, the operation is intuitive; the user can see in real-time which actions are performed after pressing the controls on the right side of the lab page; and he can easily read his own data on the display.

If the experimenter chooses one of the three toy cars and positions it, he can watch in the webcam image how the three plastic tubes with one car each move across the airstream (see Fig. 12.3 left). Next, the experimenter shall turn on the wind generator: he sees how a piece of thread in the tube - over the anemometer - depending on the air flow deflects to the right; he can read the anemometer; If he looks closely, he sees how the toy car is moved to the right, the bending beam slightly bent to the right in the air flow (see Fig. 12.3 left) The force measurement by means of strain gauges is done quantitatively by reading the voltage at the multi meter or qualitatively at the deflection of the toy cars in the airstream to the right.

Behind pressing a button for a "remote user" are the following learning objectives in a student lab:

- Select object (vehicle type, three  $c_w$  values in the range 0.3 to 0.9),
- Switch devices on / off (wind generator, anemometer, multi meter),
- Measure sizes (force determination and wind speed in form of a voltage),
- Plan and record a measurement series (wind speed versus voltage),
- Vary parameters ( $c_w$  value of the vehicle type, power of the wind generator),
- Observe relationships (wind speed and deflection of bending beam, wind speed and deflection of the thread).

### 12.2.4 Measurement result

Since only very small forces of the order of magnitude mN occur in the experiment and must be measured remotely, the air friction force is measured electronically indirectly by strain gauges. This will be explained in detail below. Each model car is attached to the upper end of a vertical leaf spring, which serves as a bending beam (Fig. 12.5).

Two strain gauges (DMS) are glued to each of the two bending beam surfaces (Fig. 12.6, left). The 4 strain gauges are resistors of a Wheatstone bridge circuit (Figure 12.6, right).

The functional principle of electronic force measurement is the following: If no air frictional force  $F$  acts on the model car, then ideally all 4 strain gauges have the same resistance and the Wheatstone bridge output voltage  $U_A$  measurable with the multi meter is zero. In the real case, the output voltage  $U_A$  is never zero due to the unavoidable mechanical stresses and preloads generated by the mounted vehicles, when the strain gauges are pasted on. A force change  $\Delta F$  leads to a proportional stretching or compression  $\Delta l$  of the beam tops, this to a proportional change in resistance  $\Delta R$  of the DMS and this to a proportional output voltage change  $\Delta U_A$ . Compared with a bridge with only one strain gauge, a bridge with 4 strain gauges delivers four times the voltage change and automatically compensates the changes of resistance due to temperature fluctuations.

An independent calibration of the force measurement results in a known relationship between the force  $F$  acting on the bending beam and the output voltage  $U_A$ . The three bending beams with model cars were horizontally bent over a low-friction roller by loading with masses of the weight force  $F = F_G$ . The result for the fire engine is shown in Fig. 12.7.

We get the following sensitivities  $\Delta U_A / \Delta F_G$  for the measurement of the frictional force on the model cars:

- Fire brigade truck: 21.77 V/N
- BMW X5: 49.33 V/N
- BMW 6er Coupe: 48.94 V/N

The cross-sectional areas  $A$  of the three model cars were determined by placing a grid over the photo of the respective vehicle in frontal view and then counting the occupied boxes (Table 12.2).

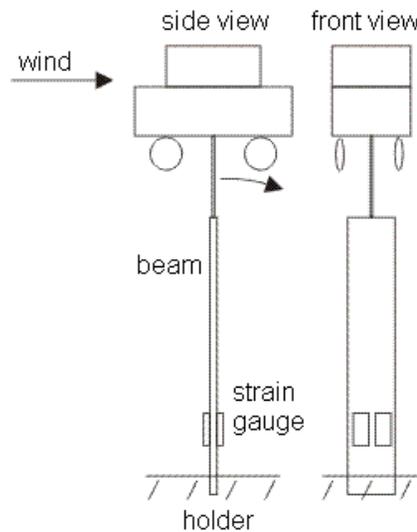


Fig. 12.5: Electronic measurement of the frictional force of air.

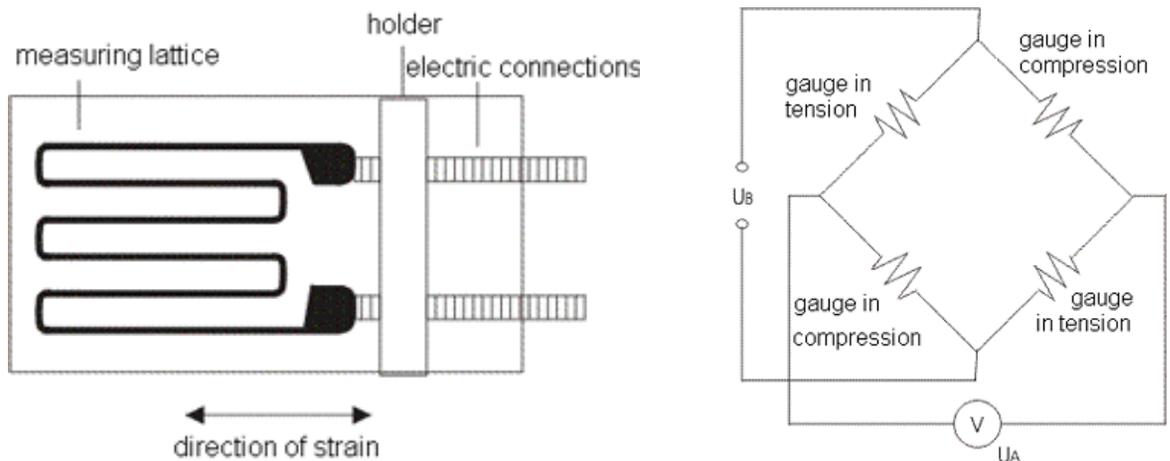


Fig. 12.6: Enlarged schematic representation of a strain gauge (left). Wheatstone's bridge circuit with 4 strain gauges (right).

#### Error analysis:

- The relative error of the flow velocity  $\Delta v/v$  is about 9%. It results from the error of the anemometer of 4% (according to the operating instructions) and an error of 5%, as eddies behind the vehicles can change the true flow velocity. This value

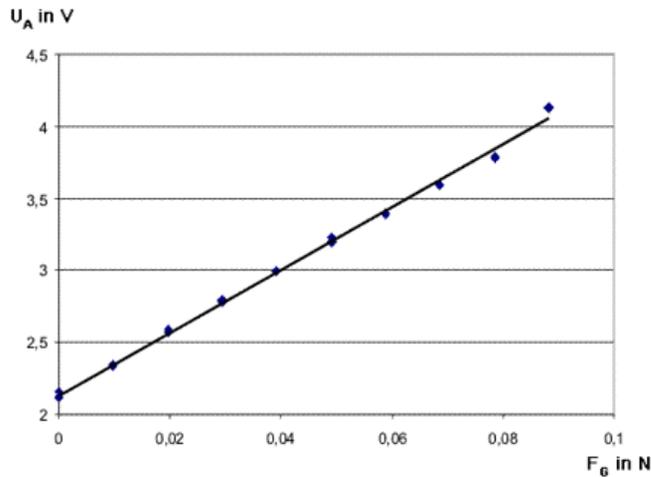
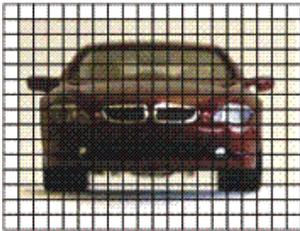
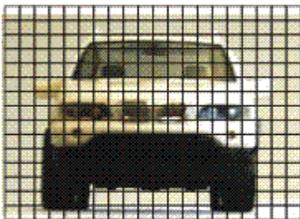
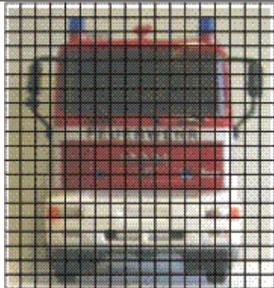


Fig. 12.7: Linear relation between output voltage  $U_A$  at the multi meter and gravitational force  $F_G$  of masses.

Tab. 12.2: Cross-sectional areas of the model cars.

BMW 6er Coupe	BMW X5	Fire brigade truck
		
$A = (258 \pm 6) \text{ mm}^2$	$A = (380 \pm 6) \text{ mm}^2$	$A = (826 \pm 18) \text{ mm}^2$

of 5% results from comparison measurements of the flow velocity in front of and behind the vehicle.

- The error  $\Delta F$  of the force measurement is approximately 0.001 N for the BMW 6 Series Coupe and the fire engine and for the BMW X5  $\approx 0.002$  N. This error results from the calibration of the force measurement.

With the aid of a single measurement (with an air flow of 34 km/h) and force measurement ( $F_R = 41$  mN) we can determine the  $c_w$  value of the fire engine at  $c_w = 0.86$  (measurement error about 20%).

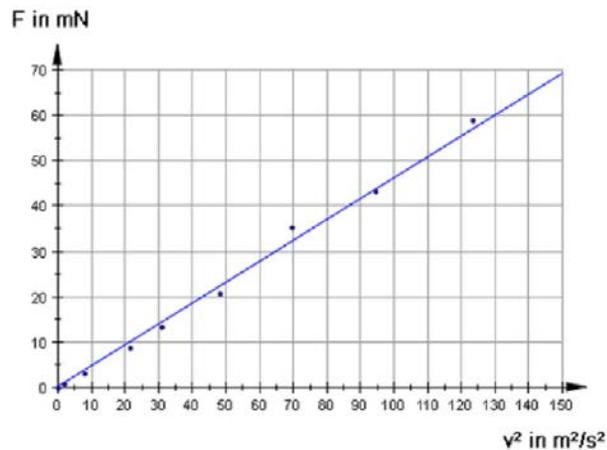


Figure 12.8: Verification of the relationship  $F \propto v^2$ .

Table 12.3: Measurements of the relationship between the air friction force  $F$  and the speed  $v$  of the fire engine.

$v$ in km/h	$v$ in m/s	$v^2$ in $\text{m}^2/\text{s}^2$	$U_A$ in V	$U_A(v) - U_A(0)$ in V	$F$ in mN
0	0	0	2.21	0	0
5	1.39	1.93	2.23	0.02	0.92
10.2	2.83	8.01	2.28	0.07	3.21
16.6	4.61	21.25	2.40	0.19	8.72
20	5.56	30.91	2.50	0.29	13.32
25	6.94	48.16	2.66	0.45	20.67
30	8.33	69.39	2.89	0.77	35.37
35	9.72	94.48	3.15	0.94	43.18
40	11.11	123.43	3.49	1.28	58.89

In order to check the flow resistance  $F \propto v^2$ , one examines the relationship between the air friction force and (relative) speed of the fire truck.

A quantitative analysis provides the measurement results in Table 12.3.

To check the relationship  $F \propto v^2$ ,  $F$  is plotted as a function of  $v^2$  in a diagram (Fig. 12.8).

The measuring points are approximately on a straight line. Doubling the speed of a vehicle quadruples the air friction force. The work done on the route quadruples (see Theory) and thus also the fuel consumption per kilo meter driven.

## 12.3 Evaluation and experience

The measurement results are so convincing that one can clearly differentiate between the  $c_w$  values of the toy cars used; as well - depending on the flow - between the flow resistances  $F \propto v$  and  $F \propto v^2$ . The measurement error of the individual measurement (wind speed, force) is around 3 to 5%; If one considers turbulence behind the vehicles, perturbations caused by the short plastic tube open on both sides with the respective model car inside, etc., this results in a total error of 10 to 15%. Single measurements are fast, measurement series take about 30 minutes; but one has to wait until a constant wind speed adjusts after changing one parameter (e.g. wind velocity).

The added value - wind tunnel as RCL experiment - we see in the following:

- Permanent and free availability of a wind tunnel/channel,
- Topics offer a high relation to everyday life and technology (connection between form, speed and energy turnover at cars),
- Air resistance formula can be confirmed with the RCL as a teacher demonstration experiment,
- RCL is well suited for rebuilding a wind tunnel as a usual real experiment (project work).

The RCL is online since 2006, without any problems. In recent years, it has been called up an average of 8 times a day and used for experimenting. We did not investigate the experimental behaviour. But one could pursue the following questions:

- Unsystematic or systematic change of vehicle types,
- Playing with the strength of the air stream and qualitatively observing what is happening or systematic measuring (force as a function of the wind speed),
- Evaluation of the user behaviour after a parameter change, e.g. observing the display and measuring the voltage?

In addition to pure measuring, it is also about evaluating our own measured data. Here one could set up a forum for the exchange of own

measured data, for the common discussion up to the change of behaviour (changing the driving style, purchase of a suitable car etc.).

## 12.4 Didactic material

We see the following application possibilities in physics lessons:

- In secondary level II - Fluid Mechanics (age of 17-19 years old)

In the federal states of Rhineland-Palatinate, Berlin and Brandenburg, the lesson topic for the elective subject »Fluid Mechanics« can be used as an everyday-oriented introduction in an appropriately adapted and streamlined form. Further, classical content such as

- the visualization of flows,
- different forms of flow,
- pressure measurements in flows,
- Bernoulli equation and
- an explanation of the origin of the flow resistance

best and closely related to the automobile. A well-planned visit to a professional wind tunnel for automobiles, prepared in advance is ideal at the beginning or end of this lesson.

- In secondary level I – Mechanics (age of 10-16 years old)

As a rule, in the topic "work-energy-power" energy forms are introduced too isolated from each other and at special physical experiments. The qualitative contents of the lesson such as "energy flow in the car", "qualitative experiments on air resistance" and "energy saving in driving" can be used concomitantly or as a conclusion of the thematic block. It remains up to the teacher to use this RCL also for a quantitative treatment of air resistance, which is not included in the curricula, to introduce quadratic dependencies in a physical context.

For the following lesson (see Tab. 12.4) we formulate a set of learning objectives:

The students should...

- acquire knowledge about energy flow diagrams, especially for automobiles (in addition to kinetic energy such as losses due to friction, waste heat, air conditioning, radio) and efficiency of combustion engines.

- develop hypotheses on air resistance determinants and review them by qualitative / semi-quantitative experiments.
- quantify the dependence of air resistance on drag coefficient and speed of a car by our RCL wind tunnel.
- assess the potential for saving fuel by reducing vehicle air resistance.
- be able to physically justify measures to reduce the fuel consumption of automobiles.

The lesson (Table 12.4) has the contents in key words:

- Energy flow in automobiles with combustion engine,
- Qualitative preliminary experiments on air resistance,
- Quantitative air resistance experiments with the RCL wind tunnel
- Air resistance of automobiles,
- Energy-saving driving,
- In-depth tasks.

Some examples from our extensive collection of tasks with model solutions (see Tab. 12.5).

As already mentioned, the physics of automobiles found its way into syllabi, textbooks and as a template for experimental material since the 1970s. As the following collection (see 12.6) shows, we find a rich literature on the professional wind tunnel of the automobile / aircraft industry, on fuel consumption and CO<sub>2</sub> emissions, on all vehicle types of all car manufacturers, on basic information in Wikipedia and special books on aerodynamics; both as a link and in paper form.

This literature collection (see Tab.12.6) can be useful both to the teacher (for reading / deepening) and to the student (presentation, project work).

Table 12.4: Lesson unit.

**Module "Wind Tunnel as Remotely Controlled Laboratory (RCL) - Air Resistance and Fuel Consumption of Cars"**

Reference to material page of lesson at Teacher Online

Phase	Contents and forms of work
<p><b>Energy flow in cars with internal combustion engine</b></p>	<p><b>Discussion: Why and why does a car need fuel?</b></p> <ul style="list-style-type: none"> <li>• Collect student contributions, record in writing, structure.</li> <li>• Video (video "energy consumers in the car") as impulse, entry (by the additional consumers to aerodynamic drag) or as additional information use.</li> <li>• Develop relevant car aggregates, energy flows and energy conversions in the car (Task "Energy flow while driving" to the lesson "and images" Slides 1 and 2").</li> <li>• Optional: Students show energetically relevant aggregates on an older car (aggregates in the engine compartment even more visible).</li> </ul>
<p><b>Qualitative preliminary tests for air resistance</b></p>	<p><b>Teacher Demonstration Experiment: Dynamic balance of forces with rolling and air friction</b></p> <ul style="list-style-type: none"> <li>• Experimental material: approx. 3 m long inclined plane with variable inclination angle <math>\alpha</math>, trolley with DIN A4 carton attachable to the direction of travel, weight with cardboard mass, light barrier and digital timer for measuring the carriage speed at any point on the inclined plane over the dark period of the carriage,</li> <li>• Entry: Car with DIN A4 cardboard stands on top of inclined plane. Students should predict movement, verify hypotheses with speed measurement and establish the connection between power and movement.</li> <li>• Identifying friction forces: For rolling friction, replace the weight of the box with the weight piece: the trolley comes to a stop on a horizontal track. By tilting the plane, constant carriage speed can be achieved (rolling friction independent of carriage speed). For air friction, replace the weight piece again with DIN A4 cardboard: At an inclined level, the car reaches the final speed (it must have additional force).</li> </ul>

<p><b>Qualitative preliminary tests for air resistance</b></p>	<ul style="list-style-type: none"> <li>• Experiment as a model experiment: Pupils' contributions from a discussion on the air resistance of cars pick up, test results transferred to the car (driving force of the engine or the car wheels corresponds to downhill force, rolling and air friction in the car), dynamic balance of power between downhill power and sum of rolling and air friction force.</li> <li>• Hypotheses are what air resistance is dependent on: How can you reach the solid angle of inclination of the road that the car sooner or later reaches its final speed?</li> </ul> <p><b>Air resistance experiments: dependence on the face, shape and speed of a body</b></p> <ul style="list-style-type: none"> <li>• Experimental material: Hair dryer with at least two blower stages, Styrofoam body with the same cross-sectional area and different shape (sphere, hemisphere shell, cylinder), rectangular rigid cardboard boxes with different surface, mounting material.</li> <li>• Measurements: Balance the carriage with the flow object on a slippery roadway and measure the pitch angle, balance the carriage with the flow object on the horizontal track via the pulley and counterweight, balance the lever with the flow object with the dynamometer, deflect the bifilar suspended body (pendulum) and measure the angle.</li> <li>• Organizational forms: sec. II as a demonstration experiment, sec. I as a pupil experiment in groups with different measuring methods (introduce experimental material to the pupil and make suggestions to the experimental set up and the experimental procedure and present experimental results.</li> <li>• Discuss advantages and disadvantages of the experiments: no rolling friction, air flow not laminar, flow velocity not measurable, no car as object of investigation.</li> </ul>
<p><b>Quantitative air resistance experiments with RCL "Wind tunnel"</b></p>	<p><b>RCL Wind Tunnel: Introduction and Measurements</b></p> <ul style="list-style-type: none"> <li>• Presentation of the RCL laboratory (→ RCL Wind Tunnel Laboratory Page): Have students explain the experimental setup and execution with as few explanations as possible, explain the force measurement with a multi meter (→ RCL Wind Tunnel Analysis), perform a single measurement.</li> <li>• Hypothesis: Proportional, quadratic or ... relationship between air frictional force and wind speed, possibility to check this relationship by plotting versus <math>v^2</math>.</li> </ul>

<p><b>Quantitative air resistance experiments with RCL "Wind tunnel"</b></p>	<ul style="list-style-type: none"> <li>• Homework: Each student group takes a series of measurements with a model car and evaluates the data.</li> </ul> <p><b>RCL wind tunnel: Evaluation</b></p> <ul style="list-style-type: none"> <li>• Formula for air frictional force: emphasis on <math>F_R \sim v^2</math>, optional theoretical derivation of the formula, determination of the <math>c_w</math> value of the model cars from the determined gradient, known frontal area and air density.</li> <li>• Optional: Experimental presentation "Force measurement with DMS" by student or teacher with (→ Task "Force measurement with bending beam, etc" to the lesson), model experiment with load-bearing wire as strain gauge in Wheatstone Bridge.</li> </ul>
<p><b>Air resistance of cars</b></p>	<ul style="list-style-type: none"> <li>• Comparison of the measured <math>c_w</math> values with those of cars, meaning of the product <math>c_w \cdot A</math> (picture material e.g. from W.-H. Hucho: Aerodynamics of the automobile, pp. 125, 276 and 277).</li> <li>• Deepening of the aerodynamic resistance formula with exercise material (→ Simulation "The force of the wind" and simulation tasks).</li> <li>• Calculation and comparison of driving resistances (→ Task for the lesson "Driving resistance while running")</li> <li>• Optional: application of the resistance formula to other movements such as downhill skiing, parachuting, cycling, ... .</li> </ul>
<p><b>Energy-saving driving</b></p>	<ul style="list-style-type: none"> <li>• Getting started with energy-saving tips for driving (→ Task for the lesson "Fuel-efficient driving")</li> <li>• Introduction of the energy content of fuels (→ Task for the lesson "Energy content of fuels")</li> <li>• Calculation of the savings potential of a reduced-speed driving style (→ Task for the lesson "Fuel economy through reduced driving speed").</li> <li>• Information on the energy flow in a car with an internal combustion engine (→ Image material for the module "Transparency6")</li> </ul>
<p><b>Advanced tasks</b></p>	<ul style="list-style-type: none"> <li>• Prepare and implement in-depth exercises (→ Tasks "Force measurement with bending beams, strain gauges and Wheatstone bridge", "Rolling-out test" and "Engine power and maximum speed of a car").</li> <li>• Optional: Experimental implementation of the roll-out test by car.</li> </ul>

Table 12.5: Task Collection.

**Task to drive and driving resistances of a car**

For a car (rolling friction coefficient  $\mu_r = 0.015$  of the tire, coefficient of resistance  $c_w = 0.35$ , frontal area  $A = 2 \text{ m}^2$ , mass  $m = 1.5 \text{ t}$ ), the relationship between the driving force  $F_a$  of the tires and that shown in Fig. 2 Vehicle speed measured for the 1(black), 2 (red), 3 (blue) and 4 (green) gears of a car:

- What is the air friction force  $F_w$  at  $v = 40 \text{ km/h}$  and at  $v = 80 \text{ km/h}$ ? Which influence on the air friction force  $F_w$  have a ride at lower temperatures and at higher altitudes?
- At what speed is the air friction force  $F_w$  in the level and in calm conditions as high as the rolling friction force  $F_r$  or the same as the weight force  $F_g$  of the car?
- What maximum speed does the car achieve with a driving force  $F_a = 1.5 \text{ kN}$  assumed, 5% incline and headwind  $v_g = 36 \text{ km/h}$ ?
- In Fig. 3, enter the course of the air friction force  $F_w$ , the rolling frictional force  $F_r$  and the downhill force  $F_h$  at a gradient of 10%.
- What acceleration  $a$  can the driver achieve with a 10% incline and a speed  $v = 50 \text{ km/h}$ ?

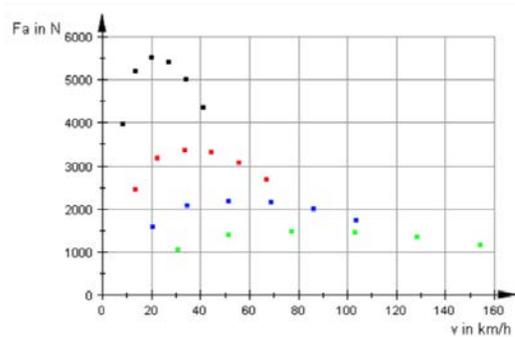


Fig. 2: Driving force of a car depending on the 1st - 4th gear.

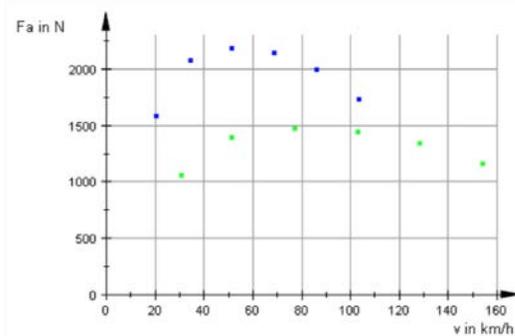


Fig. 3: Driving force of a car depending on the 3rd and 4th gear

### Solution

a) The air resistance force is

$$F_w = \left(\frac{1}{2}\right)c_w\rho Av^2 = 56.2\text{N}.$$

Double speed is followed by four times the force:  $F(80\text{ km/h}) = 224.7\text{ N}$ .

When the temperature decreases, the air density increases and the air resistance increases, with height increase and constant temperature, the air density decreases (barometric height formula) and the air resistance decreases.

b)

$$F_w = F_r \Leftrightarrow \frac{1}{2}c_w\rho Av^2 = \mu_r mg \Leftrightarrow v = \sqrt{\frac{2\mu_r mg}{c_w\rho A}} = 22,02 \frac{\text{m}}{\text{s}} = 79,29 \frac{\text{km}}{\text{h}}$$

$$F_w = F_g \Leftrightarrow \frac{1}{2}c_w\rho Av^2 = mg \Leftrightarrow v = \sqrt{\frac{2mg}{c_w\rho A}} = 180 \frac{\text{m}}{\text{s}} = 647,4 \frac{\text{km}}{\text{h}}$$

The case  $F_w = F_g$  does not occur.

c)

$$\alpha = \arctan(s/100) = 2.86$$

$$ma = F_a - F_w - F_r - F_h = 0 \Leftrightarrow F_a - \left(\frac{1}{2}\right)c_w\rho Av^2 - \mu_r mg \cos \alpha - mg \sin \alpha = 0$$

$$\Leftrightarrow v = \sqrt{\frac{2}{c_w\rho A}(F_a - mg(\mu_r \cos \alpha + \sin \alpha))} = 34,62 \frac{\text{m}}{\text{s}} = 124,63 \frac{\text{km}}{\text{h}}$$

d) Fig. 7: Roll friction force  $F_r$  (below), air friction force  $F_w$  (center), slope force  $F_h$  (top).

e) Fig. 8:  $F_r + F_w + F_h$  (black curve). Comparison with  $F_a$  at  $v = 50\text{ km/h}$  gives a difference of  $\approx 600\text{ N}$  in the third gear and  $\approx 1500\text{ N}$  in the second gear. After  $F = ma$ ,  $a = 0.5\text{ m/s}^2$  and  $a = 1\text{ m/s}^2$ .

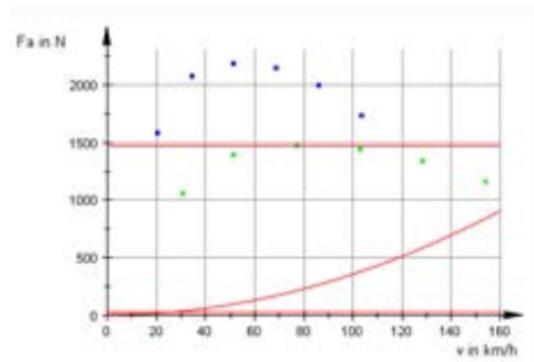


Fig. 7: Course of rolling friction force, air friction force and downhill force as a function of the driving speed.

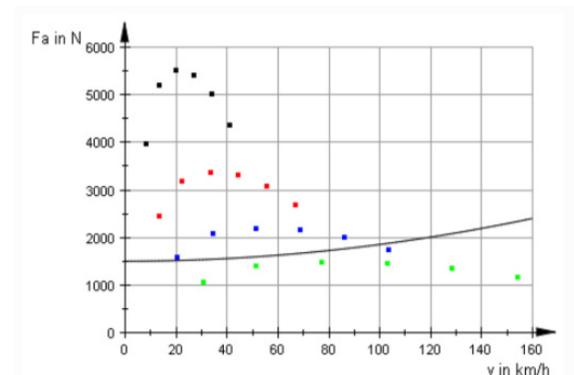


Fig. 8: Resulting driving force.

### Task Fuel-saving driving

A guidebook offers the following tips for fuel-efficient driving: "Drive on motorways under 130 km/h", "Use the vehicle's momentum", "Do not run the engine unnecessarily", "Avoid additional vehicle loads", "With proper travel drive the vehicle ", " do not switch on the auxiliary equipment unnecessarily ", " avoid changes to the vehicle shape ", " drive in as high gears as possible ":

a) Concretize the tips by driving situations / examples and substantiate them physically.

### Solution

Tip for fuel-efficient driving	Driving situations / examples	Physical reasoning
<b>Drive in as high gears as possible</b>	<ul style="list-style-type: none"> <li>• Switch early to the next higher gear</li> <li>• In town you can drive in 4th gear</li> </ul>	The fuel consumption of a motor depends on the speed and the torque (load) of the motor. The specific fuel consumption (in g / kWh) is lowest at low speeds ( $\approx 2000$ rpm) and high load, ie at higher speeds.
<b>Exploit the momentum of the vehicle</b>	<ul style="list-style-type: none"> <li>• Driving ahead, for example, remove the gas early in the event of obstacles (traffic lights, end of traffic jams, braking vehicle ...)</li> <li>• Drive calmly and evenly, "swim along" in the flow of traffic</li> </ul>	Each time it accelerates, the chemical energy of the fuel is converted into kinetic energy of the car. When braking, kinetic energy is converted into heat energy (brake discs) that can no longer be used.
<b>Do not let the engine run unnecessarily</b>	<ul style="list-style-type: none"> <li>• Start motor when all passengers are in and buckled on, the route is determined, and all activities are finished.</li> <li>• Turn off motor at closed railway-barrier, at traffic lights and during loading and unloading the car.</li> </ul>	If motor is not running fuel consumption is zero.

<p><b>Avoid additional vehicle loads</b></p>	<ul style="list-style-type: none"> <li>• Clear everything immediately after shopping</li> <li>• Uncouple unused trailer</li> </ul>	<p>Additional vehicle loads increase the vehicle mass and thus <math>E_{kin} = 0.5mv^2</math> the fuel consumption to accelerate the vehicle to the same speed.</p>
<p><b>Drive with correct tire pressure</b></p>	<ul style="list-style-type: none"> <li>• Regularly check and correct the tire pressure at petrol stations</li> <li>• Tire pressure can be increased by approx. 0.2 bar</li> </ul>	<p>Too low a tire pressure results in an increased rolling resistance (rolling friction coefficient) or rolling friction force <math>F_r</math>. After <math>W = F_r s</math> the friction work increases and with it the fuel consumption.</p>
<p><b>Do not switch on additional units unnecessarily</b></p>	<ul style="list-style-type: none"> <li>• As far as possible, do not use main consumers such as air conditioning, rear window and seat heating</li> <li>• Only switch on the daytime running lights in bad weather conditions</li> </ul>	<p>The energy of each additional unit comes from the energy of the fuel.</p>
<p><b>Avoid changes to the vehicle shape</b></p>	<ul style="list-style-type: none"> <li>• Do not drive with the windows open</li> <li>• Disassemble unused roof rack, roof box, trailer, ski or bicycle holder</li> <li>• Have sheet metal damage repaired</li> </ul>	<p>A change in the vehicle shape leads to an increased end face or an increased resistance coefficient and thus to an increased flow resistance <math>F_S = 0.5c_w \rho A v^2</math></p>
<p><b>Drive on highways under 130 km/h</b></p>	<ul style="list-style-type: none"> <li>• Leave in time to avoid "racing"</li> <li>• Do not force riders or other drivers to accelerate</li> </ul>	<p>The flow resistance resistance <math>F_S = 0.5c_w \rho A v^2</math> depends quadratically on the vehicle speed.</p>

### Task for fuel saving car driving by reduced velocity

The model VW golf VI of 2008 (heat value  $H_D = 42,5\text{MJ/kg}$ , density  $\rho = 0,83\text{g/cm}^3$ , power  $P = 81\text{kW}$ , mass  $m \approx 1150\text{ kg}$ , coefficient of resistance  $c_w = 0,32$ , front area  $A = 2,22\text{ m}^2$ , fuel consumption  $K \approx 4\text{ l/100km}$ ) and the golf I of 1974 ( $P = 40\text{kW}$ ,  $m \approx 780\text{ kg}$ ,  $A = 1,8\text{ m}^2$ ,  $K \approx 5,5\text{ l/100km}$ ) are pretty different.

a) Derive a formula to calculate the fuel consumption  $K_S$  of a car, which is driving with constant velocity  $v$ .

b) Estimate realistically the potential for saving energy when driving with reduced velocity. Compare this potential with other technical changes to save fuel and in relation to the development of cars since 1974.

### Solution

$$P = \frac{E}{t} = \frac{Hm}{t} = \frac{H\rho V}{t} = \frac{H\rho K_S s}{t} = H\rho K_S v = \frac{1}{2} c_w \rho_L A v^3 \Leftrightarrow K_S = \frac{c_w \rho_L A}{2H\rho} v^2$$

a) The biggest potential savings are due to the higher speeds on highways. The maximum average speed on highways has been reduced in recent years by increasing traffic density, increasing the proportion of heavy goods traffic, and driving down many routes to 130 km/h. A realistic assumption is therefore  $v_{\max} = 130\text{ km/h}$ . Driving at speeds of less than 100 km/h, motorways are close to rural roads and force frequent truck overtaking. Realistically  $v_{\min} = 110\text{ km/h}$ .

$$K_S (130\text{ km/h}) = 1,7 \cdot 10^{-8}\text{ m}^2 = 1,7\text{ l/100 km}$$

$$K_S (110\text{ km/h}) = 1,2 \cdot 10^{-8}\text{ m}^2 = 1,2\text{ l/100 km}$$

$$\Delta K_S / K_S (130\text{ km/h}) \approx 30 \text{ and } \Delta K_S / K \approx 12\%$$

Since the fuel consumption of cars has declined in recent decades - mainly due to improvements in the thermodynamic efficiency of internal combustion engines -  $\Delta K_S / K$  has increased.

b) The cars have become bigger, heavier and streamlined in the last decades ( $A$  larger,  $m$  greater,  $c_w$  smaller). The product  $c_w A$ , for example in the Golf, has fallen from 0.756 to 0.710, so that today a larger and simultaneously more fuel-efficient vehicle is obtained. However, the vehicle mass has increased by about a factor of 1.5, which leads to significantly higher fuel consumption, especially in city traffic with many acceleration and braking phases. The increase in mass is due, among other things, to the large number of additional electrical consumers. The additional consumer air conditioner can result in an increase in fuel consumption in the size of  $K_S$ .

Tab.12.6 Internet addresses and literature

## Internet addresses

### Information about cars

-- Everyday physics lessons using the example of "automobile" (PDF)

Werner B. Schneider, Pathways to Physics Didactics (1993); Relationship between maximum speed and engine power, experiments to determine the rolling friction coefficient and the drag coefficient

-- Unconventional considerations on the fuel consumption of cars

Helmut Tschöke, Hanns-Erhard Heinze, Magdeburg Science Journal (2001); Articles on the development of the fuel consumption of cars, the specific fuel consumption and the feasibility of extremely low consumption

-- Guide to fuel consumption and CO<sub>2</sub> emissions (PDF)

Tips from the German Automobile Trust to reduce fuel consumption, information on fuel consumption and carbon dioxide emissions of new vehicles offered in Germany (2008, 4th quarter)

-- Audi wind tunnel centre

On the website of the car manufacturer one will find a simulation to build one of the most modern, strongest and quietest wind tunnels in Europe.

-- Homepage of Rüdiger Cordes - Opel GT

Sortable table with information on the resistance coefficient, the face area and the product of resistance coefficient and face area of about 600 cars

-- World Online: When the Golf I meets the Golf VI

Comparison of the Golf I of 1974 with the Golf VI of 2008 in terms of price, ride comfort, engine, weight and design

### Wikipedia: Basic information on relevant terms of the lesson

-- Flow resistance

Laminar and turbulent flow

-- Drag coefficient

Definition, determination and application

-- Fuel consumption

Consumption data, conversions and reliability of the company information

-- Wind Tunnel

Construction and historical

-- Driving resistance

Components of the driving resistance and required drive power

## Literature

### Aerodynamics of the automobile

Wolf-Heinrich Hucho (Editor), Vieweg + Teubner 2005; Textbook with detailed background information on the lesson in the chapters "Some basic features of fluid mechanics", "Consumption and performance", "Air resistance of passenger cars" and "Wind tunnels"



# 13 Optical Fourier Transformation

## 13.1 Introduction

The RCL experiment is aimed at physics students in the second to third year of study, to interested teachers, in a few basic examples also to pupils. We are pursuing the following goals with this RCL:

- Fourier Transform (FT) experiments,
- Visualizing mathematical relationships,
- Self-study,
- As well as an experiment in an advanced students lab.

From time-dependent signals, the frequency spectrum can be determined with the one-dimensional Fourier transformation (FT). One branch of physics, Fourier optics, uses the two-dimensional Fourier transformation for wave-theoretical analysis and manipulation of optical images. The three-dimensional Fourier transformation is used in the X-ray structure analysis to calculate the crystal structure from the X-ray diffraction by crystals. Further developments of the Fourier transformation such as the Discrete Fourier Transformation (DFT) for performing the Fourier transformation on computers and an algorithm, the Fast Fourier Transformation (FFT), for faster calculation of the Fourier transform in the DFT, today allow the Fourier transformation of almost any function.

An internet search on experiments in physics faculties of German universities on optical Fourier transformation and Fourier optics revealed the following topics: intensity distribution of a diffraction pattern as square of the Fourier transform of the diffraction object, properties of the Fourier transform, modelling of the scattering of X-rays at atoms (form - and structural factor) and spatial filtering (Abbe's microscope theory, descreening of images). Decisive for the RCL optical Fourier transformation was the idea to visualize as many mathematical properties of the Fourier transformation as possible by a multitude

of diffraction objects in order to be able to investigate the structure of diffraction patterns of two-dimensional, periodic diffraction objects.

As in the case of our RCL diffraction and interference (Chapter 9), we also use here diffraction objects produced by electron beam lithography as objects. Fig. 13.1 qualitatively shows the difference between the diffraction pattern of a slit, produced by photo lithography in RCL diffraction and interference I, and the diffraction pattern of a rectangle, produced by electron beam lithography, in this RCL optical FT.

## 13.2 Experiment and RCL variant

### 13.2.1 Experimental setup and function

As can be seen in Fig. 13.2, a very simple experimental set up and standard (laser diode  $\lambda = 532$  nm). The distance  $s$  between the diffraction object and the screen is so large that Fraunhofer diffraction is present. The glass plate with diffraction objects is reproducibly positioned by means of x-y stages. The diffraction objects are summarized in Table 13.1. Details - geometrical dimension - of these approximately 150 objects can be found in RCL menu point *Experimental Setup*.

### 13.2.2 Navigation menu

After the menu point *Experimental set up*, the menu point *Theory* follows and is shown in detail such that it is sufficient for self-study; namely

- the relationship between diffraction and FT,
- the properties of convolution of functions and their FT,
- the opt. FT by means of diffraction in detail:
  - Aperture functions,
  - Diffraction patterns of individual forms,
  - Diffraction patterns of gratings/lattice,
  - Confirmation of some features of FT.

In the menu point *Theory* the RCL optical Fourier transformation provides the theoretical basis for all diffraction objects (Table 13.1) for

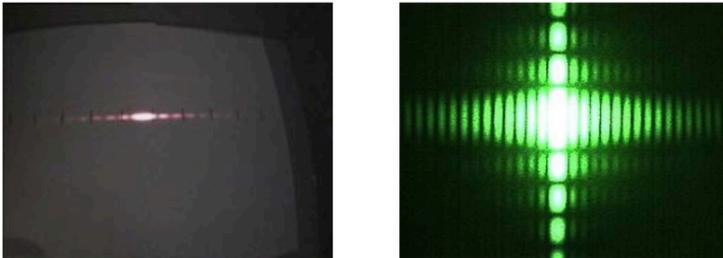


Figure 13.1: Screenshots of diffraction patterns of a photo lithographically produced slit with slit width  $a = 100 \mu\text{m}$  (left) and a rectangle produced by electron beam lithography with width  $a = 90 \mu\text{m}$  and height  $b = 30 \mu\text{m}$  (right) [1].

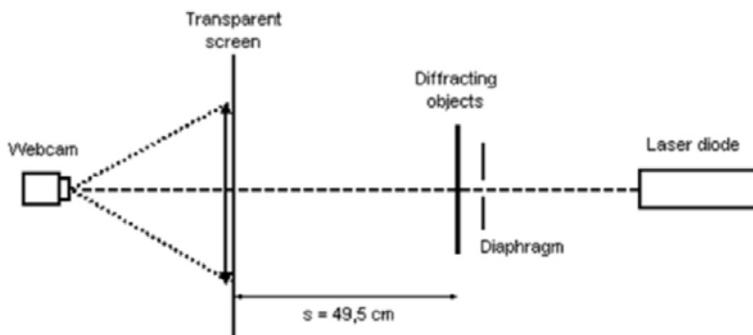
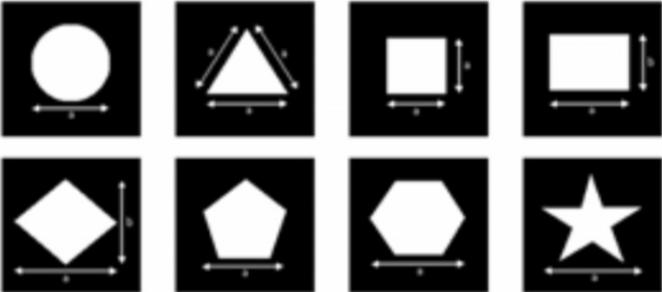
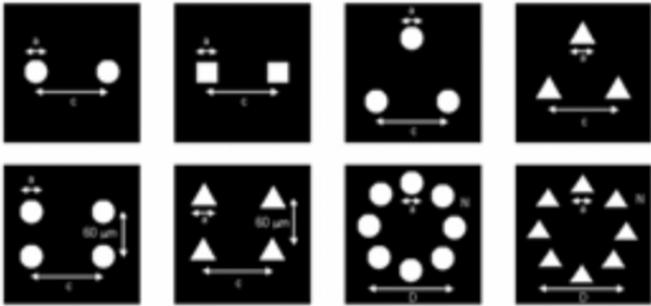
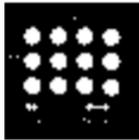
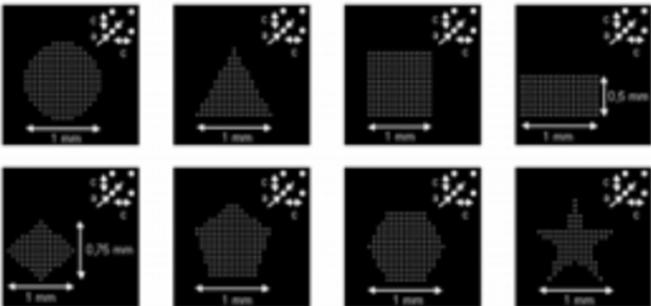


Figure 13.2: Experimental setup.

analyzing the diffraction pattern measured by the user himself (see section Measurement results). The menu point *Tasks* proposes a very complex, wide measuring program. The menu point *Laboratory* displays both the webcam image of the diffraction pattern and the geometry of the associated, even selected diffraction object from 150 options. The menu point *Analysis* describes an example of the experimental verification of two properties of the FT: the scaling law as well as the linearity and displacement theorem (see later measurement results). The menu point *Discussion* asks questions about experimental set up, theory, laboratory and analysis. The menu point *Material* contains information about the objects, the electron beam lithography process, the laser diode and the web cam used here. Hints under *didactic materials* concern applets for FT as well as specialised books about FT.

Table 13.1: Overview of the diffraction objects.

Nr.	Group	Variants	Number
1	Single forms		50
2	Single forms at the corners of forms		48
3	Circles in rectangle-limited square lattice		33
4	Circles in quadratic lattice bounded by individual shapes		16
5	Circles along segment and crossed slits		6 3

### 13.2.3 Theoretical basics (in short)

In Fig. 13.3 the diffraction object is described by the aperture function  $f(x, y)$ . If light is diffracted at the object, a diffraction pattern is created on the screen.

The electric field strength  $F$  is the Fourier transform of the aperture function

$$F(X, Y) = FT[f(x, y)]$$

and the light intensity of the diffraction pattern is

$$I(x, y) = [F(X, Y)]^2.$$

Some important properties of  $FT$  are summarized in Table 13.2.

For example, if one increases the aperture in  $x$  direction by one factor  $a$  (in  $y$ -direction by a factor  $b$ ), the diffraction pattern is compressed by a factor of  $1/a$  in the  $x$ -direction ( $1/b$  in  $y$ -direction). (See later measurement result).

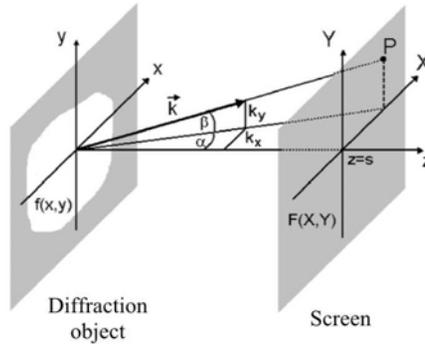


Figure 13.3: Fourier transformation of the aperture function  $f(x, y)$  into the Fourier transform  $F(X, Y)$ .

Table 13.2: Properties of the FTs.

Property	$f(x, y)$	$F(u, v) = FT[f(x, y)]$
Similarity (scaling, stretching)	$g(ax, by)$	$(1/ ab ) \cdot G(u/a, v/b)$
Linearity	$a \cdot g(x, y) + b \cdot h(x, y)$	$aG(u, v) + bH(u, v)$
Shift	$g(x-x_0, y-y_0)$	$e^{ix_0u} \cdot e^{iy_0v} \cdot G(u, v)$
Folding	$g(x, y) * h(x, y)$	$G(u, v) \cdot H(u, v)$
Reversal of folding	$g(x, y) \cdot h(x, y)$	$G(u, v) * H(u, v)$
Separation	$g(x) \cdot h(y)$	$G(u) \cdot H(v)$
Reversal of shift	$e^{iu_0x} \cdot e^{iv_0y} \cdot g(x, y)$	$G(u-u_0, v-v_0)$

### 13.2.4 Operating the experiment

Fig. 13.4 shows the laboratory page for the case of the selected object: single-form rectangle with dimensions  $a$ ,  $b$ . On the left side one can see the webcam image of the intensity distribution on the screen, including the scheme for the geometry of the diffraction object. On the right side one can see the control panel.

As one can see, the RCL can be operated intuitively and provides the user very quickly with their own measured values in form of screenshots for later evaluation. We are following a series of learning objectives in student lab:

- Select object (diffraction object from 150 options, due to physical problem),
- Record measured results (save a screenshot of the diffraction pattern),
- Take measurement series (dimensions of the diffraction object to dimensions in the diffraction pattern, order  $n$  from maxima / minima to position of maxima / minima),
- Detect relationships (number of individual objects to number of sub-maxima, separability in the diffraction object to that in the diffraction pattern, symmetry of diffraction object to symmetry of diffraction patterns, limiting single shape to the pattern in the reciprocal lattice, diffraction object of several individual shapes to the modulation in these patterns).

In summary: The operation of the RCL is simple but experiment-specific. The focus here is not so much in measuring the intensity distribution as in the analysis and discussion of the diffraction patterns.

### 13.2.5 Measurement result

In order to motivate and illustrate how good the results are obtained with the RCL optical Fourier transformation, we will explain a few quantitative measurement examples below.

Table 13.3 beautifully shows the relationship between the geometry of the diffraction object, the measured diffraction pattern, the

### Optical Fourier-Transformation

Remaining time to perform experiment: 127 s

— Laser —

— Diffracting objects —

Group

Variant

Dimensions

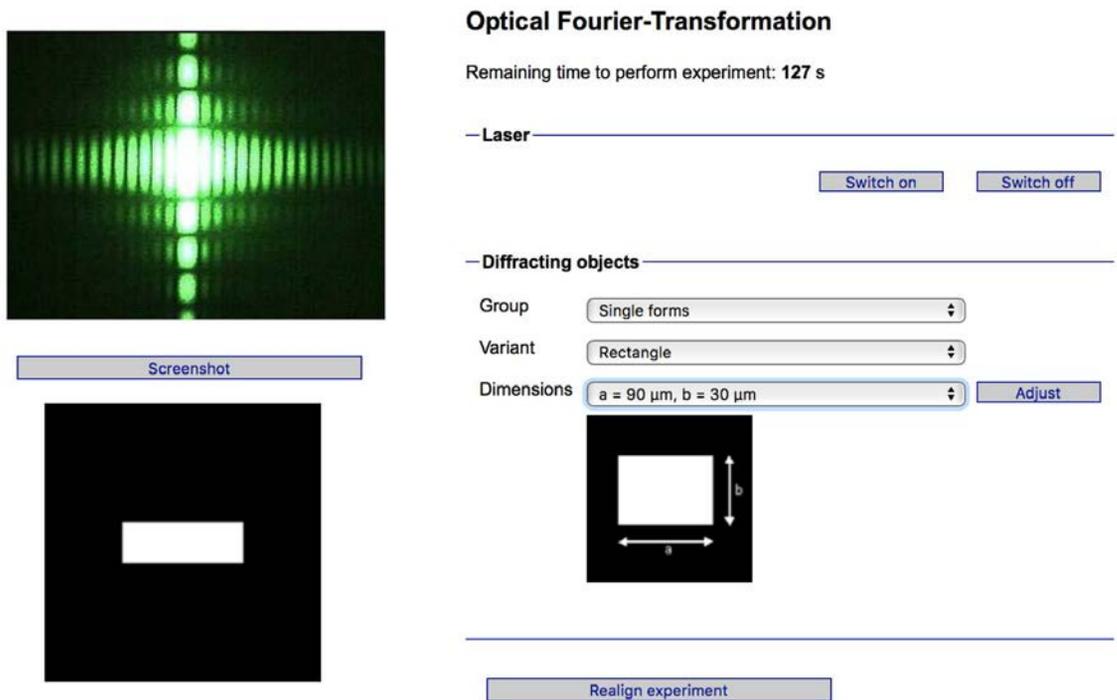


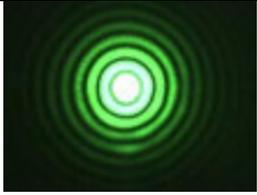
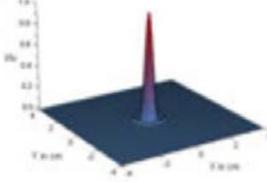
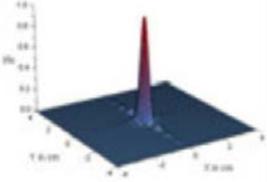
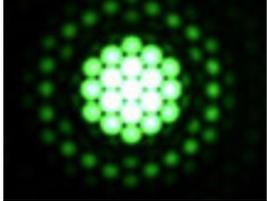
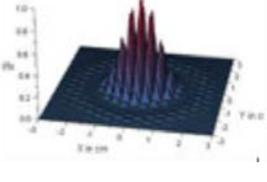
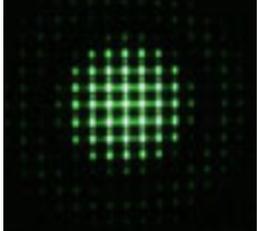
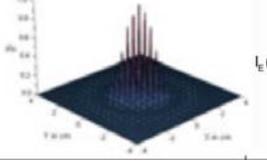
Figure 13.4: Lab page of the RCL Optical Fourier Transformation.

theoretical intensity distribution  $I/I_0$  and the mathematical expression: as an example, the pinhole ring structure Bessel function  $J_1$ ; relevant to the resolution of optical devices due to diffraction.

The second measurement example shows the determination of the minima in the diffraction pattern of a pinhole (Fig. 13.5). The evaluation can either be done in the screenshot of the diffraction pattern by a graphics program (e.g. Paint by Microsoft) or a video analysis program (e.g. with Coach).

Theoretical values  $X_{\text{theo}}$  in Table 13.4 were determined from the tabulated zeros of the Bessel function of the 1st order and the parameter values  $s = 49,5 \text{ cm}$ ,  $\lambda = 532 \text{ nm}$  and  $a = 60 \text{ μm}$ . Experimental values  $X_{\text{exp}}$  agree with the theoretical values  $X_{\text{theo}}$  within the measurement accuracy of  $\pm 1 \text{ mm}$ .

Table 13.3: Experimental and theoretical representation of the intensity distribution of diffraction patterns ( $J_1$  is 1st order Bessel function).

Nr.	Experimental intensity distribution		Analytically calculated intensity distribution	
	Geometry of the diffraction object	Diffraction pattern	Graph	Function $I(k_x, k_y)/I_0$
1				$\left[ \frac{J_1\left(\frac{1}{2}a\sqrt{k_x^2 + k_y^2}\right)}{\frac{1}{2}a\sqrt{k_x^2 + k_y^2}} \right]^2$
2				$\left[ \frac{\sin\left(\frac{a}{2}k_x\right)}{\frac{a}{2}k_x} \right]^2 \cdot \left[ \frac{\sin\left(\frac{b}{2}k_y\right)}{\frac{b}{2}k_y} \right]^2$
3				$I_c(k_x, k_y) \cdot \left[ \left( 2\cos\left(\frac{c}{2}k_x\right) + \cos\left(\frac{\sqrt{3}c}{2}k_x\right) \right)^2 + \sin^2\left(\frac{\sqrt{3}c}{2}k_y\right) \right]$
4				$I_c(k_x, k_y) \cdot \left( \frac{\sin\left(N\frac{c}{2}k_x\right)}{\sin\left(\frac{c}{2}k_x\right)} \right)^2 \cdot \left( \frac{\sin\left(M\frac{d}{2}k_y\right)}{\sin\left(\frac{d}{2}k_y\right)} \right)^2$

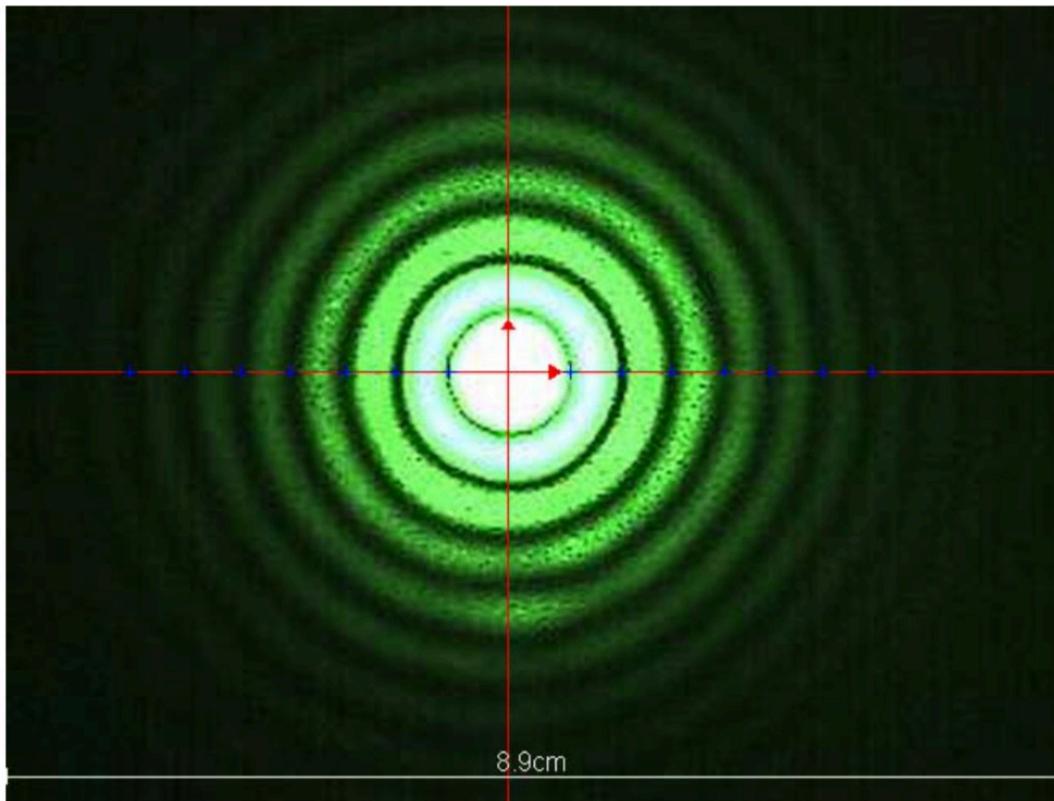


Figure 13.5: Determination of the X coordinates of the minima in the diffraction pattern of a circular aperture with diameter  $a = 60 \mu\text{m}$ .

Table 13.4: Comparison of theoretically and experimentally determined X-coordinates of the minima in the diffraction pattern of Fig. 13.5

Order $ n $	1	2	3	4	5	6	7
$ X_{\text{exp}} $ in mm	5.1	9.6	13.8	18.4	22.5	27.0	31.5
$X_{\text{theo}}$ in mm	5.3	9.7	14.1	18.4	22.8	27.1	31.5

The third example concerns the scaling law. According to the scaling property of the FT, the dimensions of the diffraction object and of the diffraction pattern are reciprocal to each other (see Table 13.2). For experimental verification, screenshots of the diffraction patterns of square apertures with different edge lengths  $a$  were created (Fig. 13.6):

Qualitatively it can be seen in the image sequence that with increasing edge length e.g. the diameter of the central maximum or the distance between the minima of the same order in the horizontal or vertical direction decrease. The PixelProfile software was used to investigate the relationship between the edge length  $a$  and the distance  $d$  of the 3rd order minima (Figure 13.7). The image width is 318 px and with the actual image width of 16 cm (see experimental set up) one gets a conversion factor of 0.0503 cm/px.

Table 13.5 shows the distance  $d''$ , the actual distance  $d$  and the product  $ad$  for checking the antiproportional relationship between  $a$  and  $d$ . It applies the product  $ad$  approximately constant with a mean value of  $1.225 \cdot 10^{-6} \text{ m}^2$  and a standard deviation of  $8.2 \cdot 10^{-9} \text{ m}^2$ . The scaling law can thus be experimentally reproduced by this RCL with high accuracy.

The fourth example shows the transition from a square aperture to a diamond-shaped one; i. e. the argument of the aperture function is transformed linearly.

$$g(x, y) = \text{rect}\left(\frac{x}{a}, \frac{y}{a}\right) \quad f(x, y) = \text{rect}\left(-\frac{a}{e}x + \frac{a}{f}y, \frac{a}{e}x + \frac{a}{f}y\right)$$

Figure 13.8 shows the diffraction object and the measured diffraction pattern.

The transformation maps the 90 degree-inside angle of the square aperture to the interior angles of the rhombus. In the diffraction pattern of the rhombus, therefore, the angle between the two crossed rows of the brighter maxima of 75 degree coincides with an interior angle  $\alpha = 2 \cdot \arctan(f/e) = 74$  degree of the rhombus.

In the fifth example, the linearity of the FT is checked (Table 13.2).

According to the linearity theorem, the Fourier transform of a linear combination of functions is the linear combination of Fourier transforms (see Theory). We show the linearity theorem in the special case of the diffraction pattern of two circular apertures of diameter  $a$  at a distance  $c$  and aperture function  $a_e(x, y)$  (Fig. 13.9).

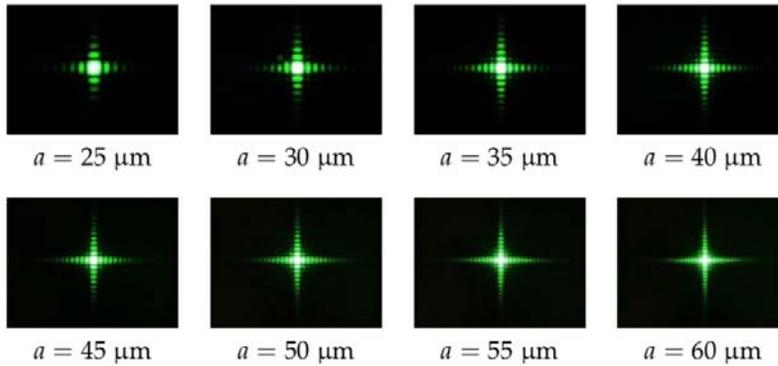


Figure 13.6: Screenshots of the diffraction patterns of square apertures with changing edge length  $a$ .

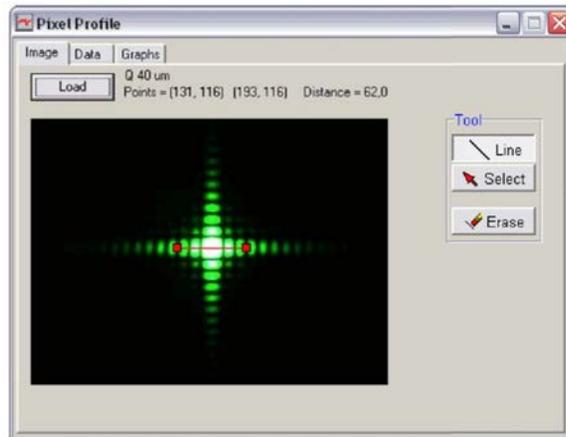


Figure 13.7: Determination of the distance of the 3rd order minima in the diffraction pattern of the square aperture with edge length  $a = 40 \mu\text{m}$ .

Table 13.5: Measurement results and check of the relationship  $ad = \text{const.}$

$a$ in $\mu\text{m}$	$d''$ in px	$d$ in cm	$ad$ in $10^{-6}$
25	97	4,8791	1,21
30	81	4,0743	1,22
35	71	3,5713	1,25
40	62	3,1186	1,25
45	53	2,6659	1,20
50	48	2,4144	1,21
55	44	2,2132	1,22
60	41	2,0623	1,24

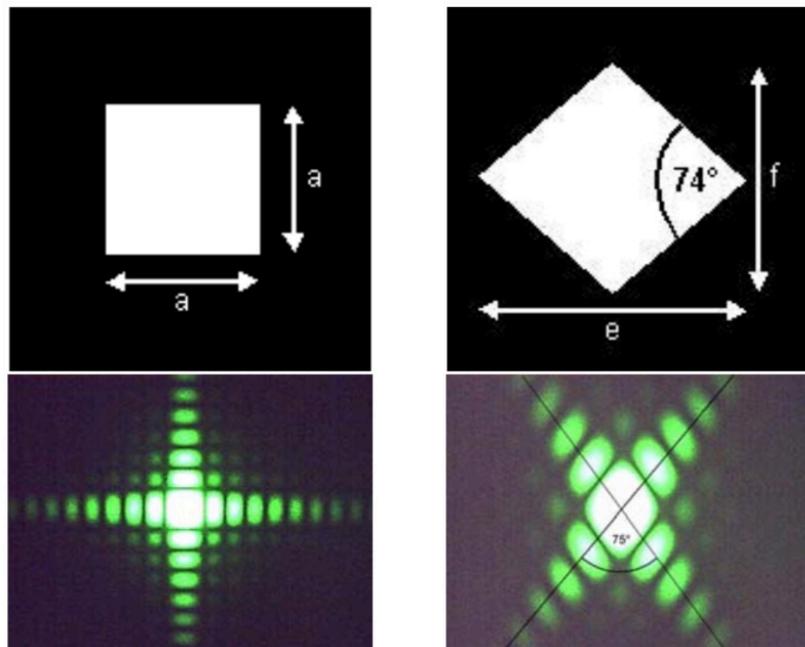


Figure 13.8: Transformation of the aperture function and the intensity distribution of a square of the edge length  $a = 50 \mu\text{m}$  into that of a diamond with the diagonal  $e = 50 \mu\text{m}$  and  $f = 37.5 \mu\text{m}$ .

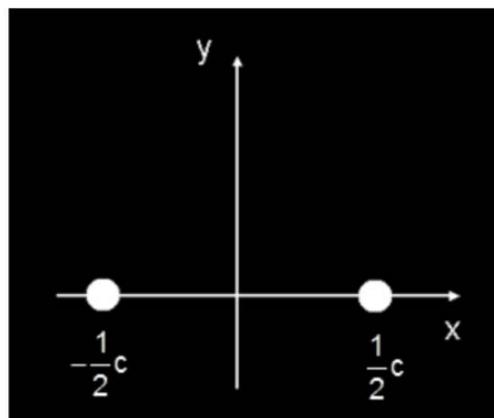


Figure 13.9: Diffraction object - two circular apertures of diameter  $a$  at a distance  $c$ .

According to this, a diffraction pattern of cosine squared modulated diffraction pattern of a circle is to be expected in a horizontal direction. Fig. 13.10 with the diffraction patterns of two circles of the same diameter  $a$  and variable distance  $c$  confirms this assumption.

According to theoretical derivation, the minima of order  $n$  must be in cosine square modulation (see Fig. 13.11 - vertical lines) for  $X_{n, \text{theo}}$ . In Table 13.6 experimental values  $X_{n, \text{exp}}$  are compared with the theoretical values  $X_{n, \text{theo}}$  for the case at distance  $c = 60 \mu\text{m}$ ; a very good measurement result with a tolerable (5%) measurement error.

In the menu point *Analysis*, this example number five is derived step by step mathematically.

In example 6, the teacher / experimenter can deal in great detail with symmetries and group theory. If the diffraction function is e.g. axisymmetric to the  $y$ -axis ( $f(x, y) = f(-x, y)$ ), then the electric field strength is axisymmetric to the  $y$ -axis ( $F(k_x, k_y) = F(-k_x, k_y)$ ) and thus also the intensity. A rotation of the diffraction object by the angle  $\alpha$  also rotates the diffraction pattern by the angle  $\alpha$ ; a shift of the diffraction object has no influence on the diffraction pattern. In Fig. 13.12 these general statements are confirmed on the basis of 8 diffraction objects and these corresponding diffraction patterns. In examples 5-8, the number  $n$  of symmetry axes and the number  $n$  of the rotation axis of the diffraction patterns are twice as large as those of the diffraction objects, respectively. (We wonder why?).

In the last example we show the diffraction pattern of a complex object (Fig. 13.13). In order to make the expected diffraction pattern in advance, one only has to go through the 3 steps mentally. What is the diffraction pattern of the single form (here circles); what is the diffraction pattern of periodicity (here quadratic lattice); what is the diffraction pattern of the limiting single form (here a rhombus)?

### 13.3 Evaluation and experience

The quality of the diffraction patterns of the illustrations presented here speak for themselves; With corresponding graphics program or video analysis programs, these diffraction patterns can be quantitatively evaluated with high accuracy. The examples, chosen here, range from a simple pinhole to complex diffraction objects.

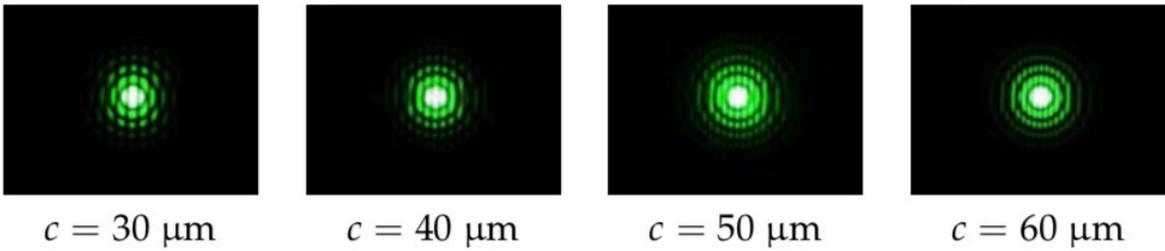


Figure 13.10: Diffraction objects from two circles each with a diameter of  $a = 30 \mu\text{m}$  and a variable distance  $c$ .

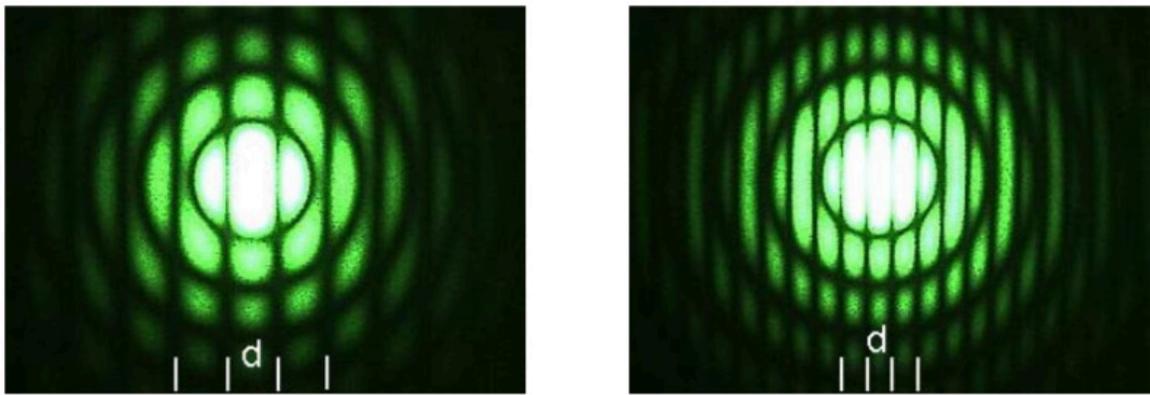


Figure 13.11: Diffraction objects from two circles each with a diameter of  $a = 30 \mu\text{m}$  and a variable distance  $c$ .

Table 13.6: Measurement results and evaluation of the cosine square modulation in the diffraction pattern of two circles (for the case  $c = 60 \mu\text{m}$ ).

Order $n$	$X_{n,\text{theo}}$ in cm	$X_{n,\text{exp}}$ in cm	$X/X_{n,\text{theo}}$ in %
1	0.18	0.19	5.5
2	0.54	0.51	-5.5
3	0.90	0.86	-4.4
4	1.26	1.22	-3.2
5	1.62	1.55	-4.3
6	1.98	1.92	-3.0

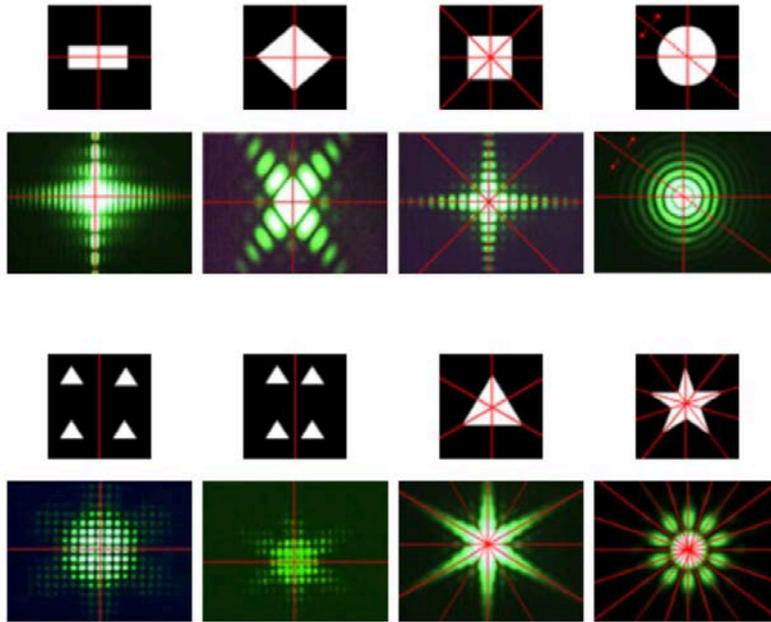


Figure 13.12: Number  $n$  of the axes of symmetry or number  $n$  of the axis of rotation (perpendicular to the image plane) of diffraction objects and their diffraction patterns.

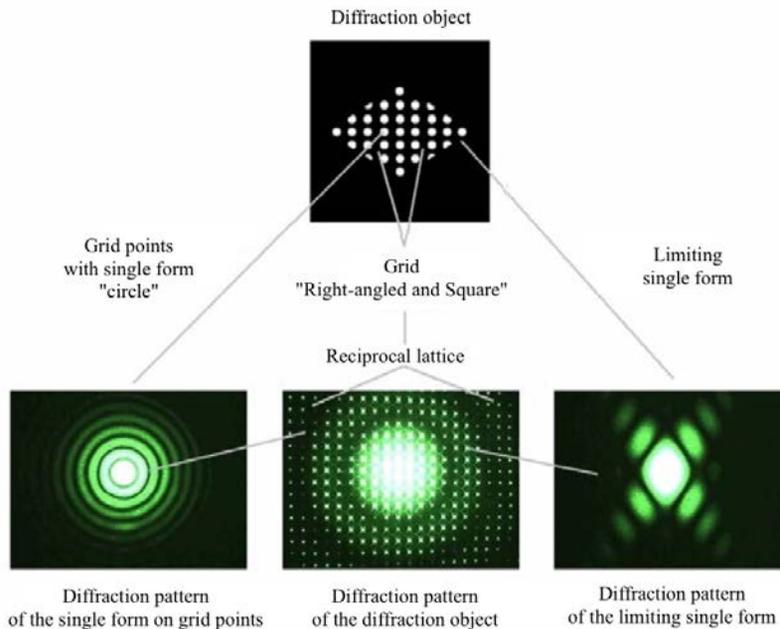


Figure 13.13: Relationship between the structure of the diffraction object (square-shaped and single-form quadratic grid) and the diffraction pattern.

The RCL experiment is online since 2009 without any problems. In order to reproducibly and precisely position the glass plate with the diffraction objects (Fig. 13.2), it requires a high-quality stage (in the original version, we used the displacement unit of an x, y plotter).

In the last years this RCL - opt. FT was used about 2-3 times a day.

As already mentioned several times, this is not so much about experimenting as much more about appropriate evaluation of own measured data; even more about the independent definition of a measurement question / measurement program based on self-study.

## 13.4 Didactic material

The topic of Fourier transformation is ideal for simulations. Fig. 13.14 shows a screenshot of such a program [2] with the diffraction pattern (right) of a complex diffraction object (left):

- Single form - circles,
- Lattice - square,
- Rectangle as a boundary.

Our search identifies up to 10 simulation programs for the FT, but of different quality.

In physics lessons at school level, the simplest examples could be measured both qualitatively and quantitatively:

- Comparing photo-lithographically objects to objects produced by electron-beam lithography (Fig. 13.1),
- Diffraction pattern of a pinhole (Fig. 13.5),
- Verification of the scaling law (Fig. 13.6, 13.7),
- Parallel modelling of the diffraction pattern of the selected diffraction object using an applet.

These topics could be treated as a project or in group work.

All other target groups - physics teachers, students - we hope to motivate intrinsically: be it by the aesthetics of the diffraction patterns, or by the challenge to mathematically manipulate self-measured diffraction patterns by the Fourier transformation.

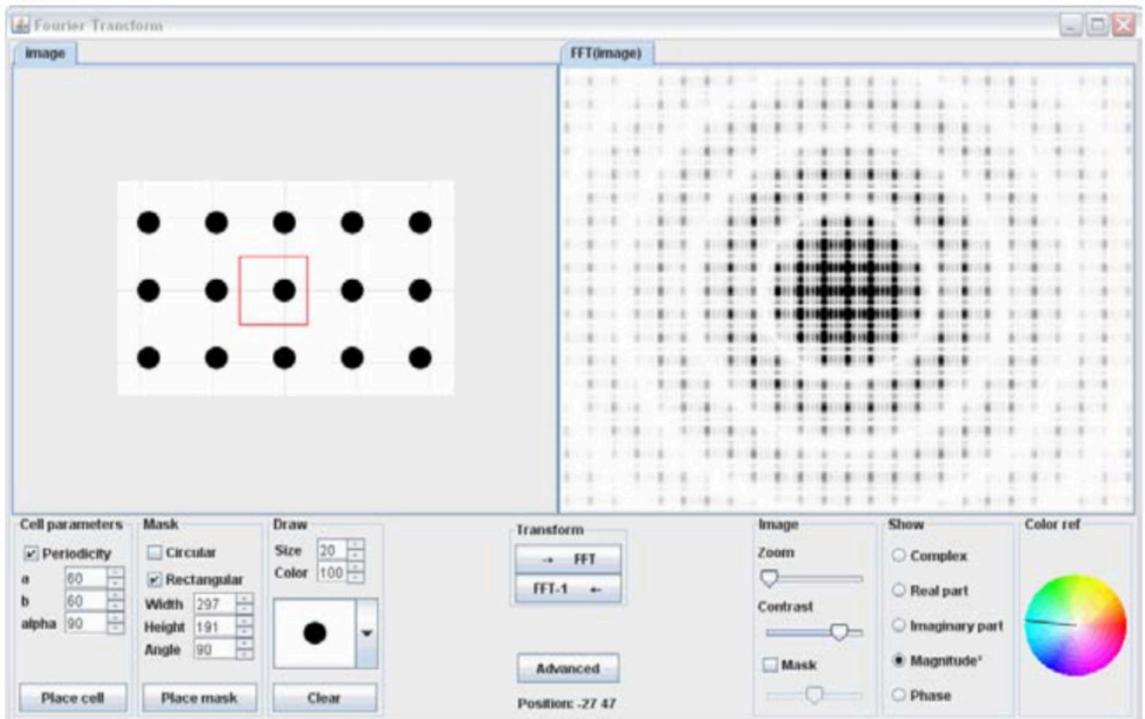


Figure 13.14: Fast Fourier Transform (FFT) of a square circled grid constrained to 5x3 circles with a rectangular function.

## 13.5 Literature

- [1] Gröber, S. "Experimenting remotely (RCL project at the Technical University of Kaiserslautern): Development, evaluation, examples and use of RCLs in teaching." Thesis. Kaiserslautern: University of Kaiserslautern, 2011.
- [2] Schoeni, N. and Chapuis, G. *Applet Fourier Transform Lausanne*. url: <http://escher.epfl.ch/fft>



# 14 Suggestions

In this chapter, we conclude on the present usage of the ten RCLs described above. For example, we explain our experiences regarding the question of what the student learns when using RCLs and what material has to be provided for the teacher. It is also interesting to see if, from a retrospective perspective, this was the right way to use RCLs and change teaching / learning methods. Finally, we ask if RCL clusters can complement or even replace the school's physics collection.

Then we dare to look ahead. This raises the question of an evaluation of our RCL experiments in comparison to demonstration experiments; including the efficiency of experimenting remotely. The research question is the analysis of the behaviour of users when dealing with RCLs. We are also looking forward to further proposals and suggestions for the construction of further RCLs, as well as the production of RCLs by students themselves and other associated student activities.

In between, we will briefly outline what supportive measures we have taken for the practicing teacher. How our RCLs are valued and accepted by practicing teachers. Finally, we will briefly discuss upcoming courses and workshops related to this book. The goal here is to work with teachers to explore the possibilities of RCLs; ultimately also to establish the use of RCLs in classroom. (This booking system is in German language only, since 90% of the users are from German speaking countries.)

## 14.1 Conclusion and experiences

Since 2001, we have built 20 RCLs by the year 2009, and since 2005, we have been monitoring their acceptance by teachers and the efficiency of experimenting by foreign users. Table 14.1 gives an overview of the RCLs described here. Of interest here is how often the RCL is called up as well as the way of experimenting.

Table 14.1: Summary assessment of our RCLs.

RCL	Online since	User per day	specific experimentation	Usage
c measurement	2006	11-12	√	Single or series measurement
Millikan experiment	2006	18-19	√	Single observation, measurement series
Rutherford scattering	2007	4	√	Single or series measurement
Electron diffraction	2001	12	√	Single or series measurement
Photoelectric effect	2005	10	√	Single or series measurement
Radioactivity	2006	15	√	Set of experiments
Diffraction and interference II	2009	5	√	Set of experiments
World Pendulum (5x)	2008	9		Global experimenting
Oscilloscope & U-I characteristic	2007	14		Set of experiments
Wind Tunnel	2006	8		Qualitatively / quantitatively measuring
optical FT	2009	2-3		Tutorial / self-study

All RCL experiments are still stable without major technical problems. Since we regularly testing all RCLs, failures of any kind can be quickly detected and remedied on site (battery change, lamp replacement, camera settings, internet access, etc.). For years, we have recorded an average of 10 - 15 users per day per RCL (total around 30 000 users per year). Since more than 90% of the users come from German-speaking countries, we can list comparative figures: number of high schools nationwide about 3000-4000 [1]; each of these RCLs is demonstrated in a GK (basic course) / LK (advanced course) as a real experiment about once a year.

The way in which our RCLs are experimented can be outlined by the following features:

- The handling of each individual RCL is experiment-specific,
- One can experiment qualitatively / quantitatively,
- Single / serial measurements are feasible,
- A special RCL replaces a special real experiment,

- Some RCLs are designed to be flexible enough to allow a set of single experiments,
- All RCL experiments have an added value compared to the corresponding real experiments.

The web presence of the individual RCLs is similar; the navigation menu reflects the scientific approach to a physical experiment; the laboratory page is intuitive to use. As a result, the user quickly gains a positive habituation effect. The same applies to the RCL portal in terms of organisation, structure and content. So far, we have no feedback that users are not coping with our RCLs. So far, we have not done any empirical research on how students are coping with these RCLs? How do they experiment with locally available experiments in comparison? What students learn for themselves, such as the use of ICT in general or work on the PC? However, over the years we have offered and supervised special promotions for students and have gained valuable experience from them. Here are two examples:

#### 1. Summer camp at the TU Munich, 2005

Fifteen students in grades 10-13 (age of 16-19 years old) worked in groups on the RCLs Toll system, Measurement of the speed of light, Labyrinth Robot, and Photo Effect. Partly prefabricated components were provided to the students. They had to build up the experiments, in part to do the programming of the interfaces and create the web pages. The results were presented to the public on the last day at the Deutsches Museum in form of posters and lectures, and these RCLs were presented via internet access. (For interested parties see details at each of these four RCLs in the sub-item didactic material under summer camp)

#### 2. Summer School at the University of Udine / Italy, 2011

In the Department of Physics of the University of Udine, a summer school (lecture, seminar, student lab) on atomic physics and quantum mechanics was offered for about 50 Italian secondary school students for one week. On two afternoons (2-3 hours each) these groups did the following RCL experiments in a kind of student lab. For half an hour each experiment, the groups worked on RCL Millikan, RCL Rutherford Scattering, RCL Electron Diffraction, RCL Diffraction and Interference, RCL Photo Effect, RCL  $c$  measurement and RCL radioactivity.

Guided by an experiment-specific worksheet (see menu point didactic material for each RCL), the groups of 2 to 4 participants successfully used these RCL experiments; successful in the sense that measurement results were obtained, partially analyzed and evaluated. In a concluding discussion of all participants, the majority of the response was positive:

- Experimenting remotely does not pose a problem; neither technical nor emotional. Also, the necessary authenticity is given.
- The handling of RCL experiments is regarded as a valuable enrichment in terms of their ICT competence.
- Girls have less problem / shyness to experiment remotely than with real experiments. They are afraid to accidentally break something at the real set up. A freer way of experimenting is encouraged.

In the period 2006-2010, we trained several hundred physics teachers and a group of instructors in workshops on the handling and use of RCL experiments. Among other things, we asked, "How well is the RCL suitable for teaching?" The RCLs presented in chapters 3 to 13 were rated as meaningful and teachable by a majority, and on a response scale of -2 for a negative and +2 for a positive assessment rated at 1.0-1.6. Several events per year were organized and carried out partly as a one-day advanced training and partly as a three-hour workshop by different providers across Germany, such as: From the association Mint EC, from the association Schools to the Internet, from the employers association Gesamtmetall and from the Intel GmbH. Several goals were pursued here:

- To raise awareness of RCLs;
- To achieve independent experimenting by RCLs with high degree of participant autonomy;
- To encourage teaching / learning with RCLs in classroom.

In addition, we have provided didactic material for a part of our RCLs in a portal for teachers - teachers online [2]. On average, each of these nine posts is accessed daily by about 12 users. In total, this is over 100 visitors to the medial RCL contributions per day (as of

summer 2011). Of course, with this virtual advanced training we reach far more interested teachers than with complex real-time advanced education events (for those who are interested, see the didactic material for each of the 9 RCLs for teachers online).

As part of the project, we were busy selecting suitable experiments for the remote operation from the canon of experiments, designing, building and testing them as RCLs. Afterwards we worked out suitable didactic material for each RCL, written it and tested it in practical use. We assessed the quality of these RCLs according to whether this RCL experiment was sufficiently used by interested teachers / students; whether these RCLs are almost always functional and available in the network; whether users (teachers and pupils) make efforts with the websites and didactic material. All of these criteria were met by our RCLs. Further investigations are still pending; For example, empirical studies should follow these questions:

- How efficient is remote experimenting with RCLs compared to real experimenting in class? Are learning goals also achieved when using RCLs?
- Does the use of RCL change the teaching / learning behaviour? Will the hoped-for goal be achieved of increasing student media literacy?
- The effectiveness of good demonstration experiments is known. Can an RCL experiment provide similar results?
- Does it make sense to cover all important physics education demonstration experiments with a cluster of about 50 RCLs?
- These studies should be planned as empirical studies, as comparative class studies (with / without RCL), as a field study with some classes.
- Should traineeship training in the standard teacher training program take into account the use of RCLs and the related media didactics questions?
- Would it make sense to build a network of interested teachers who already routinely use RCL experiments?
- How do different users (teachers, students, lay-people) deal with RCLs in detail? Keyword is the tracking / monitoring of user behaviour when dealing with RCLs.

- Does the material of the RCLs (web pages, content, didactic material) meet the quality requirements of a textbook of schools, of books about student labs?
- And many more.

Up to now, we have closely focused the evaluation of the project on the product - how good are our RCLs? As a first step, we check the internet availability and technical stability of all RCLs by regular (1-2 times per month) tests (see Fig. 2.1 in Chapter 2) and project staff will test each RCL like a casual experimenter. In the case of defects of any kind, the patron of the respective RCLs will be contacted on site. As a rule, the faulty RCL returns within one week. For larger, time-consuming repairs / maintenance, this is made public in the portal - first page under the menu point RCL experiments. As our worldwide research for RCLs has shown on the net, this customer service is essential and vital. Not so much that the reputation of the project suffers, but the interested teacher must be sure that the RCLs are available and functioning as needed.

Finally, on the costs and whether it is the right way for a cluster of RCLs to replace parts of a school's physics collection. Even if local politicians / education politicians see a chance here to continue saving money, we estimate this danger low. An RCL experiment has the usual cost of the real experiment plus the cost of Internet capability as well as a PC, i. e. relatively low additional costs. The costs for programming, writing of websites / didactic material, etc., have to be taken over by pilot projects, projects or publishers. With this method - physics collection at each school and a cluster of RCLs - it would be ensured that teachers always have the experiment as RCL available and they do not have to struggle with this experiment in their classroom.

## 14.2 The booking system

A booking system allows the user of an RCL to reserve experimentation times in advance, such as when the use of the RCL is scheduled for a specific lesson. At present, our booking system is currently in operation at RCL Photoelectric effect. (The following screenshots and explanatory texts are from the manufacturer of this tool - Dr. G. Mihelcic,

Hochschule der Bundeswehr, Munich, who programmed and tested the booking system according to our wishes.)

Basically, our RCLs are always freely accessible. This principle is maintained as far as possible even when using the booking system. If the RCL is currently not reserved, or is currently being operated by a user, then one can continue to use the RCL freely and without prior registration or reservation.

The questioned by many teachers on training courses and desired booking system can thus be tested by anyone interested. However, the current number of visitors - about 10 users per RCL per day - does not yet require the mandatory operation of this booking system. However, the booking system basically provides the practicing teacher with certainty about the availability of a specific RCL as a prerequisite for use in real-life education. In Tab. 14.2 the relevant pages of the booking system are presented in detail to show how easy this system is to operate. (This booking system is in German language only, since 90% of the users are from German speaking countries)

Table 14.2 The booking system

Documentation

RCL time management tool

Access without reservation

**RCL - Millikan**  
**Besucherangaben**

Land:

Institution:

Beruf:

E-Mail:

Passwort:

Diese Angaben sind freiwillig. Sie dienen statistischen Zwecken. Gäste erlangen nur dann Zugang zum Labor, wenn es nicht in Benutzung ist. Falls Sie das Labor reserviert haben, müssen Sie die EMail-Adresse der Reservierung und das richtige Passwort für Datum und Uhrzeit der Reservierung angeben. Sie können das Experiment im voraus reservieren. Dafür müssen Sie eine gültige EMail Adresse angeben, an die eine EMail mit den Passwort/Passwörtern für die reservierten Zellen geschickt wird.

Das Experiment ist      Reservierung ist  
nicht in Benutzung und nicht reserviert.      möglich.

[Webmaster](#)

The figure above shows the input window at the beginning of the RCL. If the RCL is not in use and is not in use at the time of the visit, any user without the input of his data can use the RCL. Just click on [Access without reservation]

## Reserve / cancel time slot for RCL

**RCL - Millikan**  
**Besucherangaben**

Land:

Institution:

Beruf:

E-Mail:

Passwort:

The e-mail address is a necessary indication if you want to create or cancel a reservation.

In addition, the entry of the sent password is necessary in order to access the RCL via a previously made reservation.

If the experiment is in use, the following information appears, signaling that access without a reservation is currently not possible. In addition, the remaining time the experiment is expected to be in use is displayed.

Das Experiment ist in Benutzung (581 Sekunden) und nicht reserviert. Reservierung ist möglich.

[Webmaster](#)

If the RCL is in use, a reservation is possible in parallel.

The following window shows a test entry of a user with the email address prof@unibw.de.

**RCL - Millikan**  
**Besucherangaben**

Land:

Institution:

Beruf:

E-Mail:

Passwort:

## RCL - Millikan

### Reservierung

### Zeitraum buchen

E-Mail:

gewünschtes Datum:

gewünschtes Anfangszeit:

gewünschtes Dauer der reservierung:

[⇒ Ich habe bereits ein Passwort](#)

Die aktuelle Serverzeit ist: 07.06.2011 21:28

[Webmaster](#)

### Bestehende Reservierungen für den 07.06.2011

Zeit	:00	:10	:20	:30	:40	:50
0:00	-	-	-	-	-	-
1:00	-	-	-	-	-	-
2:00	-	-	-	-	-	-
3:00	-	-	-	-	-	-
4:00	-	-	-	-	-	-
5:00	-	-	-	-	-	-
6:00	-	-	-	-	-	-
7:00	-	-	-	-	-	-
8:00	-	-	-	-	-	-
9:00	-	-	-	-	-	-
10:00	-	-	-	-	-	-
11:00	-	-	-	-	-	-
12:00	-	-	-	-	-	-
13:00	-	-	-	-	-	-
14:00	-	-	-	-	-	-
15:00	-	-	-	-	-	-
16:00	-	-	-	-	-	-
17:00	-	-	-	-	-	-
18:00	-	-	-	-	-	-
19:00	-	-	-	-	-	-
20:00	-	-	-	-	-	-
21:00	-	-	-	-	-	-
22:00	-	-	-	-	-	-
23:00	-	-	-	-	-	-

Here the user has the option to first select a desired date. On the right side of the page reserved or free time slots can be viewed on this date. By clicking in the overview on the right side, the desired start time is transferred to the corresponding field.

## RCL - Millikan

### Reservierung

#### Zeitraum buchen

E-Mail

gewünschtes Datum

gewünschtes Anfangszeit  (z.B. 13:00)

gewünschtes Dauer der reservierung

- 5 Minuten
- 5 Minuten**
- 10 Minuten
- 15 Minuten
- 20 Minuten
- 25 Minuten
- 30 Minuten

[⇒ Ich habe bereits ein Passwort per E-Mail erhalten.](#)

Die aktuelle Serverzeit ist: 06.06.2011 10:21

[Webmaster](#)

#### Bestehende Reservierungen für den 06.06.2011

Zeit	:00	:10	:20	:30	:40	:50
0:00	-	-	-	-	-	-
1:00	-	-	-	-	-	-
2:00	-	-	-	-	-	-
3:00	-	-	-	-	-	-
4:00	-	-	-	-	-	-
5:00	-	-	-	-	-	-
6:00	-	-	-	-	-	-
7:00	-	-	-	-	-	-
8:00	-	-	-	-	-	-
9:00	-	-	-	-	-	-
10:00	-	-	-	-	-	-
11:00	-	-	-	-	-	-
12:00	R	R	-	-	-	-
13:00	-	-	-	-	-	-
14:00	-	-	-	-	-	-
15:00	-	-	-	-	-	-
16:00	-	-	-	-	-	-
17:00	-	-	-	-	-	-
18:00	-	-	-	-	-	-
19:00	-	-	-	-	-	-
20:00	-	-	-	-	-	-
21:00	-	-	-	-	-	-
22:00	-	-	-	-	-	-
23:00	-	-	-	-	-	-

In the field "desired duration of the reservation" the length of the desired time slot can be entered. Reserved time slots are displayed in red in the right-hand pane "Existing Reservations". By clicking in this area, the user can also select his desired time slot for the reservation the previously made entries are adjusted and the selected time slot to be reserved is displayed in dark green.

## RCL - Millikan

### Reservierung

#### Reservierung bitte bestätigen

Es wurde soeben eine E-Mail an die Adresse "prof@unibw.de" gesendet.  
Diese E-Mail enthält ein Passwort.

Bitte geben Sie dieses Passwort in das nachfolgende Feld ein,  
um nachzuweisen, dass Sie der Inhaber der E-Mail Adresse sind.

**Ohne diese Bestätigung gilt die Reservierung als nicht abgeschlossen  
und kann durch andere Reservierungen verdrängt werden.**

Passwort

[Webmaster](#)

On this page, the user must enter the password sent by the system to confirm the reservation.

In parallel, the time management system sends a message with the following content to the e-mail address specified by the user.

Dear user,

Thank you for your reservation request from RCL Millikan with the following information:

Date: 06.06.2011 Time from: 14:30 Duration: 5 minutes

To confirm your request use the following password on the RCL Millikan laboratory page: FUCAJEYE

(Please do not reply to this automatically generated e-mail.)

Best regards

The RCL Millikan reservation

The message sent includes the date, time and duration as well as the necessary access password for the reservation.

The screenshot shows a web interface for managing reservations. At the top, it says "RCL - Millikan" and "Reservierung". Below that, there is a section titled "Bestehende Reservierungen". A single reservation is listed: "am 06.06.2011 von 14:30 bis 14:35". To the right of this reservation is a button labeled "Reservierung löschen". Below the reservation list, there is a blue link that says "=> weitere Reservierung hinzufügen". At the bottom left, it displays the server time: "Die aktuelle Serverzeit ist: 06.06.2011 10:28".

If the reservation has been confirmed, the above confirmation window appears in which the existing reservations can be listed and cancelled. You can also add more reservations from this page. The user also arrives at this window when he enters the e-mail address and the password sent at the start window. On the system side, the number of maximum reservations per e-mail address can be limited. (by default to 5 reservations / email).

### 14.3 About the technique

We select RCL electron diffraction to describe the technical concept of our RCLs in the RCL portal. Figure 14.1 shows the basic experimental set up of an RCL from RCL server, interface and experiment.

The electron diffraction experiment is a standard experiment, set up with conventional high-voltage power supply unit and electron diffraction tube from educational equipment manufacturers. A web cam, interface and RCL server extend the experiment to an RCL. The numbered cable connections in Fig. 14.1 have the following functions: Communication between RCL server and interface via serial interfaces (1), 12 V power supply of the interface of the plug-in power supply unit (2), switched voltage of the high-voltage power supply unit (3), control of the output voltage of the high-voltage power supply unit or the acceleration voltage via the interface (4), heating voltage for the hot cathode of the electron gun (5), acceleration voltage for the electron gun (6), USB port of the web cam on the RCL server (7) and internet connection of the RCL server (8). In order to be able to observe the diffraction pattern on the scintillation screen with the web cam without interfering extraneous light, the entire experiment in operation is located under a darkening hood.

The realization of an RCL takes place in two steps. First, the experiment is set up computer-controlled, so that the experiment can be operated locally without access to the internet from the RCL server. The interface to the internet, including the website of the RCL, is then implemented, making the experiment accessible via the internet as a remote-controlled RCL worldwide. Fig. 14.2 shows a block diagram of the functional groups of RCL server, interface and experiment that are common to all RCLs. Arrows between the function groups indicate communication or dependency directions.

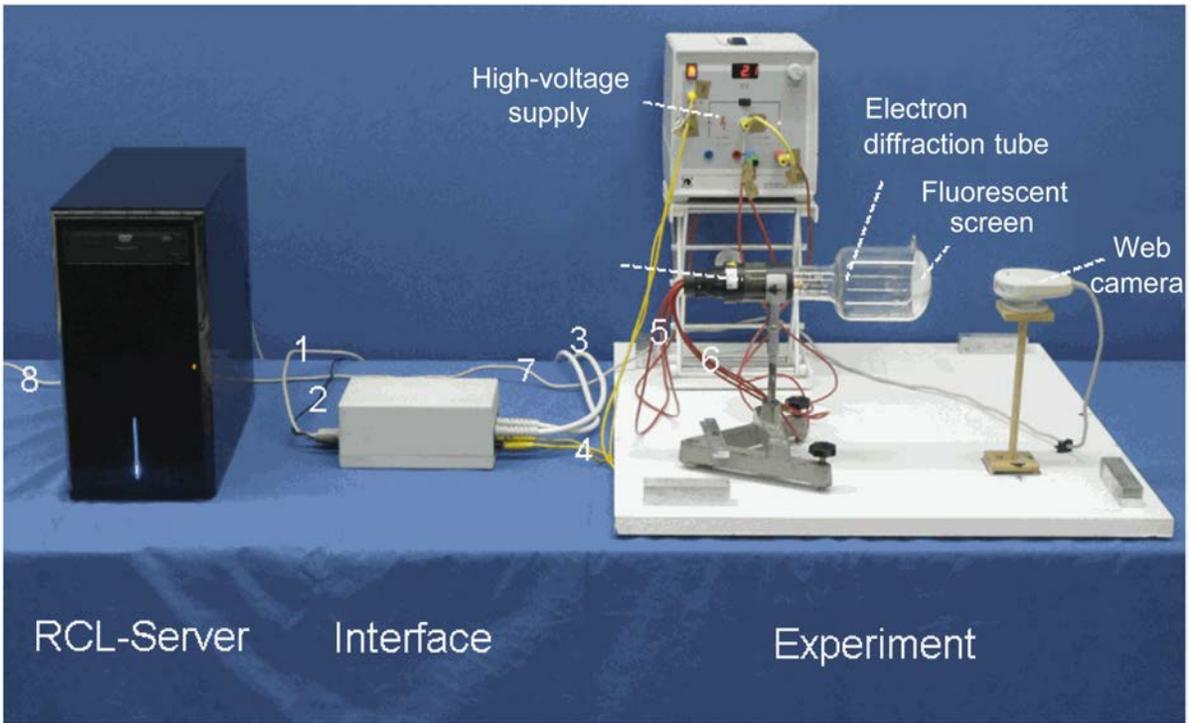


Figure 14.1: Experimental set up of an RCL using the example of the RCL electron diffraction.

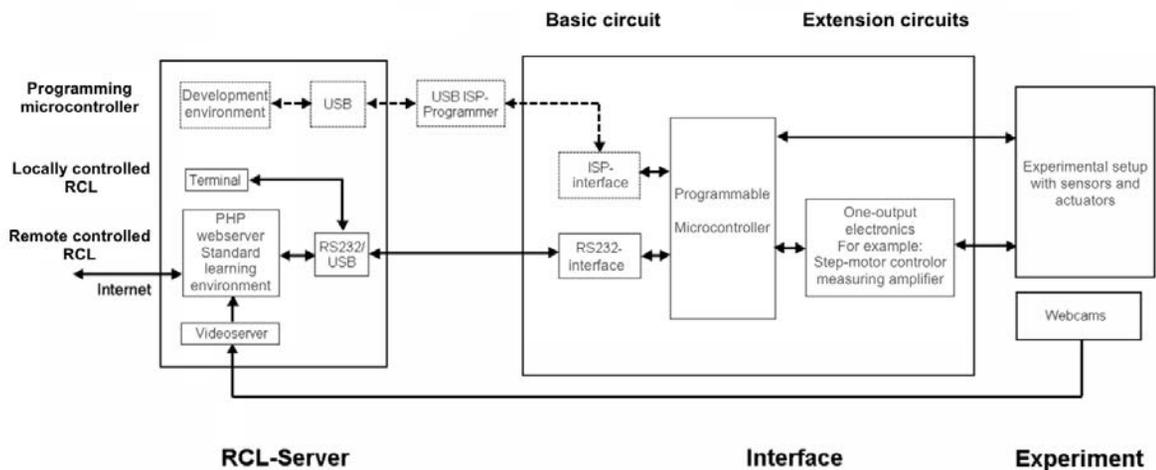


Figure 14.2: Function groups of RCL server, interface and experiment of an RCL.

- Locally controlled RCL

For the experiment to be remotely operable, the experimental set-up must be equipped with sensors (e.g. for temperature), actuators (e.g. stepper motor) or other controlled devices (e.g. high-voltage power supply unit in Fig. 14.1). The interface consists of a base circuit identical for all RCLs and expansion circuits for the sensors, actuators and controlled devices specific to each RCL.

The most important electronic component of the basic circuit is a programmable microcontroller for controlling the experiment, which can be programmed via an ISP interface. For program development, a development environment is used on the RCL server or alternatively on other computers. The program transfer from the RCL server to the microcontroller takes place via a USB ISP programmer and the ISP interface of the microcontroller. After that, the functional groups and connections shown in broken lines in Fig. 14.2 are no longer required and the RCL can be locally used, e.g. it can be operated via a terminal program.

- Remote RCL

In order to be able to access the RCL worldwide, a web server is installed on the RCL server and internet access is set up. Commands from the laboratory page user side, for example such as parameter inputs, are interpreted server-side by a PHP program and transmitted via the RS232 interface to the microcontroller for controlling the experiment. In the opposite direction, server side the PHP program transmits states of the experiment or measurement results to the laboratory page via queries to the microcontroller. A video server is set up to transmit video images of one or more web cams, which provide visual feedback on the status of the experiment. In addition to the dynamically generated laboratory website for operating and monitoring the real experimental set-up, the RCL server also provides the static web pages of the RCL's standard learning environment.

The software for the RCL server, the microcontroller and the standard learning environment:

Tab. 14.3 contains an overview of the programs for the RCL server and another computer that we use for programming the interfaces and creating the web pages. The links lead to the website for downloading

Table 14.3: Programs for the RCL server and other computers (links lead to web sites for downloading (status May 2010)).

	Type	Manufacturer, name and version
RCL server	Operating system and terminal	Microsoft, Windows XP Professional with Service Pack 3 Microsoft, HyperTerminal in Windows XP Professional under Start / Programs / Communications / Hyperterminal
	Web server and PHP	Apache Friends, XAMPP 1.7.4 for Windows, installer version The PHP Group, PHP 5.3.1 (included in XAMPP 1.7.4)
	Video server	Moonware Studios, webcamXP 5 Free (a video source) Moonware Studios, webcamXP 5 Private (up to 5 video sources)
	RCL Software	University of Kaiserslautern, RCL folder htdocs
	Virus Scanner	Avira, AntiVir Personal
	Remote maintenance and desktop sharing	TeamViewer GmbH, TeamViewer 6 Host
	Web Editor	Notepad ++ team, Notepad ++ 5.9
Computer	Development environment for microcontroller ATmega16	ATMEL, AVR Studio 4.18
		Sourceforge, WinAVR
		MCS Electronics, BASCOM-AVR demo version (maximum 4 kB program code)
		MCS Electronics, BASCOM-AVR full version
	Web Editor	MikroElectronics, MikroPascal Pro for AVR
		Notepad ++ team, Notepad ++ 5.9 Adobe, Dreamweaver CS5.5
Remote maintenance and desktop sharing	TeamViewer GmbH, Teamviewer 6 full version	

the program. Installation and configuration of programs will be discussed in the different sections of the tutorial.

The operating system used was Windows XP Professional for the RCL server. Microsoft has not been distributing Windows XP since December 2008, and security patches have been released by April 2014. A switch to the successor operating system Windows 7 is currently being tested and successfully realized meanwhile (status 2017). For the internet connection, we use the Apache web server and the PHP interpreter from the open-source package XAMPP. Since RCLs usually require two webcam images to be transmitted over the internet, we use the web cam XP5 video server (not for free). The hyper terminal

program as part of Windows XP allows direct communication with the interface, such as maintenance of the RCLs.

The selected hardware and software for RCLs offers the following advantages:

- Low hardware and software costs
- Simple adaptability of the interface and the PHP basic software to the experiment

The microcontroller of the interface can be freely programmed. By dividing the circuit of the interface into a base circuit common for all RCLs and RCL-specific expansion circuits, the interface can be easily adapted to the respective experiment. Besides the peripheral modules integrated in the microcontroller a few additional components are sufficient such that the widest variety of measuring and control variables can be processed. The PHP basic software only needs to be extended by a few program blocks.

- Easy access to resources of RCL technology

The widespread use of the microcontroller ATMEL®ATmega16 in the hobby sector corresponds to extensive, cost-free information material on the hardware and software of the microcontroller on the internet. A more structured learning of functions and programming of AVR microcontrollers is possible through the mentioned tutorials on the internet and books.

- Programming the microcontroller in Basic

In particular, the possibility of programming the microcontroller in the standard language Basic with Bascom AVR makes it easier to get started in the production of RCLs by students themselves. In addition, analogous to PHP programming, the microcontroller programming consists of basic programming which is only adapted to the respective RCL.

- Operating system independence

The interface does not require operating system-specific drivers. PHP and HTML are supported across operating systems. The Apache web server XAMPP is available for Windows, Linux, Mac OS X, and Solaris.

- Maintenance of programming and interface

PHP / HTML programming changes can easily be made by remote access to the RCL server. Since the PHP / HTML source code is always available in an executable form in RCL mode, personnel changes during programming, maintenance or further development of the RCLs do not lead to failures of the RCLs. Changes and repairs to the additional circuits of the interface can be easily carried out due to the breadboard portion of the board.

- Destructive experimental components

Components are protected by the programming of the microcontroller against incorrect operation of the RCL and at the same time also against direct access from the internet. Since the microcontroller monitors the permissibility of parameter values, it is not possible for third parties to misuse the experiment via the internet. Crashes of the RCL server do not lead to undefined states of the experiment because the microcontroller controls the experiment in the interface. In the lifetime more limited experimental components, for example the electron diffraction tube in RCL electron diffraction, can be turned off by a programmed standby function of the microcontroller when not in use.

- No installation of additional software

Users only need a free web browser to experiment with RCLs, such as Internet Explorer, Opera, Firefox, Safari or Konquerer with JavaScript enabled functionality. No additional software, such as plug-ins, has to be installed.

An alternative technical solution for RCLs compared to our chosen hardware and software is, for example, LabVIEW (Laboratory Virtual Instrument Engineering Workbench) of National Instruments (NI). LabVIEW is a very comprehensive, industry-standard, graphical programming environment for measuring, controlling, and regulating, and especially labware. Extensive driver libraries enable almost all common devices equipped with an appropriate interface to be integrated in LabVIEW. This makes the high prevalence in laboratories of universities and industry understandable. It is not surprising that most RCL projects in engineering departments are using LabVIEW. In our RCL project, LabVIEW was not used as a technical solution for several reasons:

- Visitors must first install the LabVIEW Run-Time Engine before experimenting with RCLs.
- There are only a few school equipments with the required interfaces.
- The license cost of about 1300 € for the base version and about 2800 € for the full version is high.
- LabVIEW is oversized for the RCLs to be developed or for the target audience of students. The replication of RCLs by interested pupils and students would be difficult because of cost and requirement reasons.
- LabVIEW's graphical programming interface still requires adjustments to be made in the programming language G, which has been specially developed for LabVIEW. LabVIEW thus differs from the typical high-level languages taught in computer science education.
- LabVIEW familiarization is at least as high in terms of time and requirements as it is for microcontroller programming and PHP programming.
- A lab page, designed with finished LabVIEW elements, is not necessarily more user-friendly than a lab page created with PHP / HTML

We asked ourselves if students are able to build a simple RCL by themselves (topics are abundant, see later); Half of our 20 RCLs were designed, built and tested by students, who intend to become a physics teacher - without special knowledge. As part of the summer camp 2005, which was mentioned several times, we built four RCLs with a group of students from schools. Out of this group of students, a student stood out with all the necessary skills: electronics, programming, manual skills and organization. This student (Markus Ludwig) together with the inventor of our technique (Dr. M. Vetter) wrote a technical tutorial. (Link: RCL project, then self construction, then tutorial on RCL technology, downloadable with about 50 pages.)

This tutorial (Table 14.4) guides one step-by-step from start to finish: schematics and component list, tools, board assembly, stepper motor control module as an example, microcontroller programming source code, php programming, web cam embedding, etc. We have no

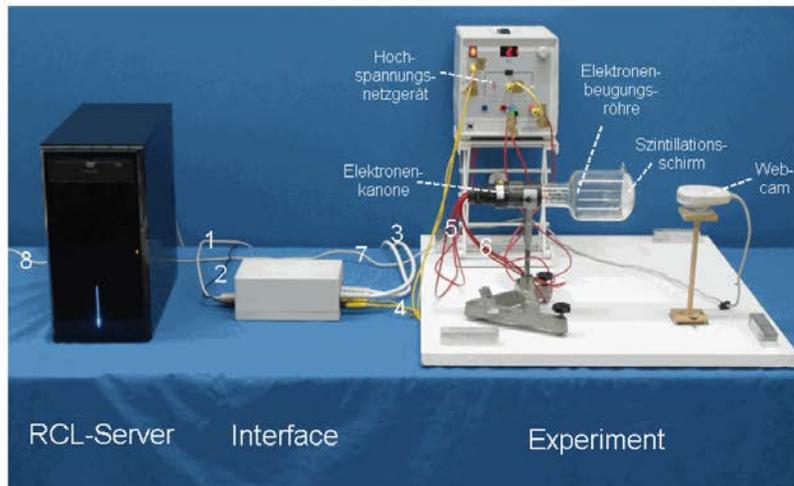
feedback on how often this self-assembly guide is used - in whole or in part. In advanced training course, we asked about 100 physics teachers if they were motivated to supervise the self-assembly of an RCL by students. About 10% expressed interest. In addition, we asked how much knowledge / prior knowledge the teachers have, especially on sensors and actuators, microcontroller programming, PHP programming, board assembly, mechanical design, HTML programming, etc. About 90% of the teachers interviewed said that they need support in these areas. Even if it seems that the vast majority of physics teachers could not handle self construction with this tutorial, and that very few students currently have time / interest and perseverance to make their own, we believe that in the future such student activity will be / should be more supported.

Table 14.4: Tutorial

## Remotely Controlled Laboratories (RCLs)

Technik-Tutorial der RCLs des RCL-Portals

<http://rcl-physics.de>



Arbeitsgruppe Didaktik der Physik  
an der Technischen Universität Kaiserslautern  
Juni 2011

## 14.4 RCLs open up new teaching / learning methods - become the subject of research

In chapter 2.2 we briefly touched on how the "pressing buttons" in the laboratory page is related to learning goals in student labs. With our approach, we have achieved that our RCL experiments are experiment-specific and fairly faithful to the real experiment. We have mentioned the different forms in dealing with an RCL for students and teachers as users - there the tracking / monitoring only hinted. And we have described a variety of new teaching / learning methods when using RCLs. We want to deepen some of them here by way of examples.

We present a blended-learning course for the self-construction of RCLs, including the self-assembly technique tutorial detailed in the previous section. The aim of the blended-learning course (see Table 14.5) is the foundation of RCL working groups in schools. In this course teachers and students in grade 10-12 (age of 17-19 years old) will be introduced the self construction of RCLs; partially during school lessons, partially during homework at home.

This course includes four days of presence at intervals of 1-2 weeks. Times between the presence days at schools serve to deepen the previous days or prepare for the next presence days. The technique of RCLs and physics are taught one after the other with a focus on technology (vocational preparation). Estimated costs for five working groups and multiple use about 1000 euros.

The evaluation of multimedia is a wide field. Here we would like to briefly outline the evaluation of RCLs as a product and RCLs in the teaching / learning process using three examples:

1. Quality of RCLs involving students (media literacy), in which students apply the following criteria to multimedia products.

- Availability

(Technical stability, availability on the Internet)

- Accessibility / Restriction

(Exist web pages, register / login, restricted user group, personal data, booking, language, if the link works, loading time, additional software, test questions, cost liability, link search, status display.)

Table 14.5: Course of the blended learning course "Self-construction of RCLs".

Phase	Content
Technics of RCLs	
1. Presence day electronics	<ul style="list-style-type: none"> <li>•Objective of the course, introduction to soldering and functional groups of the interface in basic circuit, construction and testing of the interface in basic circuit</li> <li>•Introduction to sensors and sensors for temperature, light intensity and time measurement</li> <li>•Switched voltage sources</li> <li>•Construction and examination of the circuits with an experimental board</li> </ul>
School	<ul style="list-style-type: none"> <li>•Setup and testing of the sensor circuits in the interface</li> <li>•Soldering of 2 step motor controls according to instructions</li> </ul>
2. Presence day microcontroller programming	<ul style="list-style-type: none"> <li>•Introduction to microcontroller programming, explanation of the basic program, development environment BASCOM, Program transfer with USB programmer</li> <li>•Programming and measurements by the sensors</li> <li>•Programming and testing of stepper motors</li> <li>•Presentation of the materials for kinetic experiment, objective of the kinetic experiment</li> </ul>
School	<ul style="list-style-type: none"> <li>•Own programming experiments with sensors and stepper motors</li> <li>•Planning of the mechanical and functional experimental setup of a kinetic experiment</li> </ul>
3. Presence day mechanics	<ul style="list-style-type: none"> <li>•Realization and test of the kinetic experiment</li> <li>•Presentation of the kinetic experiment</li> </ul>
Physics	
School	<ul style="list-style-type: none"> <li>•Develop proposals for a physical experiment</li> <li>•Prepare a presentation to plan an RCL</li> </ul>
4. Presence day planning RCL	<ul style="list-style-type: none"> <li>•Presentation and discussion of the planned RCLs</li> <li>•Information about integrating RCLs into the RCL portal</li> </ul>
School	<ul style="list-style-type: none"> <li>•Realization of RCLs with the aim of its publication on the RCL portal</li> </ul>

- User friendliness

(Scrolling, pop-up windows, arrangement of elements, redundant input / output elements, feedback, logging in / out, function of images, diagrams ...)

- Web cam pictures

(Display, charging time, continuous transmission of video without perturbations, sharpness, size / resolution, test setup in the long shot, clarity, recognizability of experimental components, perspective, co-observation ...)

- Text information

(Language, redundancy, superfluity, missing, wrong / unintelligible, wrongly placed, abbreviations ...)

- Functionality

(General, automated measurement ...)

- Concept

(Selection of the experiment, professional accuracy, added value.)

- Interactivity

(see earlier chapter 2.2)

- Authenticity

(see earlier chapter 2.2)

We imagine that students in the context of media education are clearly able to define these criteria, to apply them to multimedia products (checklist) and finally to learn to value (for interested parties, see details in [3]).

2. In Table 14.6, we compare the forms of the real experiments with RCL experiments to sharpen the gaze of the practicing teacher "Am I willing to work with RCL experiments?"

In this confrontation of significant four forms of real experiment - two with the teacher (L) and two with students (S) as an experimenter - the RCL experiment shows its own profile, strengths and weaknesses.

Table 14.6: Comparison of forms of the real experiment.(index L stands for teacher ,S for student).

	<b>Demonstration Experiment (L)</b>	<b>Free-hand experiment (L)</b>	<b>Student experiment (S)</b>	<b>RCL (S)</b>
Student determines experimental location?	No	No	No	Yes
Student determines experimental time?	No	No	No	Yes
Student determines experimental duration?	No	No	No	yes
Material effort for experiment?	Medium	Low	High	None
Protection against destruction of components?	No	No	No	Yes
Amount of preparation for teacher?	Low - high	Low	High	None
Direct interaction between student and experiment?	No	No	Yes	Yes
Planning the experiment by students?	No	No	Yes	Yes
Carrying out qualitative experiments?	Yes	Yes	Yes	Yes
Carrying out quantitative measurements?	Yes	No	Yes	Yes
Combination of experiment and theory?	Easy	Heavy	Medium	Easy
Material and technical requirements?	High	Low	High	Low
Parallel experimenting of several students?	No	No	Yes	No
Personnel supervision of the students during the experimenting?	Yes	Yes	Yes	No
Variability of the experimental setup?	Medium	Low	Medium	No
Building the experiment by students?	No	No	Yes	No
Time required to carry out the experiment?	Low - high	Low	High	Medium
Proximity to the experiment in research?	No	No	No	No
Technical Support for Component Defects?	Yes	-	Yes	Yes

3. At university level, e.g. as part of the teacher training, one could imagine empirical studies with the following questions:

- Which organizational models for using RCLs throughout upper secondary education at gymnasium level are feasible and successful?
- Which amount of time for experimenting with RCLs besides school lessons makes organizational sense and is accepted by the pupils?
- Which forms of teaching / learning prove themselves in the classroom? Which forms of teaching / learning are particularly suitable for the preparation and support of learning with RCLs outside classroom?
- Do RCLs have the didactic potential to change physics education in schools in the long term towards larger experimental proportions?
- Can students develop a culture of experimentation and a better understanding of the experiment as a method of physics by RCLs?
- Do students, when experimenting with RCLs at home alone, develop their own hypotheses and questions rather than by demonstration experiment in class?
- Do students prefer an active experimenting with RCLs to the passive pursuit of a demonstration experiment?
- How do teachers and students assess the learning of physics compared to RCL, demonstration and student experiments?
- Are students able to acquire physical content based on an RCL and, if necessary, additional materials outside classroom, given existing learning prerequisites?
- Are student groups outside classroom able to collect and evaluate a larger amount of measured data by digital communication and self-organization?
- How long do students need to complete experimental homework with RCLs?

- How important is it for students with RCLs to experiment at home without any time limit and without the influence of classmates and the teacher?
- Do students at home experimenting with RCLs use only the standard learning environment of the RCL or other sources of information?

Finally, questions about monitoring, i.e. how does a user (teacher, student, layman) handle an RCL experiment?

- How long is the user logged in?
- How are the web pages of the standard learning environment clicked, in which order, how long?
- Which technical parameters in the lab page are being changed? Random, systematic, repeated?
- How many interactions ("press buttons") are made in which time interval?
- etc.

This question - how does a user deal with a medium - already existed in the 1970s: learning programs, branched programs, hyper text. However, at that time powerful PCs and suitable tools were missing.

We would like to briefly explain an example of how we realized this monitoring in a first / single passing and with what success.

Basically, the user monitoring of the RCL lab pages is done with the help of log files: The lab pages of RCLs are programmed in such a way that actions of visitors in the control panel are stored in a log file on the server. This log file can either be opened in a browser and saved or downloaded remotely from the RCL server. Using the example of the RCL electron diffraction, Fig. 14.3 shows the relationship between actions in the control panel of the laboratory page and the log file of the RCL: The visitor's date, time, IP address and action (ACTION) are recorded line by line. The date, time, and IP address can be used to count the number of visits in a given time period. The development of visitors of the use of our RCLs, but also the experimental behaviour, can be investigated in this way.

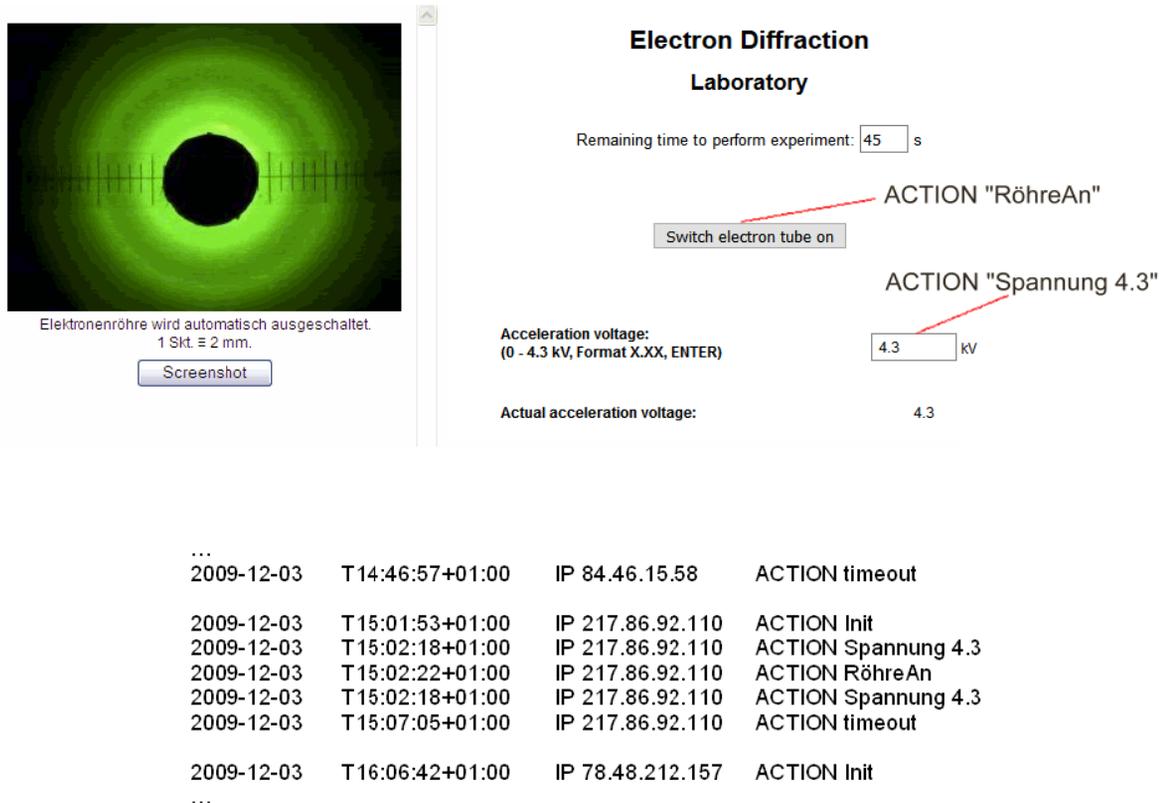


Figure 14.3: Relationship between actions on the laboratory side of the RCL Electron diffraction and their storage in a log file.

In chapter 3-13 we have already described for each RCL the respective result; in section evaluation and experience we analysed how the users were dealing with each RCL. Table 14.7 shows a kind of rough summary. The following became clear:

- Users are operating each RCL differently, i. e. experiment specific.
- Some of the users glance at the websites (minutes), one part measures qualitatively (5-10 minutes), one part measures quantitatively with long series of measurements (up to hours).

It is also planned to use the new booking system to design and apply a new, more in-depth, broader monitoring tool. The following questions are of particular interest:

Table 14.7: Amount of possible experimentation with RCLs

RCL	Observation time	visitors	Number of possible actions	Number of actions	Maximum experimentation period in h	Percentage in %		
						0-5 actions	6-10 actions	>10 actions
Speed of light	1.12.2008-30.11.2009	917	Decrease or increase distance of mirror, measure this, vary the height of reference signal and measuring signal (5)	419	4,0	17	29	54
Photo-electric effect	1.6.2008-31.5.2009	1037	Hg lamp on, choose frequency filter, choose grey filter, align experiment (3)	124	1,5	20	32	48
Radioactivity	1.6.2008-30.6.2009	924	Position distance of detector, angle of detector, choose direction of magn.field, magnet on /off, choose radioactive source, choose absorber, choose measuring time, time between 2 events, align experiment (9)	426	4,5	25	17	58
Electron diffraction	1.6.2007-31.1.2009	3292	Diffraction tube on, choose acceleration voltage (2)	140	1,5	-	-	-

- How do users work with the web pages of the learning environment (typically 15 pages per RCL?) How much is read? Does the user always leave the RCL at the same place or situation? Do they work with the tasks of each RCL, with the questions in the discussion part of each RCL, with the exemplary evaluation? Which didactic materials are downloaded (worksheet, tasks and solutions, lesson plans)?
- Does one and the same user return to an RCL experiment? Does he change his behaviour / experimenting? Does he start exchanging measured data, results, graphs, metric tables with other users from the internet? Is there a physical discussion growing between users about this experiment as RCL?
- Are there gender differences in experimental behaviour? From real experimenting and student labs such differences are

well known. It could be that girls trigger unbiased "press buttons" / interactions without fear of breaking anything.

- Questions about experimenting / laboratory page, see above. And many more.

Finally, another aspect of the meaningful combination between RCL experiment and simulation in the sense of integrated e-learning is the following. The development of simulation programs in the past has shown amplitudes in extreme directions, like a pendulum. Until the 1980s, the experiment was in the focus. Until the years 1990 - 2000 simulations / animations were praised as an experiment replacement. Now there are enough and very good simulation programs for almost all topics of physics [4]; a combination of RCL and suitable simulation is a good option. In chapters 3 to 13, we discussed this already in detail in the presentation of the 12 RCLs (see Table 14.8 as a summary).

In addition to the illustration of the RCL experiment by simulation / animation, a number of common tools are used in the evaluation of the own measured data of each RCL experiment (see Tab. 14.9).

All these additional media - simulation / animation for illustration and deepening and tools such as spreadsheets, computer algebra systems, data analysis, video analysis, etc. - are intended to deepen the media competence of students; not so much under the aspect of learning physical content.

## 14.5 Suggestions for additional RCLs

In our portal there are a number of RCL experiments that can be used either in natural science subjects (biology, chemistry, mathematics, computer science, especially physics) or in technical subjects; RCLs on other topics are conceivable. In addition, we have realized three simple RCLs that reflect projects produced by pupils. Here, too, we propose further topics. Furthermore, three topics suitable for self-studies are presented.

### 14.5.1 RCL in Science and Technology

The RCL optical Fourier transform applicable to the subjects of mathematics and computer science was discussed in section 13.

Table 14.8: RCL experiment and other media.

c-measurement	Animation (time of flight method)
Millikan experiment	Simulation of the process
Rutherford scattering	Simulation / Modelling of the scattering of alpha particles by gold
Electron diffraction	Animation (diffraction at lattice planes)
Photoelectric effect	Animation / Simulation of processes
Radioactivity	Animation of nuclear decay
Diffraction and interference	Modelling / Fitting of experimental data to theoretical hypothesis
U-I characteristic	Virtual electronic kit in student labs
Wind tunnel	Videos for the ideal, laminar, turbulent flow

Table 14.9: Possible use of tools on our RCLs.

Nr.	RCL	Paper, pen and calculator	Spreadsheet calculation e.g. Excel	Computer algebra e.g. Mathcad, Mathematica	Data analysis e.g. Origin	Graphic e.g. Paint, GIMP	video analysis e.g. Coach 6, Studio MV, Measure Dynamics
1	Optical computed tomography	X					
2	Diffraction and interference II	X		X		X	X
3	Semiconductor characteristics	X				X	
4	Radioactivity	X	X				
5	Optical Fourier transformation			X		X	X
6	Rutherford scattering experiment	X	X	X			
7	World pendulum	X	X	X			
8	Millikan experiment		X		X		
9	Diffraction and interference I	X	X			X	X
10	Speed of Light	X	X			X	X
11	Wind Tunnel	X	X				
12	Oscilloscope	X				X	
13	Electron diffraction	X				X	X
14	Photoelectric effect	X	X				
15	Toll system						
16	Hot wire						
17	Robot in a maze						

With optical tweezers one can take and position very small (micrometer-sized) objects. This instrument is currently considered the "modern" device in biological and medical laboratories. Figure 14.4 shows this experimental setup. As an RCL experiment, the user can turn the laser on / off, adjust the focal plane of the laser (vertical z-axis) and move the slide (polystyrene balls in liquid between two glass plates) relative to the laser focus in the horizontal x-y plane. A video camera on the microscope shows the user as a live image the quality of the laser focus and whether the laser has just captured a particle.

Interested readers will find an introductory article on optical tweezers [5]. This experiment is an experiment and in an RCL form in the Deutsches Museum, Munich [6].

Other topics could be:

- Modelling the solar spectrum based on continuum lamps and frequency filters,
- Comparison of bulbs of a household with regard to light intensity, colours, efficiency,
- Digital image processing and image recognition,
- Photosynthesis,
- Biological oscillations,
- Robotics, for example, grasping and manipulating sensitive objects.

### 14.5.2 RCL as projects for pupils

With the hot wire we simulated a well-known game of skill as an RCL: between a wire loop and a metal eyelet an electrical voltage is applied. Upon contact of wire and eyelet, a short circuit occurs which triggers an optical signal. In the game, the metal eyelet along the wire from start to finish is to be moved in the shortest possible time. Figure 14.5 shows the principle on the left and the experimental set up with Fischer Technik on the right. An initially green shining LED signals a touch by red colour. One could think of this game as an international contest by publishing the list of fastest time users in the RCL.

How a toll systems works for trucks on the motor highway shows the RCL toll. A Lego railroad locomotive with two cars (# 16 and # 17)

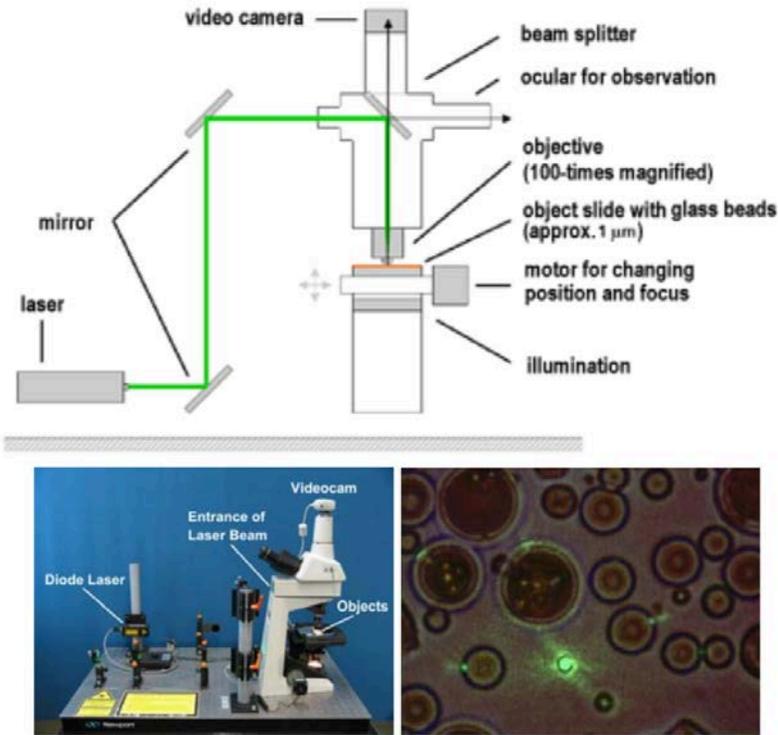


Figure 14.4: Optical tweezers: simplified scheme (top) and photo of the real set up (bottom left). The picture below right shows a still photo from the video of the microscope camera. The laser has captured a particle; Height of the insert about 20 microns.

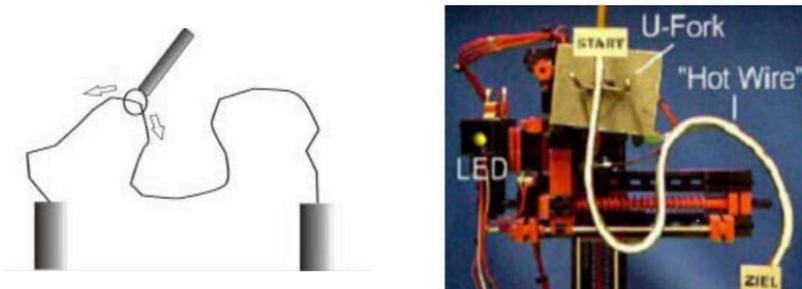


Figure 14.5: Hot wire as a game; left principle; right photo of the experimental set up. The user can move the fork along the wire; "Buttons" allow the movement up / down as well as partial rotation.

can be started and stopped on an elliptical orbit. Each car transmits an individually coded IR signal, which is decrypted by an IR detector with counter. A counter registers the signals transmitted from the carriages 16 and 17 and represents then the number of revolutions.

With the RCL robot in the labyrinth we have recreated the well-known Mars and Moon explorer probe. A robot is to be moved through a changeable maze (removable shelves, obstacles, mirrors, posters from the location of the RCL) and the user has to solve tasks. Two perspectives are possible: Lab view from diagonally above, as well as robot view (web cam on robot cart) (see Fig. 14.6).

At the end of this section we describe a list of possible other topics for RCL to build as a student/pupils project.

### 14.5.3 Self-study with RCLs support

In Chapter 11, we discussed in detail the RCL experiment U-I characteristics and the handling of an oscilloscope as RCL. In conjunction with a virtual laboratory "electronic construction kit" [7], a user / experimenter can independently work on the topic of electronics, technical components, and semiconductor physics.

The RCL wind tunnel (Chapter 12) is also useful, starting from the operation of the wind tunnel, to independently dealing with aero- and hydrodynamics with the help of special books.

As a final example, we introduce RCL optical computer tomography; This "analogy" experiment explains the widespread medical technique of computer tomography CT: instead of X-rays, we use light (red laser diode); instead of the X-ray detector, we use a light detector; instead of X-ray source and several detectors on a circle to turn around the patient on table, we move light source and detector along a sample and rotate this sample. From the shadow profiles measured per angle setting, the numerical back projection indirectly closes the geometrical shape of the sample.

In addition to pure experimenting - two differently shaped specimens, different rotation angles, number of scans, resolution - the user can work independently with different texts in the theory section: about the physics of CT, about mathematics, about computer science, medicine, technology itself. For us, this RCL was a prototype for self-paced learning by RCLs in many ways.

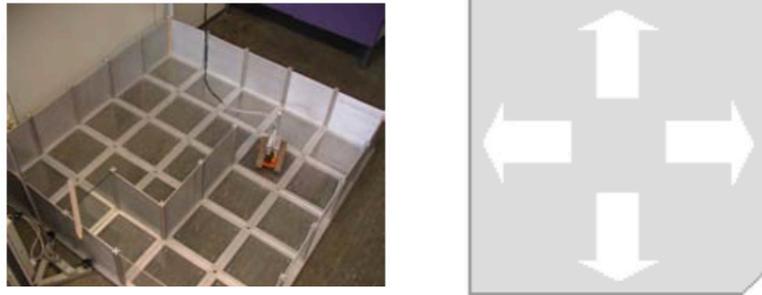


Figure 14.6: Lab view (left), right the control panel. For example, one task for the user is to find the location in the maze where the user can see the robot in a mirrored wall in the robot view.

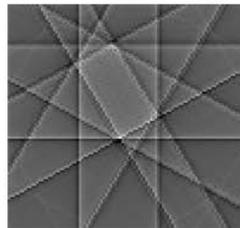


Screenshot

Instruction for experimenting see menu item "instruction"

### Optical Computed Tomography Laboratory

Remaining time to perform experiment:  s



Demo CT

Clear image

After data acquisition or change of parameters it will take a few seconds till the image is processed and displayed.

Align experiment

Actual sample: **cuboid**

Select sample

Resolution:  Pixel

Set resolution

Single scan at angle  $\theta =$   °

1 scan

5 scans with start angle  $\theta =$   °

and steps of  $\Delta\theta =$   °

5 scans

Window CW:  /

Set window

Shepp-Logan filter: **active**

Filter on/off

Actual angle of sample object  $\theta = 150$  °

Figure 14.7: Optical CT. On the left the experiment, on the right the control panel. We have two specimens mounted on a rotatable disc - below a cuboid, above principle of a vertebral structure. The control panel shows a vertical band at the top left. If one chooses the sample cuboid and scans once at 0 degrees, this picture is created. With this presetting the carriage moves from left to right passing the specimen holder. The laser is interrupted by the cuboid, we recognize the corresponding shadow strip.

#### 14.5.4 Suggested topics for further RCLs

The following list of further RCLs already considers the criteria for selecting a topic, whether it is suitable as an RCL experiment (see Section 1.2).

- Electrons in electric and magnetic fields,
- $e/m$  determination of electrons,
- Spectroscopy of nuclear gamma radiation,
- Michelson interferometer,
- Electromagnetic induction,
- Magnetic field of current-carrying conductors and coils,
- Electric field of charge distribution,
- Thermodynamic state diagrams ( $p - V$ ,  $p - T$ ,  $T - V$ ),
- Experiments with ultrasound,
- Compton effect,
- X-ray physics (e.g. generation, absorption, scattering),
- LED and Planck constant,
- Electrical oscillating circuits,
- Franck-Hertz experiment
- Wilberforce pendulum,
- 2D thermal conduction in a material by IR camera,
- Pohl's rotary pendulum,
- Chaos phenomena at the dripping faucet,
- Noise (electronic or acoustic, generation, Fourier spectrum, etc.),
- Humanoid robots.

A single provider (institute, school, educational manufactory industry, training centre, etc.) can not afford this offer to build, provide, and maintain a number of such RCLs. We envision a Europe-wide cluster of RCLs. In our experience, such a cluster is fully utilized to offer 10-20 RCLs.

### **14.5.5 RCL for DIY (do it yourself)**

Pupils and students should be motivated, trained and supervised to build their own RCLs themselves (keyword media literacy and preparation for the modern professional life). The training goal is not only to convey natural sciences, technology and ICT elements, but also to train and qualify pupils and students, to independently apply what they have learned at school, to trigger further self-study and to prepare for the future professional world.

First of all, the technical tutorial "RCL - DIY" (see section 14.3) can help the interested person. In the long term, easy plug and play technology for the educational materials industry should be provided, for example, in the form of standardized equipment components à la Fischertechnik, simple interface and software modules. The goal should be not to create a perfect RCL for teaching and use by strangers, but to build simple topics as RCL itself. It would also be advantageous to combine individual topics into a project that works with a group of students.

Possible topics that make the networking of schools meaningful in the long term:

- Disco applications

One student measures the noise level, another measures the humidity, another measures the lighting, another measures the number of visitors and records their dance movement, etc.

- Weather station

One pupil measures the pressure, the other student temperature, humidity, wind speed and direction, sunrise and sunset times measure others; a student realizes how to collect and display data. Finally, weather stations at schools can exchange data across Europe.

- Sports and Biology / Medicine

Students can write and compare personal training activities by web cams, Wii, and smart phones.

- Musical instruments

Stimulating the instrument, measuring the frequency spectrum, measuring the volume etc. of different instruments.

- Pollution near and in schools

One student measures the noise level, another uses a gas detector, one measures the fine powder in the air, etc., and compares schools in Europe.

- School garden / school pond

Detailed aspects are here monitoring and control as well as partial automation of school garden, greenhouse and school pond. Here, too, recording of important parameters (eg air / soil moisture) and sensor technology play a major role.

Individual topics can be dealt with on site or at different locations by different students - global experimenting. Internet communication allows for the exchange of experience, passing on tips and tricks as well as success and results - global communication.

## 14.6 Literature

- [1] Information from the Federal Statistical Office for the school years 2010/11 to 2011/12.
- [2] Lehrer-Online ([www.lehrer-online.de](http://www.lehrer-online.de)), see secondary level -> Physics -> Specialist Media -> Remotely Controlled Laboratories (RCLs).
- [3] Gröber, S. »Experimenting remotely (RCL project at the Technical University of Kaiserslautern): Development, evaluation, examples and use of RCLs in teaching«. Diss. Kaiserslautern: University of Kaiserslautern, 2011.
- [4] An International Group of Physics Professors meets annually. The group is grouped under the name "Multimedia in Physics Teaching and Learning (MPTL)" and collects and evaluates multimedia

products (currently freely available media over the Internet, primarily simulations). The website is [www.mptl.eu/](http://www.mptl.eu/). The evaluation and collection of the internet addresses can be found under the menu point "Evaluations of MM" (as of December 2013).

- [5] See, for example, the entry "Optical tweezers" at Wikipedia. As a lab experiment proposed by S.P. Smith, S.R. Bhalotra, A.L. Brody, B.L. Brown, E.K. Boyda and M. Prentiss: "Inexpensive Optical Tweezers for Undergraduate Laboratory", *American Journal of Physics* 67/1 (1999), 26-35.
- [6] Location of the experiment "Optical Tweezers" in the Deutsches Museum in Munich - Department: Centre for New Technologies.
- [7] Circuit simulation on a virtual board (electronic workbench); can be found as accompanying material on CD-ROM in school textbooks (e.g. Dorn-Bader, *Physics Sec. I*, Schroedel) or can be downloaded from the Internet (Physics Education Technology – PhET, [phet.colorado.edu/](http://phet.colorado.edu/)).



# 15 Conclusion

In the previous chapter, we finally evaluated our approximately 20 RCLs and summarized our experience over several years. The principle of the RCL techniques used and the open source programs used have been described to give the interested user / teacher sufficient insight. We presented the technique tutorial - for self-construction of RCL - for self-study. In addition, among the many new, possible teaching / learning forms when using RCLs, a blended learning course was also described, if an interested teacher would like to supervise a working group - RCL for self-construction. We described how students in media literacy could evaluate RCL experiments as a new medium by defining and applying criteria. Finally, we suggest a variety of new RCLs to be built in physics / science and engineering. As part of the initiative - RCL for self-construction - we list several individual experiments as part of higher-level project from the field of experience of the students.

In the first chapter, we gave an introduction to the position of real experiments in physics teaching, then described our concept of RCLs, and highlighted the educational scientific political aspect of RCLs. In the second chapter, we explained the basics based on the key question »what is a good RCL?«. We also discussed details and the implementation of our concept as well as the RCL experiment as a new medium. In chapter 3 to 13 we have presented about 10 RCL experiments in detail.

We take up the preface again, what are the goals of this book?

- Present RCL experiments as a useful substitute for real on-site experiments.
- The question - What is a good RCL? – was answered.
- Make a comparison: experimenting remotely and on-site in class rooms.
- Describe in detail the quality and potential of RCLs.
- Introduce several RCL experiments with teaching materials for the hand of the practitioner / teacher.

The reader may judge for himself how far the authors have realized these goals with the present work. In addition to presenting this thematic complex, we could hopefully assist the interested reader / teacher in facilitating their access to RCLs and the use of RCLs in self-study and teaching.

# 16 Acknowledgments

In the project (2001-2011), 20 RCL experiments were set up and tested, many teacher training courses were held about the use of RCLs in physics lessons, as well as around 40 publications and around 30 lectures were held. In the project group, the following employees were involved with special tasks. Without them, this project would not have been so successful. Thank you very much.

Teaching students have each built, tested and used a RCL as their scientific exam work:

- König, C. (2005): Diffraction and interference with Fischer Technik,
- Glas, F. (2006): Millikan's experiment,
- Söhnlein, H. (2006): U-I characteristics, oscilloscope,
- Zorn, C. (2006): Wind Tunnel,
- Hoffmann, M. (2007): Optical CT,
- Klinck, C. (2007): Radioactivity,
- Knecht, T. (2007): Rutherford scattering,
- Bender, K. (2008): Fourier Optics,
- Lüttkefedder, A. (2008): Diffraction and Interference,
- Schuhmacher, S. (2008): World pendulum,
- Thijs, R. (2008): Optical Crystallography.

The first RCL prototypes (electron diffraction, electrons in the B field, robots, IR camera) were built by D. Roth and S. Maus as part of the distance learning program FiPS at the department. Dr. M. Vetter supervised the technology of the following 20 RCLs, especially designed the interface; Dr. B. Eckert designed the RCL portal and the websites (including languages); Dr. S. Gröber in turn has adapted the complex Didactics of RCLs - such as lessons, evaluation, publications, teacher training courses .

Most of the RCL experiments were located at different locations (high schools, institutes, colleges, universities) and were well looked after locally. Special thanks are due to these patrons. Currently, the RCLs are mainly concentrated in a few locations with several RCLs, such as at the Hochschule der Bundeswehr in Munich (supervised by T. Krug), as at the Fachhochschule in Heilbronn (supervised by A. Szasz), as at the Saarpfalz-Gymnasium in Homburg (supervised by A. Wagner); the 4 world pendulums are in different places; the RCL optical CT is at the Technikmuseum in Berlin. The technical support of these 20 RCLs works perfectly thanks to the patrons on site. Thank you.

Over the years, the project has been generously supported by three sponsors: The Eberhard von Kuenheim Foundation of BMW AG with Dr. Glaser, Graf Kospoth and Mr Rohm, the Intel GmbH with Mr. Enslé and the employers' association Gesamtmetall with Mr. Gollub. All were convinced from the beginning of the potential of the RCLs and have helped over many years, so that sustainability could grow. Thank you very much.

From the summer of 2012 this project has changed hands: Prof. R. Girwidz (LMU Munich) with his coworkers S. Richtberg and L.-J. Thoms; and Prof. S. Pickl (Hochschule der Bundeswehr in Munich) with his coworkers T. Krug and G. Mihelcic. Since 2012, the project and the 20 RCLs have been excellently managed by this group. Thank you very much.

Finally, I thank Ms. T. Putzmann-Thoms for their help with the design of the book; from typing my handwritten manuscript to the L<sup>A</sup>-T<sub>E</sub>X version of the book. Thank you very much.

Munich, August 2013

Hans-Jörg Jodl  
(as head of the project)

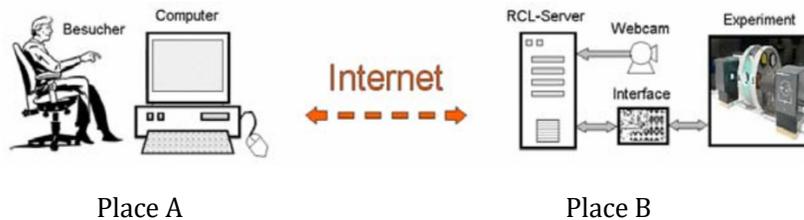
The authors would like to thank Prof. Dr. G. Torzo from the Physics Department in Padua (Italy) for helping us to translate the German version of the book to an English one.

Munich, February 2018

HJJ

# 17 Spine text (for the backside of the book)

An RCL experiment is a real experiment at location B that can be operated via the Internet from a location A with a PC.



The following RCL experiments are described, evaluated and put into a teaching context:

- Measuring the speed of light,
- Millikan's Oil Droplet experiment,
- Rutherford scattering experiment,
- Electron diffraction on graphite foil,
- Photoelectric effect,
- Radioactivity,
- Diffraction and interference,
- World pendulum to determine the location dependence of gravity,
- Current-voltage characteristics of semiconductor elements,
- Oscilloscope,
- Wind tunnel.

Each RCL experiment will be presented with in-depth didactic material, such as pupil worksheets, didactic analysis, lesson suggestions,

and very large-scale tasks with model solutions to almost all RCL experiments.

In the RCL portal ([www.remote-lab.de](http://www.remote-lab.de) as well [rcl-physis.de](http://rcl-physis.de)) all teaching materials for the book are available for download.

In a RCL project from 2001-2011, the writing team designed, set up and put into operation around 20 RCL experiments, including web pages and accompanying didactic material. Hereby Dr. M. Vetter was focussing on technology, Dr. S. Gröber on the didactic material, Dr. B. Eckert on the Internet pages and Prof. H.-J. Jodl led the project.