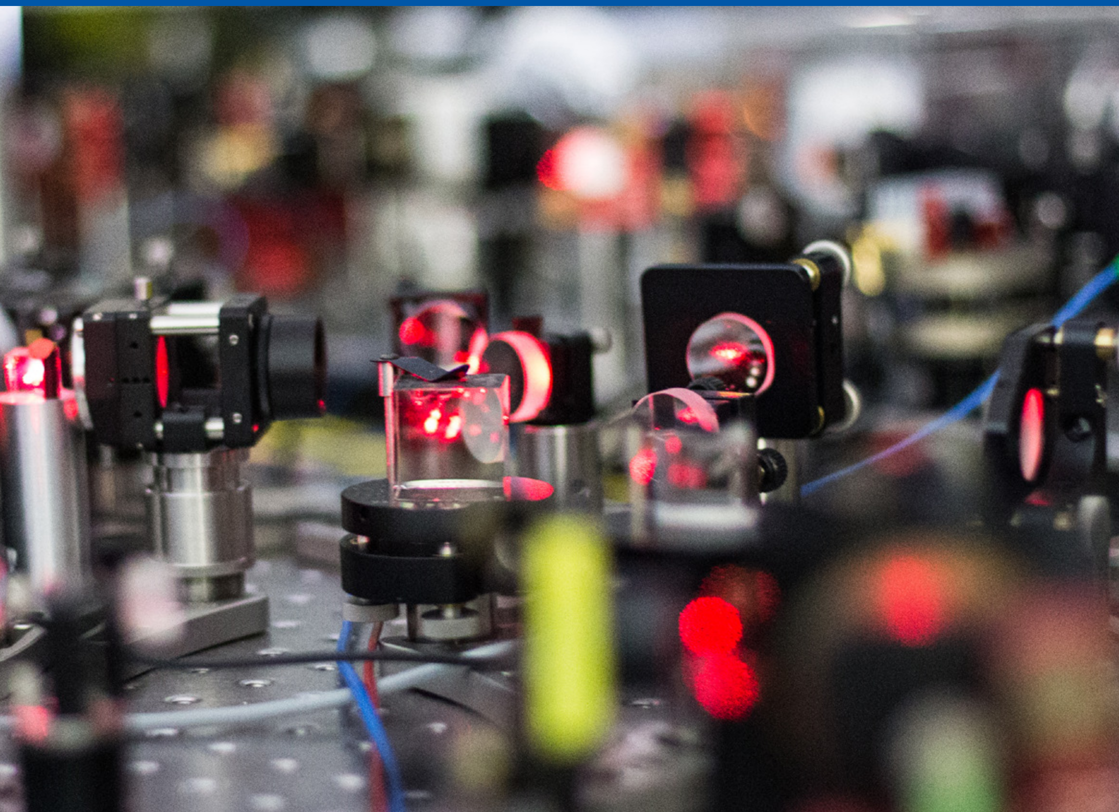
School of Science and Technology
Department of Physics

UNIVERSITÄT SIEGEN

# Master of Science (Physics)

## Focus Area: Quantum Optics and Quantum Information

Description of the Study Program



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## Introduction

Quantum mechanics was developed in the beginning of the 20th century and is nowadays a cornerstone of physics. While the theory was originally designed for explaining the spectra of atoms, it soon turned out to be a fruitful tool to explore the physics of elementary particles and condensed matter systems. Since quantum mechanics breaks with several classical concepts, some mysteries remained, but the quantum formalism has been very successful when applied to practical problems.

Throughout the last 30 years a significant renewed interest in the foundational research on quantum mechanics has emerged. This development was driven by progress in two research areas. First, the connection between quantum physics and information theory enabled novel methods of information processing. Examples are quantum cryptography, which allows provably secure communication between two parties, and quantum computers, which hold the promise to solve problems significantly faster than any classical computer. Second, novel techniques in quantum optical experiments allowed control and manipulation of single quantum systems, such as ions or photons. This makes it possible to carry out experiments which were only thought experiments before and moreover, it provides a hardware for quantum information processing. Altogether, the birth of quantum information science has led to a significantly improved understanding of quantum theory as such, as well as to the development of quantum technologies for computation, communication and sensing, which are nowadays in the focus of many key players in academia and industry worldwide.

For young physicists like you, these developments in quantum physics bear unique opportunities. Many fundamental research questions arose and are urgently waiting to be answered. Novel techniques enable tremendous experimental progress, and unknown phenomena as well as quantum effects remain to be observed. Finally, quantum technologies have reached a strong awareness in the industry with many start-up companies, as well as established key players, who are currently looking for physicists with knowledge in the field.

In recent years, the Department of Physics at the University of Siegen has developed a strong research focus on quantum optics and quantum information, where several research groups collaborate on experimental or theoretical aspects of this field. As a result, a rich course and research program has attracted many students from abroad. This brochure gives you a short overview of the possibilities to pursue a Master of Science degree in Physics at the University of Siegen specializing in quantum optics and quantum information.

## Program Objectives

After the successful completion of the study program **Master of Science (Physics)**, the students will be qualified to participate in topical research in their chosen field of specialisation, that is, **Quantum Optics and Quantum Information**. The program is designed for four semesters, and the basis is laid in a two-semester course program consisting of lectures, seminars, and a laboratory course, followed by one semester of preparation for research work, which culminates in a master thesis to be prepared during the last semester.

Aside from the scientific specialisation, which qualifies students for an academic or research-oriented career, the program aims at providing a number of additional skills and competences. By being embedded in an international research environment, the students acquire intercultural as well as teamwork competences. Further skills, such as analytic thinking, pragmatic problem solving, presentation skills and efficient use of digital media are among the qualification goals, ensuring an outstanding employability of our graduates.

After completion of the master program, students with outstanding records are encouraged to join a doctoral program. The Department of Physics at the University of Siegen offers a broad range of opportunities to pursue research in quantum physics at the doctoral level, and the main research directions of the research groups are listed at the end of this document. The doctoral program builds on the multitude of specialised courses offered in the master program, which facilitates the transition to the doctoral studies, while also embedding the students in a lively and intensive research program, where they learn early on what research in quantum physics consists of.

## Admission Requirements

To enter the Master of Science degree program with a focus on Quantum Optics and Quantum Information, a qualified Bachelor's degree in Physics is mandatory. The necessary prerequisites are a solid foundation of the mathematical methods as well as a good knowledge of the introductory physics courses, such as classical mechanics, electrodynamics, thermodynamics and — in particular — quantum mechanics.

## Structure of the Program

The study program has a modular structure and it comprises a one-year phase of course work followed by a one-year research phase. The workload for individual modules is specified using credit points (CP) according to the European credit transfer and accumulation system (ECTS). The workload to earn the M.Sc. Physics degree amounts to 120 CP. The program is designed in a way that students can choose to focus on either experimental or theoretical topics. However, to ensure a certain breadth of knowledge, it is required to obtain at least 9 CP in experimental physics and in theoretical physics, respectively.

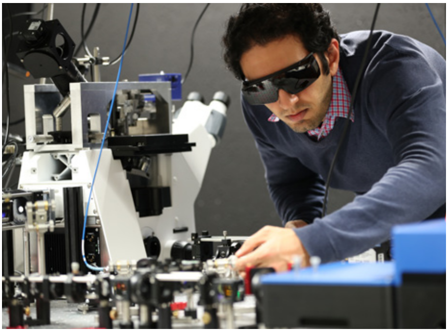
## Course work phase

The coursework phase can be divided into three types of modules (summarised in the table below) that are designed to give students the required background before they enter the research phase of their studies.

| Module Type | Components | Credit points |
|---|---|---|
| **Mandatory courses** | Laboratory course | A selection of projects adding up to 9 CP |
| | Master Seminar | 6 CP |
| **Mandatory core modules and chosen elective** | 1 core module + 1 elective + additional oral exam about both | 9 CP + 6 CP |
| | Additional core module | 9 CP |
| **Electives** | Selection of core modules and electives up to the required CP | 21 CP |

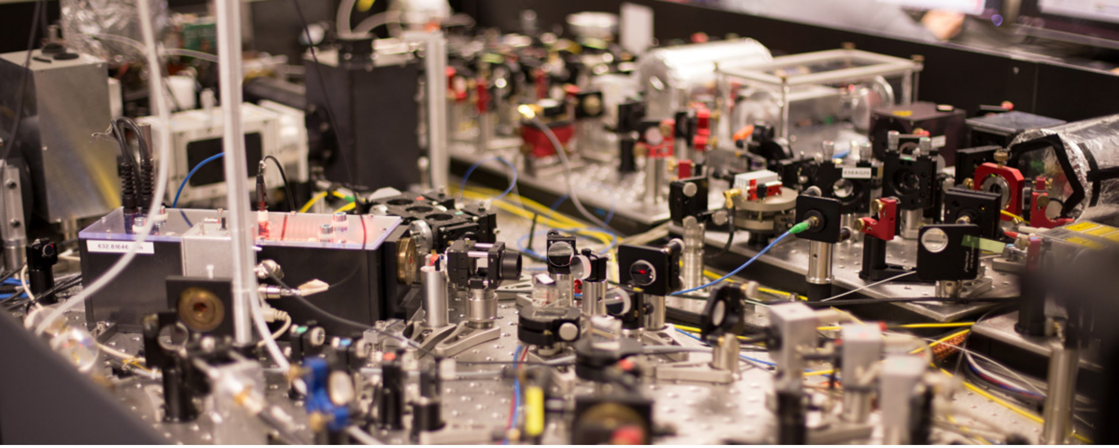
## Laboratory Course

The **Laboratory Course** is designed to train practical skills, which can range from experimental work performed in laboratory experiments to project work in theoretical physics. To complete the course, 9 CP must be earned from a selection of elective projects. The workload for each project is either 1.5 to 3 CP, and includes, aside from on-site hours, also the time for preparation and for writing a report to document the work.



The Department of Physics currently offers a variety of Laboratory Course projects, of which the following may be most relevant for students interested in Quantum Optics and Quantum Information (each project has 1.5 CP unless otherwise stated):

- Laser Spectroscopy (3 CP)
- Surface Plasmon Resonance Sensing
- Optically Detected Magnetic Resonance
- Single-Photon Sources
- Fluorescence Correlation Spectroscopy
- Scanning Tunneling Microscopy
- Atomic Force Microscopy
- X-ray Fluorescence
- X-ray Reflection
- Experiencing Quantum Computers (3 CP)



## Master Seminar

The **Master Seminar** is a seminar on current topics in physics. The goal is to broaden the student's knowledge about physics research beyond what is covered in the lecture program. The students are required to prepare an oral presentation, which is followed by a discussion, and the evaluation is based both on the presentation and the engagement in the discussions during the whole seminar series.

## Core Modules and Electives

The students choose a **Focus Area** in either experimental or theoretical quantum physics, which consists of two Core Modules (2 x 9 = 18 CP) and one Elective (6 CP). After completing the individual modules, they are required to pass an oral exam on topics from one Core Module and one Elective.

Additionally, students must choose a combination of **Core Modules** and **Electives** that cumulatively credit them with 21 CP. These choices can be made from courses offered by the Department of Physics or by other departments of the School of Science and Technology. In the latter case, the students should contact the Examination Office in advance to check if a module can be credited as an Elective for the study program M.Sc. Physics. The table below contains examples of courses usually offered, where each corresponds to 6 CP unless indicated otherwise.

| **Core Modules** |
|---|
| Advanced Quantum Optics (Exp. 9 CP) |
| Experimental Solid-State Physics (Exp. 9 CP) |
| Foundations of Quantum Mechanics (Theor. 9 CP) |
| Quantum Information Theory (Theor. 9 CP) |
| **Theoretical Electives** |
| Aspects of Machine Learning |
| Condensed Matter Theory |
| Mathematics of Quantum Mechanics (3 CP) |
| Quantum Effects and Paradoxa |
| Quantum Thermodynamics |
| Quantum Theory of Light |
| **Experimental Electives** |
| Experimental Methods of Quantum Nano Optics |
| Laser Spectroscopy |
| Nanoscale Quantum Optics |
| Nano-Optics |
| Solid-State Physics of Nanostructures |
| Ultrafast and Non-linear Optics |

| Examples for Electives in other departments |
| --- |
| Advanced Algebra (Mathematics) (9CP) |
| Algorithmic Algebra (Mathematics) (9CP) |
| Complexity Theory (Computer Science) |
| Functional Analysis (Mathematics) (9 CP) |
| Machine Learning (Computer Science) |
| Nanotechnology (Electrical Engineering) |
| Nonlinear Optimization (Mathematics) (9CP) |
| Optoelectronics (Electrical Engineering) |
| Photonic Devices (Electrical Engineering) |

The content of all courses is described in the Module book, which is available on the website of the department.

### Research Phase

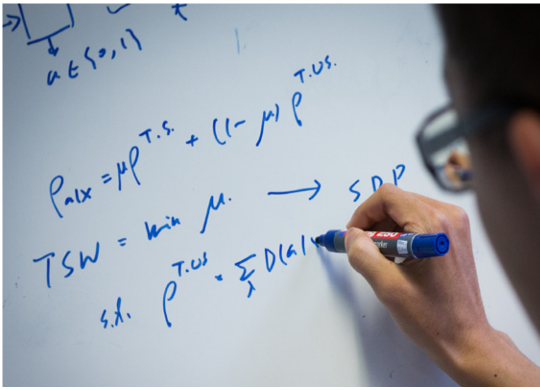
Towards the end of the first year, a research supervisor must be chosen and contacted. This will set into motion the Research Phase, which is designed to encompass a one-year period fully dedicated to a specialised project, culminating in the Master's thesis.

The **Research Phase** starts with a **Preparation Phase** (15 CP), which is mainly aimed at the familiarisation with research skills and integration into the supervisor's working group. Subsequently, the **Training Phase** (15 CP) consists of a hands-on training approach to the research work, where, according to the chosen topic, one should develop software, carry out experiments or calculations.

Finally, in the **Master Thesis** (30 CP), the students shall demonstrate an understanding of the state of the art in the field and potentially contribute to the chosen research topic. Although these three phases are frequently intermingled, it is important to follow some administrative procedures, such as registering for the thesis work after the Preparation Phase.

## Exemplary Curricula

The Master of Science (Physics) with a specialization in Quantum Optics and Quantum Information offers a variety of interesting courses that can be chosen according to personal preferences. The following tables are examples of the Winter Term (WT) and the Summer Term (ST) curricula for Quantum Optics and Quantum Information. Depending on which is the starting semester, the first and second columns in the tables can be interchanged. Notice that the experimental modules must account for at least 9 CP in total – and likewise for the theoretical courses. Choices of electives from other specialization areas, such as cosmology or particle physics are, of course, also allowed.



The following colour code is used:

- Core Modules
- Electives
- Mandatory Courses
- Research Phase

### Specialization: Experimental Quantum Optics

| Semester 1 (WT) | Semester 2 (ST) | Semester 3 | Semester 4 |
|---|---|---|---|
| Laser Spectroscopy (6 CP) | Advanced Quantum Optics (9 CP) | Oral Exam (on Laser Spectroscopy and Advanced Quantum Optics) | |
| Quantum Therory of Light(6 CP) | Foundations of QM (9 CP) | | |
| Experimental Solid-State Physics (9CP) | Experimental Methods of Quantum and Nano Optics (6 CP) | | |
| Laboratory Course (9 CP) | Master Seminar (6 CP) | Preparation and Training (15+15 CP) | Master Thesis (30 CP) |

### Specialization: Quantum Information Theory

| Semester 1 (WT) | Semester 2 (ST) | Semester 3 | Semester 4 |
|---|---|---|---|
| Aspects of Machine Learning (6 CP) | Quantum Information Theory (9 CP) | Oral Exam (on Aspects of Machine Learning and Quantum Inf. Theory) | |
| Condensed Matter Theory (6 CP) | | | |
| Quantum Theory of Light (6 CP) | Advanced Quantum Optics (9 CP) | | |
| Mathematics of Quantum Mechanics (3CP) | Quantum Thermodynamics (6CP) | | |
| Laboratory Course (9 CP) | Master Seminar (6 CP) | Preparation and Training (15+15 CP) | Master Thesis (30 CP) |

Specialization: Nano Quantum Optics

| Semester 1 (WT) | Semester 2 (ST) | Semester 3 | Semester 4 |
|---|---|---|---|
| Nano Optics (6 CP) | Advanced Quantum Optics (9 CP) | Oral Exam (on Nano Optics and Advanced Quantum Optics) | |
| Nanotechnology (6 CP) | Quantum Information Theory (9 CP) | | |
| Experimental Solid-State Physics (9CP) | Nanoscale Quantum Optics (6 CP) | | |
| Laboratory Course (9 CP) | Master Seminar (6 CP) | Preparation and Training (15+15 CP) | Master Thesis (30 CP) |

Specialization: Mathematical Physics

| Semester 1 (WT) | Semester 2 (ST) | Semester 3 | Semester 4 |
|---|---|---|---|
| Quantum Theory of Light (6 CP) | Foundations of QM (9 CP) | Oral Exam (on Quantum Theory of Light and Foundations of QM) | |
| Functional Analysis (9 CP) | Advanced Quantum Optics (9 CP) | | |
| Mathematics of Quan-tum Mechanics (3 CP) | Advanced Algebra (9 CP) | | |
| Laboratory Course (9 CP) | Master Seminar (6 CP) | Preparation and Training (15+15 CP) | Master Thesis (30 CP) |

## Students' Impressions

*"I will be finishing my master's degree in theoretical quantum optics in about 9 months. I chose Siegen University, because of the strong and interesting structure of its curriculum. My best experience at Siegen University until now is the friendly environment conducive to learning."*
Salwa Shaglel (MSc student)

*"I was keen on working in Siegen, because the research group was brimming with exciting new developments in areas which overlapped with my interests. When I arrived, I found the ambience to be warm, friendly and welcoming and was left inspired by the dedication of the entire team, their passion for science. Due in large part to their expert guidance and collaboration, I was able to obtain results which were later published and that aided me with my doctoral applications."*
Atul Singh Arora (Internship in Siegen in 2015, now postdoc at Caltech, USA)

*"The main reason for me to choose Siegen is that the professor I want to work with is in Siegen University. The best experience for me is that I met very nice supervisors here, they are very kind and generous. With their help, I overcame one by one research work problems which are hard for me. As a foreigner, they also give me a lot of help for starting life here at the beginning."*
Mei Yu (PhD student)

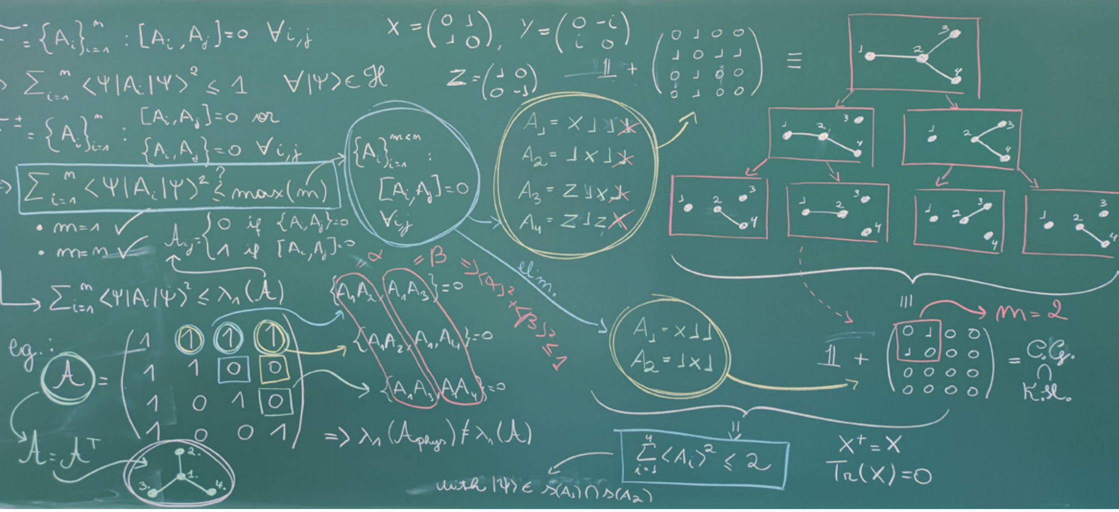
*"I came here because of personal reasons and the interesting research fields in Siegen. The study environment in Siegen was very familiar due to the good student/prof ratio and the small courses. The lecturers have been very responsive to students questions and needs. A very good experience was the nice integration in the working group, where I did my master thesis. Since I did my Master thesis in a field strongly related to my current position I gained a lot of technical expertise, but I also learned how to approach a bigger research project and how to keep up the motivation if things don't work out as expected."*
Sebastian Bock (MSc (2020), now at Fraunhofer FOKUS in Berlin)

*"I believe that especially in our increasingly technocratic society, the adaptation to new technologies is existential. The University of Siegen pushes this advancement. Our scientific groups work on problems that may revolutionize the industry and society in a few years. The physics campus is placed in a nice building with a lot of green space around. It is located close to the city center but at the same time it has a calm atmosphere. Last, but not least, our Mensa cooks really nice."*
Pau Dietz Romero (PhD student)

*"In general, I am delighted with the variety and quality of courses in nano and quantum optics offered at the University of Siegen. The Laboratory of Nano-Optics is an exceptional environment to learn experimental techniques and experience research first hand. I wholeheartedly enjoy its multi-cultural and friendly family atmosphere."*
Philipp Reuschel (MSc student)

*"I really appreciated contributing in a team of PhD and MSc students to actual and relevant research. Visiting international conferences and workshops to present the achieved results was also a highlight. The Physics Department of Siegen University is rather small but this familiarity also offers a lot of advantages. You always knew your fellow students and also the professors knew you and had a chance to discuss questions also apart from the lectures."*
Christian Piltz (MSc and PhD (2017), now at Domino Laser in Hamburg)

*"I chose Siegen because of the research group working in quantum information theory. Siegen provides everything that a motivated young student could need to excel in their field of study. In addition to the scientific aspects, I gained great insight into how German universities and research groups operate, which is tremendously helpful in starting my new research group."*
Mariami Gachechiladze (PhD (2019), now assistant professor for computer science in Darmstadt)

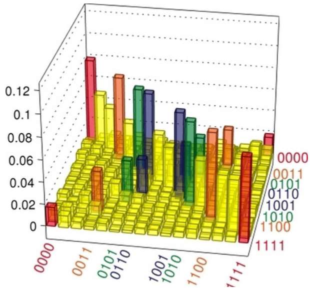


## Theoretical Quantum Optics

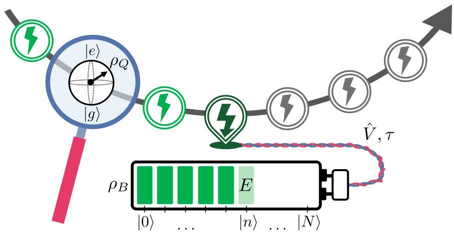
The research group Theoretical Quantum Optics focuses on foundational questions in quantum information and open quantum systems. A first major topic is the phenomenon of quantum entanglement. According to the rules of quantum mechanics, two or more particles can be prepared in such a way, that their state can only be understood as a common system and not by looking at the parts only. This phenomenon was named "spooky action at a distance" by Albert Einstein and may lead to paradoxical effects, but is also central for applications like quantum cryptography. For research, this leads to many questions: How can we characterize entanglement theoretically? For which tasks is entanglement useful? How is entanglement affected by noise and decoherence?

A second major research topic is quantum thermodynamics. The laws of thermodynamics govern the energetic behaviour of macroscopic systems and explain how thermal devices such as heat engines, refrigerators, batteries, or thermometers operate. In quantum thermodynamics, we extend and refine these laws using tools from quantum optics and information theory in order to understand how microscopic quantum systems exchange heat, work, and information with their environment. This may enable future applications superseding classical technology, such as efficient quantum engines, accurate quantum thermometers, and powerful quantum batteries.

In their research, the group forges a bridge from advanced mathematical methods and analytical proofs to collaborations with experimental groups, where the design and analysis of experiments with trapped ions or photons requires theoretical support. The group works closely with the groups of M. Agio and C. Wunderlich, as well as with groups from the Department of Mathematics in Siegen. In addition, the group collaborates with many partners world-wide, at the moment especially with researchers from China, Finland, Sweden, and Spain.




A quantum state of four trapped ions is described by a density matrix. Are the particles entangled?

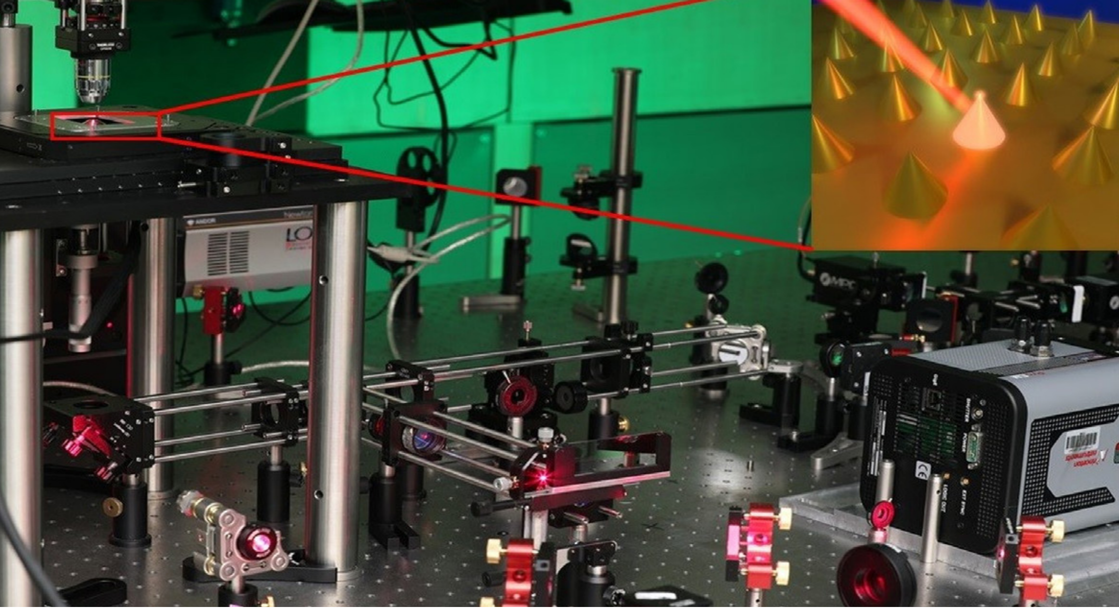



Charging a quantum battery as fast as possible with a stream of two-level systems.

[www.physik.uni-siegen.de/tqo](http://www.physik.uni-siegen.de/tqo)

|TQO⟩ Theoretical Quantum Optics

Dr. Chau Nguyen, Prof. Dr. Stefan Nimmrichter, Prof. Dr. Otfried Gühne, Dr. Matthias Kleinmann



## Laboratory of Nano-Optics

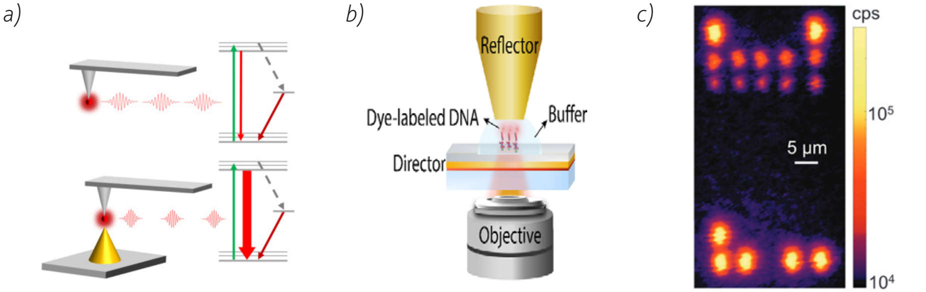
The Laboratory of Nano-Optics encompasses experimental and theoretical research activities in Quantum Nano-Optics, Nano Spectroscopy and Nano Sensing, in tight cooperation with local, national, and international research groups. We investigate the properties of light beyond the diffraction limit and study its interaction with nanoscale matter, specifically the interrogation of single quantum systems and the exploration of quantum phenomena that occur at the sub-wavelength scale. Whilst addressing fundamental questions related to light, matter and their interaction, our efforts may also make their way into practical devices, such as a new class of light-sources, sensors, and functional materials. In detail we focus on the following research directions:

**Quantum Nano-Optics:** We are particularly interested in coupling novel quantum emitters to nanoscale resonators and in investigating such hybrid systems using ultrafast techniques that may allow us to explore quantum phenomena in the presence of strong decoherence.

**Nano Spectroscopy:** Using concepts such as nanofocusing, we aim at implementing advanced spectroscopic techniques like pump-probe and multidimensional approaches in nano-optics to push their spatial resolution beyond the diffraction limit and to improve their ability to address individual quantum systems.

**Nano Sensing:** We focus on nanophotonics-based sensing as it promises to build on the advantages of optical sensing, while overcoming its limitations by providing a high sensitivity, specificity, dynamic range, as well as the possibility for easy integration into simple and affordable devices.

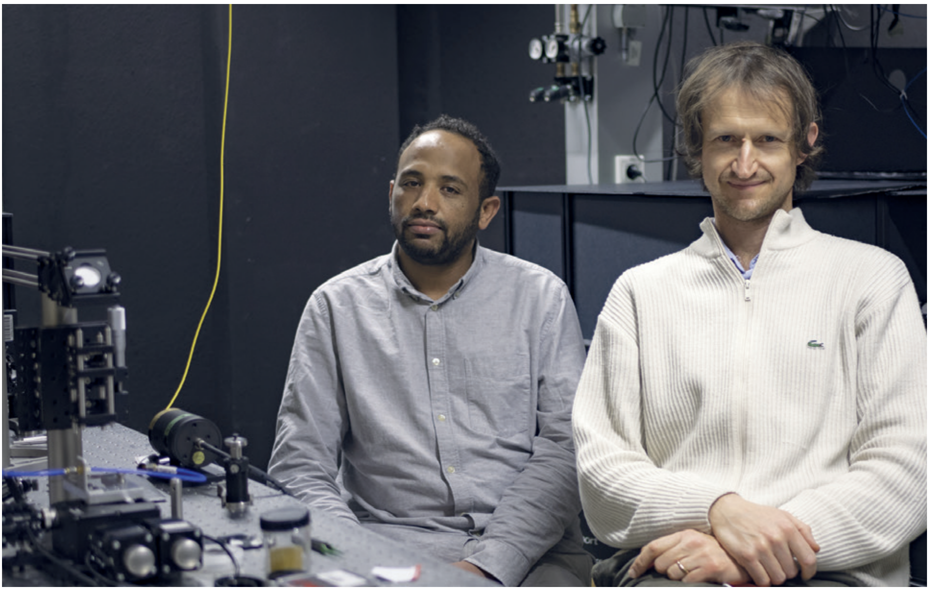
Recent results selected from the three research fields of the Laboratory of Nano-Optics are shown on the next page.



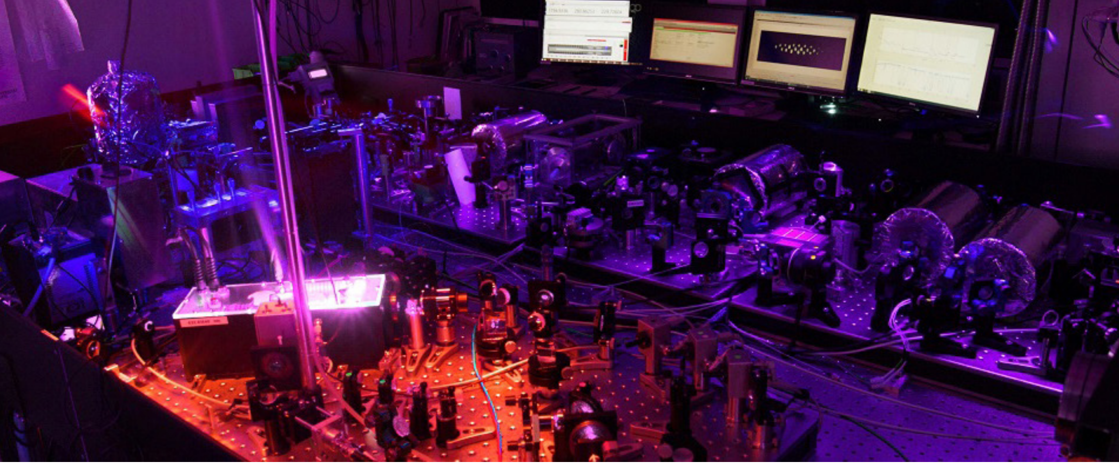

*a) A high degree of control on the photophysics of a bare quantum dot solely by plasmon coupling to a gold nano cone. b) Dye-labeled DNA molecules in a liquid environment using a scanning planar Yagi-Uda antenna, focusing on the collection enhancement. c) The scalable production of silicon-vacancy color centers in diamond at comparatively large depths and with a high lateral precision.*

[www.physik.uni-siegen.de/nano-optics/](http://www.physik.uni-siegen.de/nano-optics/)

Lab of Nano-optics



*Dr. Assegid M. Flatae (left) and Prof. Dr. Mario Agio (right)*



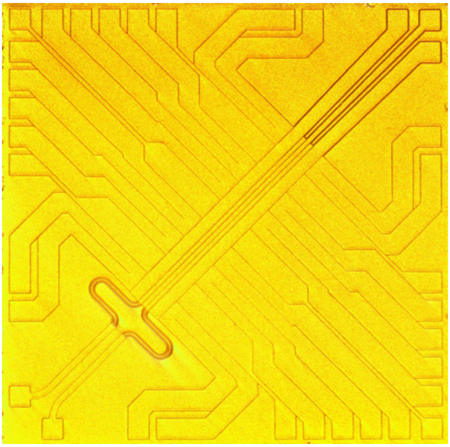
## Experimental Quantum Optics

Today, researchers deterministically prepare individual quantum systems and explore the intriguing, often non-intuitive laws of quantum physics in vivo. This approach has long been considered impossible, as reflected in Nobel Prize winner Erwin Schrödinger's statement that „... we never experiment with just one electron or atom ...". By now, comprehensive control of individual quantum systems – in particular, ions trapped in electromagnetic fields in the Experimental Quantum Optics (EQO) group – allow for new applications such as quantum sensors able to detect minute fields and forces, and even more ambitious, freely programmable quantum computers.

Applications of quantum computers, with potentially far-reaching impact, are, on the one hand, in the realm of science itself. For example, applying the power of quantum computers to extremely hard and as of yet unsolved problems in physics or quantum chemistry is likely to yield unprecedented new insights. On the other hand, quantum computers will lead to applications that are directly highly relevant for industry and will result in disruptive technologies.

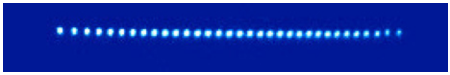
The EQO group strives for contributing to a better understanding of the fundamentals of quantum physics, for example, of creating and analysing entanglement. In parallel the group develops and implements novel methods for ground-breaking trapped-ion quantum computers. This research is carried out in close collaboration with other groups at the department and numerous international partners and succeeded in building one of the first quantum computers in Europe.

Taming trapped ions and using them as quantum-bits comes with a wide variety of experimental challenges. These include, for example, designing, simulating, building, and testing new types of traps, efficient laser cooling and detection of ions, and designing and implementing novel quantum gates. In the EQO group you have the possibility to contribute to and learn about ion traps, lasers, optics, microwave signals, latest vacuum technology, electronics, computer simulation, real-time experimental control, novel quantum gates, and quantum algorithms.

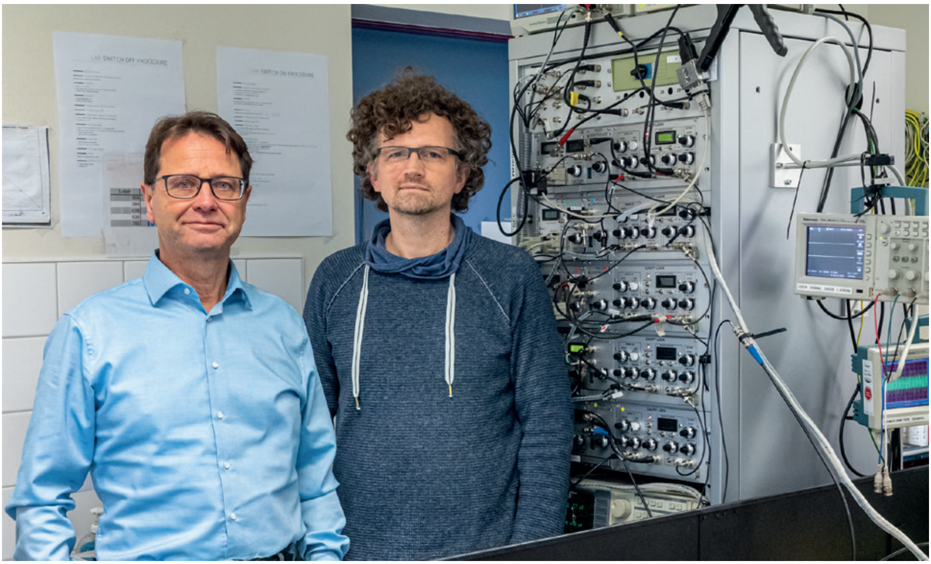


*Left: Chip-based core of a quantum computer for confining trapped atomic ions that serve as memory and processor quantum-bits.*

*Below: A quantum register of trapped Yb+ ions. The ions scatter laser light that is imaged onto a spatially resolving photo detector. Each bright spot signifies a single ion.*



[www.physik.uni-siegen.de/quantenoptik/](http://www.physik.uni-siegen.de/quantenoptik/)



*Prof. Dr. Christof Wunderlich (left) and Dr. Michael Johanning (right).*

## Contact

For questions concerning the study program Master of Science (Physics) with focus on Quantum Optics and Quantum Information please contact the Coordinator of the international master program:

Dr. Matthias Kleinmann,
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Phone: +49 (0)271 740 3799
international.master@physik.uni-siegen.de

More information about the course program and research can be found on the webpage of the department www.physik.uni-siegen.de.

Note: This document provides a non-committal overview of the program. Legally binding information is to be found in the Book of Modules and Examination Regulations.

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Page 15 a) J. Phys. Chem. Lett. 10, 2874 (2019) b) Biomed. Opt. Express 13, 539 (2022) c) Adv. Quantum Technol. 2100079 (2021)

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