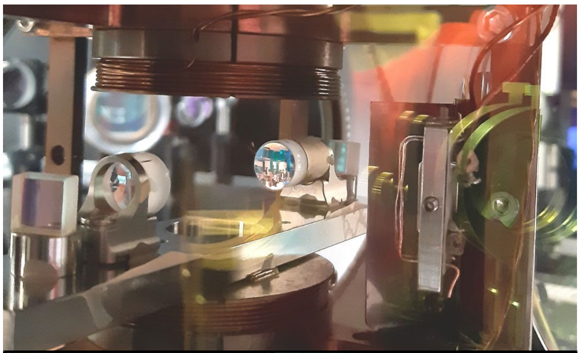
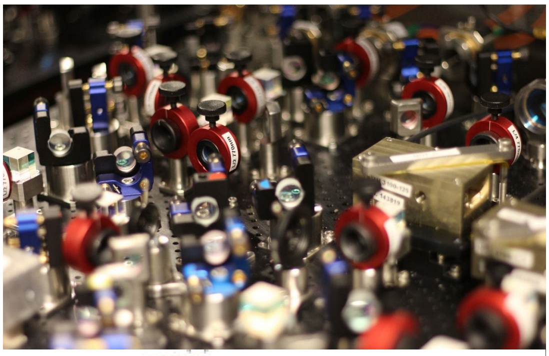
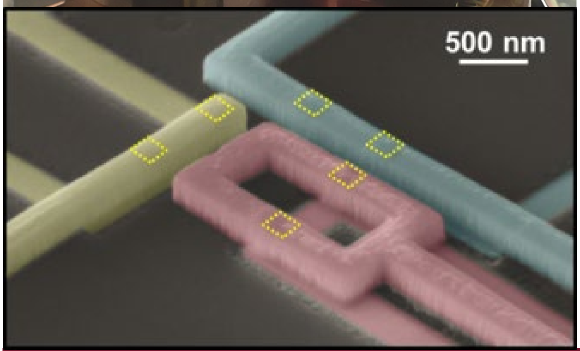
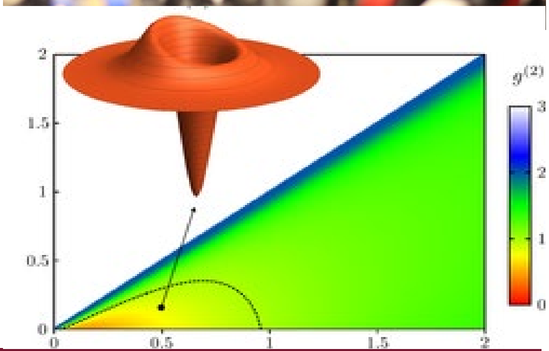
EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN








# Module Handbook

## Advanced Quantum Physics (AQP)

## Master of Science

Winter term 2021/22

Version: April 2025

FACULTY OF SCIENCE
Department of Physics
Center for Quantum Science

# Contents

# 1. Objectives of the Program

The Master of Science program in Advanced Quantum Physics is an international research-oriented two-year master's program established by the Center for Quantum Science of the University of Tübingen. The Center for Quantum Science is part of the Department of Physics within the Faculty of Science of the University of Tübingen. It consists of experimental and theoretical research groups in the fields of quantum optics with ultracold atoms and solid-state superconductors, many-body quantum physics and mathematical physics. Scientists of the Center for Quantum Science investigate complex quantum systems using different experimental platforms and various theoretical approaches with the goal of deepening our understanding of the quantum world, gaining ultimate control over quantum systems, and advancing quantum technology in order to develop new devices for quantum metrology, quantum simulation, quantum communication, and quantum information.

The Southern Germany region concentrates industrial companies with a strong Hi-Tech and quantum component. These and other companies elsewhere have a high demand for well qualified young people with a strong background in natural sciences and quantum science in particular. Presently many physicists educated at the University of Tübingen work in technology oriented companies in this region, and the graduates from this master's program will find an industrial environment with a strong demand on highly skilled people and jobs in high-tech spin-off companies, as well as in midsized companies and large enterprises.

The graduates of the master's program Advanced Quantum Physics receive a comprehensive education in experimental as well as theoretical physics with a practical section and they are well prepared for the duties in industry and in other research-oriented institutions. They are also highly qualified for a PhD project in one of the subfields of quantum science. Tuition will be in English which prepares the students for the increasing internationalization in industry and modern society. Due to the various research topics within the Center for Quantum Science students will obtain an education in a wide variety of topics ranging from different experimental quantum platforms, to theoretical and mathematical quantum physics. The focus of the educational program is put on a distinct quantitative approach as usual in physics, along with the acquisition of essential practical skills (primarily in the lab) with respect to problem sets in the field of quantum science.

The overall goal of the master course is to impart solid knowledge and competences to qualify students to independently plan and carry out original scientific research in quantum science and to critically evaluate their findings in comparison with published results.

The qualification goals in more detail:

- The graduates have a sound understanding of basic and advanced quantum physics covering various research fields including for instance quantum optics, ultracold atoms, Rydberg physics, optical and microwave resonators, superconducting quantum devices, many-body quantum physics, and many others. They have got an overview over various experimental and theoretical approaches in quantum science and know the state-of-the-art.

- The graduates are capable to critically scrutinize the suitability of specific scientific methods for studying various questions in quantum physics. In addition, they are able to combine different techniques in order to make complex physical problems accessible.

- The graduates are able to plan and undertake independently appropriate theoretical and laboratory investigations (collecting, recording and analysing relevant data sets and combining these with theoretical studies). They can divide a complex project into specific sub-problems that are easier to solve and can apply approximations with critical reflection of their validity. Furthermore, they can develop computer programs to simulate physical systems.

- The graduates can present scientific findings of their research orally and in writing. Moreover, in discussions they are skilled to answer scientific questions in a proficient manner. At scientific meetings, they can communicate – in English – with experts in the field and contribute to discussions on current quantum physics related topics.

- The graduates have got key competences of project implementation as team competence and time management.

## 1.1 Structure of the Master's Program

The master's program is a 2-year consecutive study with a modular structure. Students may join the program once a year in the winter semester. In the first year the students attend lectures, seminars and practical courses consisting of 60 ECTS credit points. The students take both experimental and theoretical quantum optics, which lays the foundations for all students. These are augmented by a lab course. In the second term students can choose modules from a variety of different topics. Moreover, the students will learn to discuss problems of quantum science in a comprehensive way both within a journal club where they present a current topic of quantum science, and within a peer-learning seminar where they discuss topics of quantum science in small groups of their peers. For this seminar, they choose three of the modules that they have passed. In the second year the students begin with research on a topic of their choice in the areas of the Center for Quantum Science and finally write their master thesis, all together again 60 CP (30 for acquiring research-oriented skills and 30 for the thesis). The thesis is concluded with an oral scientific presentation of the results. The students are advised during the master's program in a regular term-meeting with a tutor from the group of lecturers.

## 1.2 Requirements for Entering the Master's Program

To participate in the MSc program a bachelor's degree in physics or a similar degree in an equivalent subject with a minimum grade of B (2,5 on the German scale) is required. The bachelor's studies must have included courses in quantum mechanics, atomic physics, and condensed matter physics which is confirmed by the transcript of records. Ideally, lab experience has been acquired by having taken practical physics courses or by scientific experimental work during the bachelor's project.

The exam committee (Prüfungsausschuss) decides on the equivalence of the degree and possibly additional requirements such as additional lectures or lab classes that must be taken. In case of a too large number of applicants a selection committee will decide on acceptance. English is the language of instruction and examination in the Advanced Quantum Physics master's degree program. An adequate knowledge of English is required (level B2 of the Common European Framework of Reference for Languages).

Students from universities other than the University of Tübingen can enter the master's program in Advanced Quantum Physics after a typical three-year bachelor's program. A special arrangement is provided for students from the University of Tübingen, where the BSc Physics is a four-year program. In this case, modules from the BSc Physics with a maximum amount of 60 CP can be recognized towards the AQP master's program. The exam committee (Prüfungsausschuss) decides on the recognition. As many of the modules in the AQP master are shared with the "Vertiefungsfach" of the physics bachelor, we advise BSc Physics students to choose those modules for a smooth recognition. The obligatory module "Discussing Comprehensive Problems of Quantum Science" of AQP can be replaced by the "Vertiefungsfachprüfung" of the BSc program. In cases where the full amount of 60 CP has been recognized the student can enter the AQP MSc program in the third term.

# 2. Module Overview

In order to complete the program, students have to earn in total 120 credit points from a suite of compulsory and elective modules.

## 2.1 Overview by Modules

The following list contains the modules offered within the Master program Advanced Quantum Physics

| Module Code | Obligatory / Elective | Module Title | Lecture exp. or theor. | Recommended Semester | Credit Points |
|---|---|---|---|---|---|
| AQP101 | O | Experimental Quantum Optics | Exp. | 1 | 6 |
| AQP102 | O | Theoretical Quantum Optics | Theor. | 1 | 9 |
| AQP103 | O/E | Quantum Lab I – Lasers and Elements of Quantum Optics | | 1 | 6 |
| AQP104 | O/E | Quantum Lab II - Superconductors | | 1 | 6 |
| AQP105 | O | Discussing Comprehensive Problems of Quantum Science | | 2 | 9 |
| AQP201 | E | Quantum Matter | Exp. | 1 | 3 |

| | | | | | |
|---|---|---|---|---|---|
| AQP202 | E | Fundamentals of optical quantum technology | Exp. | 1 | 6 |
| AQP203 | E | Cold atomic quantum systems | Exp. | 2 | 6 |
| AQP204 | E | Quantum Lab III – Photons and Statistics | | 2 | 6 |
| AQP211 | E | Mathematical Quantum Theory | Theor. | 1 | 9 |
| AQP212 | E | Quantum Information Theory | Theor. | 2 | 9 |
| AQP213 | E | Theory of Open Quantum Systems | Theor. | 2 | 6 |
| AQP214 | E | Many-body Quantum Optics | Theor. | 1 | 6 |
| AQP221 | E | Basics of Superconductivity | Exp. | 1 | 3 |
| AQP222 | E | Macroscopic Quantum Phenomena in Josephson Junctions and Related Systems | Exp. | 1 | 3 |
| AQP223 | E | Applications of Superconductivity | Exp. | 2 | 3 |
| AQP301 | O | Module of Neighbouring Field | | 2 | 6 |
| AQP401 | O | Methods and Project Planning | | 3 | 15 |
| AQP402 | O | Scientific Specialisation in Thesis Topic | | 3 | 15 |
| AQP403 | O | Master thesis | | 4 | 30 |

**Notes:**

The first section AQP101 – AQP105 contains obligatory modules on the basics of advanced quantum mechanics. Modules AQP101 and AQP102 give a profound introduction into the experimental and theoretical concepts of quantum optics. Module AQP103 is a lab course where the students learn how to work in a quantum optics lab. The lab course is recommended in combination with module AQP203 (Lasers and Optics in Quantum Science), where the corresponding topics are treated theoretically. Module AQP104 is a lab course where the students learn to work with superconductors. The students can choose which of the two modules AQP103 and AQP104 they attend obligatory. The second module is then elective.

Module AQP105 consists of two parts, the first being a journal club where the students prepare and give a presentation on a current topic in quantum physics. The second part is a special seminar where the students discuss comprehensive problems of quantum science within peer-learning groups and thus connect the contents of the individual modules. This module is completed with a graded exam.

The second section AQP201 – AQP 223 contains elective modules that allow the students to further specialize within quantum science. Module AQP201 is at the connection of cold atom physics and solid state quantum physics. AQP202 – AQP204 deal with experimental cold atom and photon systems, modules AQP211 – AQP214 extend the theoretical and mathematical concepts, and modules AQP221 – AQP224 are concerned with superconducting solid-state devices.

There are several options to fill the module AQP301. One option is to take courses from neighboring scientific fields, i.e. modules beyond the Advanced Quantum Physics master's program. This includes for example advanced modules from the 4-year Bachelor study of physics, modules from the Master of Astro and Particle physics (not listed explicitly in the above table), or other advanced modules from mathematical physics. These modules will allow the students to acquire knowledge, methods and skills in related scientific areas that will be helpful in their master research in Advanced Quantum Physics, and will teach the students how to cooperate with other disciplines and find joint solutions. A second option are courses from other departments within the University of Tübingen that prepare the students for a work as project leaders in industry. We specifically recommend courses in project management and development organization. The third option for module AQP301 is an internship at an industrial company. The lecturers of the master's program help the students to get into contact with corresponding companies. The duration of such an internship would be 6 weeks with 35 working hours per week, corresponding to 6 CP. The choice of what is taken in module AQP301 has to be approved by the exam committee (Prüfungsausschuss) on an individual basis.

The final part, modules AQP401 - AQP403, are obligatory and contain the master thesis itself (AQP403) and two preparatory modules (AQP401, AQP402) introducing into scientific research. The results of the master thesis are presented by the student in an oral presentation.

**Exams and grading:** Lecture courses are passed either by fulfilling the course achievements (exercises, presentation, portfolio, …), or by ungraded exams, i.e. "pass" or "fail". Module AQP105 is the only course that is completed with a graded exam. For this exam, the students choose three of the completed lecture modules (no lab courses) under following constraints:

1) One (and only one) of the two modules AQP101 and AQP102 is included.
2) At least one experimental and one theoretical lecture (according to the list above) is included.
3) The chosen modules have been completed with "pass".
4) The chosen modules add up to a minimum of 18 CP.

5) Modules from neighbouring fields are not permitted.
6) The modules may not have been examined in an oral or written exam.

The final grade of the MSc. in Advanced Quantum Physics is calculated as 1/2 times the grade of the Master Thesis plus 1/2 times the grade of module AQP105.

## 2.2 Sample Study Plan

The following table shows exemplarily a sample plan for a possible two year study within the Master program.

<table>
<tr><th rowspan="2">Semester</th><th rowspan="2">Credit Points</th><th colspan="4" rowspan="2">Modules from<br>Advanced Quantum Physics</th><th rowspan="2">Module from Neigh-bouring Field</th><th colspan="2" rowspan="2">Research</th></tr>
<tr></tr>
<tr><td rowspan="2">1</td><td rowspan="2">30</td><td rowspan="2">AQP101<br>Experimental Quantum Op-tics<br>(6 CP)</td><td rowspan="2">AQP102<br>Theoreti-cal Quan-tum Optics<br>(9 CP)</td><td>AQP103<br>Quantum Lab I<br>(6 CP)</td><td rowspan="2">AQP202<br>Laser cooling and quan-tum gases<br>(6 CP)</td><td rowspan="2"></td><td colspan="2" rowspan="2"></td></tr>
<tr><td>AQP201<br>Quantum Matter<br>(3 CP)</td></tr>
<tr><td>2</td><td>30</td><td colspan="2">AQP105<br>Discussing Comprehensive Problems of Quantum Sci-ence (9CP)<br>Choice:<br>- AQP101<br>- AQP202<br>- AQP214</td><td>AQP214<br>Many-body Quantum Sys-tems<br>(6 CP)</td><td>AQP212<br>Quantum Infor-mation Theory<br>(9 CP)</td><td>AQP301<br>Neigh-bouring Field<br>(6 CP)</td><td colspan="2"></td></tr>
<tr><td>3</td><td>30</td><td colspan="2"></td><td colspan="2"></td><td></td><td>AQP401<br>Methods and Pro-ject planning<br>(15 CP)</td><td>AQP402<br>Scientific specializa-tion in the-sis topic<br>(15 CP)</td></tr>
<tr><td>4</td><td>30</td><td colspan="2"></td><td colspan="2"></td><td></td><td colspan="2">AQP403<br>Master thesis<br>(30 CP)</td></tr>
</table>

## 2.3 Overview by Study Progress and Credit Requirements

| Abbreviations are explained below | | **Assessment** | | | | **Course** | | | | **Semester** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | The allocation of exams to semesters is a recommendation only. Compulsory allocations are marked as such. | | | |
| The allocation of CPs to courses is for information only. Credits are only awarded upon completion of the module | | **Grading** | **Type of Exam** | **Duration** | **Weight** | **Contact hours** | **Status** | **Type of Course** | **Total CP (example)** | **1** | **2** | **3** | **4** |
| | | | | | | | | | | **CP** | **CP** | **CP** | **CP** |
| **Basic modules in Advanced Quantum Physics** | | | | | | | | | **27** | | | | |
| AQP101 | Experimental Quantum Optics | ne | -- | -- | -- | 4 | O | L/E | | 6 | | | |
| AQP102 | Theoretical Quantum Optics | ne | -- | -- | -- | 6 | O | L/E | | 9 | | | |
| AQP103 | Quantum Lab I – Lasers and Elements of Quantum Optics | ne | -- | -- | -- | 4 | O / E | P | | 6 | | | |
| AQP104 | Quantum Lab II - Superconductors | ne | -- | -- | -- | 4 | O / E | P | | 6 | | | |
| AQP105 | Discussing Comprehensive Problems of Quantum Science | g | O | 60 | 1 | 6 | O | S | | | 9 | | |
| **Specialisation** | | | | | | | | | **27** | | | | |
| AQP201 | Quantum Matter | ng | O* | 30 | -- | 2 | E | L | | 3 | | | |
| AQP202 | Fundamentals of optical quantum technology | ne | -- | -- | -- | 4 | E | L/E | | 6 | | | |
| AQP203 | Cold atomic quantum systems | ne | P | 15 | -- | 2 | E | L/E | | | 6 | | |
| AQP204 | Quantum Lab III – Photons and Statistics | ne | -- | -- | -- | 4 | e | P | | | 6 | | |
| AQP211 | Mathematical Quantum Theory | ng | O/W* | 30 | -- | 6 | e | L/E | | 9 | | | |
| AQP212 | Quantum Information Theory | ne | -- | -- | -- | 6 | e | L/E | | | 9 | | |
| AQP213 | Theory of Open Quantum Systems | ne | -- | -- | -- | 6 | e | L/E | | | 6 | | |
| AQP214 | Many-body Quantum Optics | ne | -- | -- | -- | 4 | e | L/S | | 6 | | | |
| AQP221 | Basics of Superconductivity | ng | O* | 30 | -- | 2 | e | L | | 3 | | | |
| AQP222 | Macroscopic Quantum Phenomena in Josephson Junctions and Related Systems | ng | O* | 30 | -- | 2 | e | L | | | 3 | | |
| AQP223 | Applications of Superconductivity | ng | O* | 30 | -- | 2 | e | L | | | 3 | | |
| **Neighbouring Field** | | | | | | | | | **6** | | | | |
| AQP301 | Module of Neighbouring Field | ne | -- | -- | -- | 4 | o | | | | 6 | | |
| **Research** | | | | | | | | | **60** | | | | |
| AQP401 | Methods and Project Planning | ne | -- | -- | -- | 30 | o | PR | | | | 15 | |
| AQP402 | Scientific specialization in thesis topic | ne | -- | -- | -- | 30 | o | PR | | | | 15 | |
| AQP403 | Master Thesis | g | MT | -- | 1 | 60 | o | MT | | | | | 30 |
| **Total** (Credit Points) | | **-** | **-** | **-** | **-** | **-** | **-** | **-** | **120** | **30** | **30** | **30** | **30** |

*optional, see module description for details

## 3. Module description

The following module descriptions give a comprehensive overview of the Advance Quantum Physics Master course (AQP). The information reflects the course profiles as of June 2020. The module content, the lecturers as well as single lectures might be subject to changes. The following abbreviations are used in the individual module prescriptions and in the previous overview of the study progress:

| KEY | |
|---|---|
| **Grading** | g = graded; ng = not graded (pass/fail);<br>ne = no module examination |
| **Type of Exam:** | W = written exam; O = oral exam; T = term paper; P = classroom presen-tation, A = assignment / term paper, written report |
| **Duration:** | Duration of the examination in minutes |
| **Weight:** | courses: weighting of the examination grade towards the module grade<br>modules: weighting of the module grade towards the final grade |
| **Contact Hours:** | CH; hours spent in the classroom per week during the semester |
| **Status:** | o = obligatory; e = elective |
| **Type of Course:** | L = lecture; S = seminar; E = exercise; T = tutorial, P = practical work, PR = project related research, MT = Master-Thesis |
| **CP:** | Credit Points (ECTS Credits) |

**Notes:** Several of the modules described in the following consist of a lecture (L) in combination with exercise (E) classes. This is the most common form of teaching and learning in the field of physics. Typically, it contains independent homework of the students as well as team-working through joint discussions of the (weekly) problem sheets. The results of their homework will have to be presented and discussed by the students in the corresponding exercise classes. Some of the modules are also organized as combination of a lecture (L) with a seminar (S). In this case the students have to prepare seminar talks as homework and present them within the class.

<table>
<tr><td colspan="2">Module Code:<br>AQP101</td><td colspan="6">Module Title:<br>Experimental Quantum Optics</td><td colspan="4">Type of Module:<br>Obligatory</td></tr>
<tr><td colspan="2">CP (ECTS Credits)</td><td colspan="10">6</td></tr>
<tr><td colspan="2">Workload:<br>- Time in Class<br>- Self-Study</td><td colspan="2">Total Workload:<br>180 h</td><td colspan="4">Time in Class:<br>60 h / 4 SWS</td><td colspan="4">Self-Study:<br>120 h</td></tr>
<tr><td colspan="2">Duration</td><td colspan="10">1 Semester</td></tr>
<tr><td colspan="2">Frequency</td><td colspan="10">Winter semester</td></tr>
<tr><td colspan="2">Language of In-struction:</td><td colspan="10">English</td></tr>
<tr><td colspan="2">Forms of Teaching and Learning</td><td colspan="10">Experimental lecture with exercises, homework assignments</td></tr>
<tr><td colspan="2">Exam</td><td colspan="10">The exam consists of the delivery of solutions to weekly task sheets and presenting the solutions in the exercise class. For passing the exam, each student must have presented solutions to at least two problems in front of the class.</td></tr>
<tr><td colspan="2">Content</td><td colspan="10">This course teaches fundamental concepts in quantum optics with special emphasis on related experiments. This includes topics as light field quantization, number states, coherent states, squeezed states, Jaynes-Cummings model, the 1-atom-maser, dressed states, coherences and correlations, the quantum measurement process, entangled photons and quantum cryptography.</td></tr>
<tr><td colspan="2">Objectives</td><td colspan="10">Students understand the fundamental concepts in quantum optics. They have seen and are acquainted with related experiments. They are able to solve simple prob-lems of experimental quantum optics independently based on their theoretical knowledge. They can present and discuss their solutions with their peers.</td></tr>
<tr><td colspan="2" rowspan="3">Requirements for Obtaining Credit, Grading, weight if applicable:</td><td colspan="2"></td><td>Type of Course</td><td>Status</td><td>CH (SWS)</td><td>CP</td><td>Type of Exam</td><td>Duration of Exam</td><td>Grading</td><td>Weight for Grade</td></tr>
<tr><td colspan="2">Lecture</td><td>L</td><td>o</td><td>2</td><td>3</td><td rowspan="2">A/P</td><td rowspan="2">--</td><td rowspan="2">ng</td><td rowspan="2">--</td></tr>
<tr><td colspan="2">Exercise</td><td>E</td><td>o</td><td>2</td><td>3</td></tr>
<tr><td colspan="2">Transfer</td><td colspan="10">The module can be also used for following studies:<br>- BSc in Physics (Vertiefungsfach, 4th year)</td></tr>
<tr><td colspan="2">Prerequisites</td><td colspan="10">Quantum mechanics.</td></tr>
<tr><td colspan="2">Responsible</td><td colspan="10">Andreas Günter, Christian Groß</td></tr>
</table>

<table>
<tr><td>Module Code:<br>AQP102</td><td colspan="8">Module Title:<br>Theoretical Quantum Optics</td><td colspan="4">Type of Module:<br>Obligatory</td></tr>
<tr><td>CP (ECTS Credits)</td><td colspan="12">9</td></tr>
<tr><td>Workload:<br>- Time in Class<br>- Self-Study</td><td colspan="4">Total Workload:<br>270 h</td><td colspan="4">Time in Class:<br>90 h / 6 SWS</td><td colspan="4">Self-Study:<br>180 h</td></tr>
<tr><td>Duration</td><td colspan="12">1 Semester</td></tr>
<tr><td>Frequency</td><td colspan="12">Winter semester</td></tr>
<tr><td>Language of Instruction:</td><td colspan="12">English</td></tr>
<tr><td>Forms of Teaching and Learning</td><td colspan="12">Theoretical lecture with exercises, homework assignments</td></tr>
<tr><td>Exam</td><td colspan="12">The exam consists of the delivery of solutions to weekly task sheets and presenting the solution of exercises in the exercise class. For passing the exam, the number of omitted task sheets may not exceed two, the total amount of points reached in the task sheets must exceed 2/3 of all points, and the solution of at least two complete exercises must be presented in the group.</td></tr>
<tr><td>Content</td><td colspan="12">1. Quantization of the e.m. Field: Quantization of a single mode, Quantum fluctuations, Single mode field quadrature operators, Quantization of free e.m. field (multi-mode case), Thermal states, Coherent states<br>2. Phase space representations: Wigner W function, Glauber-Sudarshan P function, Husimi-Kano Q function, Relationship between W, P, Q functions, Quantumness (= non-classicality) of the e.m. Field<br>3. Measurement of electromagnetic fields: Beam splitter physics, Homodyne and heterodyne measurements, Theory of photodetection, Coherence theory, Quantum noise in quantum optical measurements, Introduction to the theory of quantum parameter estimation and optimal measurements<br>4. Coherent manipulation of atoms: Driving an atom with a classical light field, From multi-level atoms to two-level atoms, Rabi-Hamiltonian, AC Stark shift, dressed states, power broadening, Coherent manipulation of three-level atoms: Raman processes, adiabatic population transfer (STIRAP)<br>5. Interaction of atoms with quantized fields: Open quantum optical systems, Master equation, Laser theory, Light forces on atoms</td></tr>
<tr><td>Objectives</td><td colspan="12">Students understand basic concepts and tools in theoretical quantum optics. They are able to solve simple problems of theoretical quantum optics independently. They present and discuss their solutions with their peers.</td></tr>
<tr><td rowspan="3">Requirements for Obtaining Credit, Grading, weight if applicable:</td><td colspan="4"></td><td>Type of Course</td><td>Status</td><td>CH (SWS)</td><td>CP</td><td>Type of Exam</td><td>Duration of Exam</td><td>Grading</td><td>Weight for Grade</td></tr>
<tr><td colspan="4">Lecture</td><td>L</td><td>o</td><td>4</td><td>6</td><td rowspan="2">A/P</td><td rowspan="2">--</td><td rowspan="2">ng</td><td rowspan="2">--</td></tr>
<tr><td colspan="4">Exercise</td><td>E</td><td>o</td><td>2</td><td>3</td></tr>
<tr><td>Transfer</td><td colspan="12">The module can be also used for following studies:<br>- BSc in Physics (Vertiefungsfach, 4th year)</td></tr>
<tr><td>Prerequisites</td><td colspan="12">Quantum mechanics.</td></tr>
<tr><td>Responsible</td><td colspan="12">Daniel Braun, Igor Lesanovsky</td></tr>
</table>

<table>
<tr><td>Module Code:<br>AQP103</td><td colspan="4">Module Title:<br>Quantum Lab I – Lasers and Elements of Quantum Optics</td><td colspan="4">Type of Module:<br>Obligatory</td></tr>
<tr><td>CP (ECTS Credits)</td><td colspan="8">6</td></tr>
<tr><td>Workload:<br>- Time in Class<br>- Self-Study</td><td>Total Workload:<br>180 h</td><td colspan="4">Time in Class:<br>60 h / 4 SWS</td><td colspan="4">Self-Study:<br>120 h</td></tr>
<tr><td>Duration</td><td colspan="8">1 Semester</td></tr>
<tr><td>Frequency</td><td colspan="8">Winter semester</td></tr>
<tr><td>Language of Instruction:</td><td colspan="8">English</td></tr>
<tr><td>Forms of Teaching and Learning</td><td colspan="8">Practical course</td></tr>
<tr><td>Exam</td><td colspan="8">Delivery of a lab-book where the work done in the course is presented.</td></tr>
<tr><td>Content</td><td colspan="8">Hands-on training on typical elements in a quantum optics lab: Lasers, laser beams, optomechanics, polarizers, waveplates, beamcubes, photodiodes, acousto-optic modulators, optical cavities, lock-boxes, frequency-modulation, Pound-Drever-Hall technique</td></tr>
<tr><td>Objectives</td><td colspan="8">The students are prepared to work in a quantum optics laser lab and can handle the basic devices. They are able to design and set up modern experiments and conduct these experiments under guidance. They are able to collate and categorize the data gained and spot typical errors.</td></tr>
<tr><td rowspan="2">Requirements for Obtaining Credit, Grading, weight if applicable:</td><td></td><td>Type of Course</td><td>Status</td><td>CH (SWS)</td><td>CP</td><td>Type of Exam</td><td>Duration of Exam</td><td>Grading</td><td>Weight for Grade</td></tr>
<tr><td>Practical course</td><td>P</td><td>o</td><td>4</td><td>6</td><td>A</td><td>--</td><td>ne</td><td>--</td></tr>
<tr><td>Transfer</td><td colspan="8">The module can be also used for following studies:<br>- BSc in Physics (Vertiefungsfach, 4th year)</td></tr>
<tr><td>Prerequisites</td><td colspan="8"></td></tr>
<tr><td>Responsible</td><td colspan="8">Sebastian Slama</td></tr>
</table>

| **Module Code:** AQP104 | **Module Title:** Quantum Lab II – Superconductors | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Type of Module:** Obligatory | | | | | | | | | |
| **CP (ECTS Credits)** | 6 | | | | | | | | |
| **Workload: - Time in Class - Self-Study** | Total Workload: 90 h | Time in Class: 30 h / 2 SWS | Self-Study: 60 h | | | | | | |
| **Duration** | 1 Semester | | | | | | | | |
| **Frequency** | Summer semester and winter semester | | | | | | | | |
| **Language of Instruction:** | English | | | | | | | | |
| **Forms of Teaching and Learning** | Practical course | | | | | | | | |
| **Exam** | Delivery of a lab report | | | | | | | | |
| **Content** | Deposition of single-crystalline thin films from high-temperature superconductors (vacuum technology, thin film techniques, film growth); Micropatterning of thin films by means of photo and / or electron beam lithography and chemical and / or physical etching; characterization of single-crystalline films and thin-film microstructures (X-ray diffraction, scanning electron microscopy, atomic force microscopy, characterization of the electrical transport properties). | | | | | | | | |
| **Objectives** | The students are prepared to work in a condensed matter lab. They master operation of equipment used for thin film fabrication, micropatterning structural analysis l and electrical characterization at cryogenic temperatures. | | | | | | | | |
| **Requirements for Obtaining Credit, Grading, weight if applicable:** | | Type of Course | Status | CH (SWS) | CP | Type of Exam | Duration of Exam | Grading | Weight for Grade |
| | Practical course | P | o | 4 | 6 | A | -- | ne | -- |
| **Transfer** | The module can be also used for following studies:<br>- BSc in Physics (Vertiefungsfach, 4th year) | | | | | | | | |
| **Prerequisites** | Superconductivity | | | | | | | | |
| **Responsible** | Dieter Kölle, Markus Turad | | | | | | | | |

| **Module Code:** AQP105 | **Module Title:** Discussing Comprehensive Problems of Quantum Science | | **Type of Module:** Obligatory |
|---|---|---|---|
| **CP (ECTS Credits)** | 9 | | |
| **Workload:**<br>**- Time in Class**<br>**- Self-Study** | Total Workload:<br>270 h | Time in Class:<br>90 h / 6 SWS | Self-Study:<br>180 h |
| **Duration** | 1 - 2 Semester | | |
| **Frequency** | **Journal club**: summer semester<br>**Peer-learning seminar**: winter semester and summer semester | | |
| **Language of Instruction:** | English | | |
| **Forms of Teaching and Learning** | **Journal club:** After an introductory lecture, each student studies a topic in theoretical or experimental quantum optics and gives a presentation on that topic in front of the class.<br>**Peer-learning seminar**: The students discuss topics in small groups in a question/answering format. The seminar starts after the usual lecture period when the exams of the other modules are finished. The exam of this module takes place at the end of the semester break. | | |
| **Exam** | Oral exam | | |
| **Content** | The contents of the journal club are current topics in theoretical and experimental quantum physics. These will include quantum information and simulation, interacting many-body quantum systems, and quantum optics, among others.<br>The contents of the peer-learning seminar are the sum of three modules that each student chooses. | | |
| **Objectives** | The students get acquainted with the latest developments in quantum science research. They will acquire experience in doing literature and background research and are able to present the results to an audience. The students can orally discuss problems of quantum science in a comprehensive way and make connections between topics from different modules. | | |
| **Requirements for Obtaining Credit, Grading, weight if applicable:** | (see table below) | | |
| **Transfer** | The journal club can be also used for following studies:<br>BSc in Physics (Vertiefungsfach, 4th year) | | |
| **Prerequisites** | For entering the peer-learning seminar the students have passed sufficient modules from the Advanced Quantum Physics master program to make a valid choice:<br>1) One (and only one) of the two modules AQP101 and AQP102 is included.<br>2) At least one experimental and one theoretical lecture is included.<br>3) The chosen modules are completed with a “pass” mark<br>4) The chosen modules add up to a minimum of 18 CP.<br>5) Modules from neighbouring fields are not permitted.<br>6) The modules may not have been examined in an oral or written exam. | | |
| **Responsible** | Journal club: Beatriz Olmos<br>Peer-learning seminar: Sebastian Slama | | |

**Requirements for Obtaining Credit, Grading, weight if applicable:**

| | Type of Course | Status | CH (SWS) | CP | Type of Exam | Duration of Exam | Grading | Weight for Grade |
|---|---|---|---|---|---|---|---|---|
| Journal club | S | o | 2 | 3 | | | | |
| Peer-learning seminar | S | o | 4 | 6 | O | 60 | g | 1 |

| **Module Code:** AQP201 | **Module Title:** Quantum Matter | | | | | | | | **Type of Module:** Elective | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **CP (ECTS Credits)** | 3 | | | | | | | | | | |
| **Workload: - Time in Class - Self-Study** | Total Workload: 90 h | | | Time in Class: 30 h / 2 SWS | | | | | Self-Study: 60 h | | |
| **Duration** | 1 Semester | | | | | | | | | | |
| **Frequency** | Winter semester and summer semester | | | | | | | | | | |
| **Language of Instruction:** | English | | | | | | | | | | |
| **Forms of Teaching and Learning** | Experimental lecture | | | | | | | | | | |
| **Exam** | The module is by default examined in an oral exam. In this case it cannot be chosen for module AQP105 "Discussing Comprehensive Problems of Quantum Science". In case that students choose this module for AQP105, the exam can be suspended and replaced by the oral exam of module AQP105. | | | | | | | | | | |
| **Content** | Microscopic and macroscopic quantum states; Bosons and fermions; Superconductors, Bose-Einstein condensates, superfluid 4He, superfluid 3He and related systems: basics and theoretical descriptions; Josephson effects in superconductors, Bose-Einstein condensates and Suprafluids; Hybrid Atom/Superconductor Quantum Systems | | | | | | | | | | |
| **Objectives** | Students can discuss the properties of quantum matter using the examples of superconductors, superfluids and atomic quantum gases. They can identify common features of these systems. Furthermore, they can describe hybrid quantum systems that consist of combinations of the discussed systems, and know their applications in quantum science and technology. | | | | | | | | | | |
| **Requirements for Obtaining Credit, Grading, weight if applicable:** | | Type of Course | Status | CH (SWS) | CP | Type of Exam | Duration of Exam | Grading | Weight for Grade | | |
| | Lecture | L | o | 2 | 3 | O | 30 | ng | -- | | |
| **Transfer** | The module can be also used for following studies:<br>- BSc in Physics (Vertiefungsfach, 4th year) | | | | | | | | | | |
| **Prerequisites** | Quantum mechanics | | | | | | | | | | |
| **Responsible** | Jozsef Fortágh, Reinhold Kleiner | | | | | | | | | | |

<table>
<tr><td>Module Code:<br>AQP202</td><td colspan="4">Module Title:<br>Fundamentals of optical quantum technologies</td><td colspan="4">Type of Module:<br>Elective</td></tr>
<tr><td>CP (ECTS Credits)</td><td colspan="8">6</td></tr>
<tr><td>Workload:<br>- Time in Class<br>- Self-Study</td><td>Total Workload:<br>180 h</td><td colspan="4">Time in Class:<br>60 h / 4 SWS</td><td colspan="4">Self-Study:<br>120 h</td></tr>
<tr><td>Duration</td><td colspan="8">1 Semester</td></tr>
<tr><td>Frequency</td><td colspan="8">Winter Semester</td></tr>
<tr><td>Language of In-struction:</td><td colspan="8">English</td></tr>
<tr><td>Forms of Teaching and Learning</td><td colspan="8">Lecture with exercises, homework assignments, or seminar</td></tr>
<tr><td>Exam</td><td colspan="8">Delivery of solutions to weekly task sheets, or oral presentation</td></tr>
<tr><td>Content</td><td colspan="8">This course teaches basic concepts of cooling, trapping and working with cold atoms and corresponding optical technologies. This includes Doppler – and sub-Doppler cooling, magneto-optical traps, dipole traps and optical tweezers, diode lasers, laser spectroscopy, laser frequency stabilization techniques, Gaussian optics, and optical cavities.</td></tr>
<tr><td>Objectives</td><td colspan="8">The students can discuss the basic cooling methods in cold atom physics. They are able to explain the working principle of diode lasers and techniques to stabilize their frequencies. They can further calculate the propagation of laser beams and the properties of optical cavities.</td></tr>
<tr><td rowspan="3">Requirements for Obtaining Credit, Grading, weight if applicable:</td><td></td><td>Type of Course</td><td>Status</td><td>CH (SWS)</td><td>CP</td><td>Type of Exam</td><td>Duration of Exam</td><td>Grading</td><td>Weight for Grade</td></tr>
<tr><td>Lecture</td><td>L</td><td>o</td><td>2</td><td>3</td><td rowspan="2">ne</td><td rowspan="2">--</td><td rowspan="2">--</td><td rowspan="2">--</td></tr>
<tr><td>Exercise</td><td>E</td><td>o</td><td>2</td><td>3</td></tr>
<tr><td>Transfer</td><td colspan="8">The module can be also used for following studies:<br>- BSc in Physics (Vertiefungsfach, 4th year)</td></tr>
<tr><td>Prerequisites</td><td colspan="8">Quantum mechanics, atomic physics</td></tr>
<tr><td>Responsible</td><td colspan="8">Andreas Günter, Christian Groß, Jozsef Fortagh, Sebastian Slama</td></tr>
</table>

<table>
<tr><td>Module Code:<br>AQP203</td><td colspan="5">Module Title:<br>Cold atomic quantum systems</td><td colspan="4">Type of Module:<br>Elective</td></tr>
<tr><td>CP (ECTS Credits)</td><td colspan="9">6</td></tr>
<tr><td>Workload:<br>- Time in Class<br>- Self-Study</td><td>Total Workload:<br>180 h</td><td colspan="4">Time in Class:<br>60 h / 4 SWS</td><td colspan="4">Self-Study:<br>120 h</td></tr>
<tr><td>Duration</td><td colspan="9">1 Semester</td></tr>
<tr><td>Frequency</td><td colspan="9">Summer semester (FROM SoSe 2026 on)</td></tr>
<tr><td>Language of In-struction:</td><td colspan="9">English</td></tr>
<tr><td>Forms of Teaching and Learning</td><td colspan="9">Lecture with exercises, homework assignments, or seminar</td></tr>
<tr><td>Exam</td><td colspan="9">Delivery of solutions to weekly task sheets, or oral presentation</td></tr>
<tr><td>Content</td><td colspan="9">The course discusses the properties of cold thermal atoms and quantum gases, i.e. Bose-condensates and Fermi-gases in free space, traps, optical lattices and optical cavities. It further introduces the physics of interacting Rydberg gases and their applications for quantum computing, quantum simulation and quantum sensing. Theory-wise the course describes these systems with corresponding quantum models like the Bose-Hubbard-, Jaynes-Cummings-, Ising-, Heisenberg-, and the Dicke-model.</td></tr>
<tr><td>Objectives</td><td colspan="9">The students can explain the properties of Bose-Einstein condensates and Fermi gases in different environments. They can further discuss Rydberg physics and its applications for the quantum technologies. They can connect and describe these atomic systems using corresponding model Hamiltonians.</td></tr>
<tr><td rowspan="3">Requirements for Obtaining Credit, Grading, weight if applicable:</td><td></td><td>Type of Course</td><td>Status</td><td>CH (SWS)</td><td>CP</td><td>Type of Exam</td><td>Duration of Exam</td><td>Grading</td><td>Weight for Grade</td></tr>
<tr><td>Lecture</td><td>L</td><td>o</td><td>2</td><td>3</td><td rowspan="2">ne</td><td rowspan="2">--</td><td rowspan="2">--</td><td rowspan="2">--</td></tr>
<tr><td>Exercise</td><td>E</td><td>o</td><td>2</td><td>3</td></tr>
<tr><td>Transfer</td><td colspan="9">The module can be also used for following studies:<br>- BSc in Physics (Vertiefungsfach, 4th year)</td></tr>
<tr><td>Prerequisites</td><td colspan="9">Quantum mechanics, atomic physics, Fundamentals of optical quantum technologies</td></tr>
<tr><td>Responsible</td><td colspan="9">Andreas Günter, Christian Groß, Jozsef Fortagh, Sebastian Slama</td></tr>
</table>

| **Module Code:** AQP204 | **Module Title:** Quantum Lab III – Photons and Statistics | | | | | | | | **Type of Module:** Elective | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **CP (ECTS Credits)** | 6 | | | | | | | | | | | |
| **Workload: - Time in Class - Self-Study** | Total Workload: 180 h | | | | Time in Class: 60 h / 4 SWS | | | | Self-Study: 120 h | | | |
| **Duration** | 1 Semester | | | | | | | | | | | |
| **Frequency** | Summer semester | | | | | | | | | | | |
| **Language of Instruction:** | English | | | | | | | | | | | |
| **Forms of Teaching and Learning** | Practical course | | | | | | | | | | | |
| **Exam** | Delivery of a lab report | | | | | | | | | | | |
| **Content** | Quantum optic experiments on single photons and entangled photon pairs:<br>Experiment 1: parametric down conversion<br>Experiment 2: proof of the existence of photons<br>Experiment 3: single-photon interference<br>Experiment 4: quantum-state measurement<br>Experiment 5: test of local realism (Bell inequality) | | | | | | | | | | | |
| **Objectives** | The students will learn how to set up, conduct and understand modern quantum optic experiments and gain experience on data analysis and documentation. | | | | | | | | | | | |
| **Requirements for Obtaining Credit, Grading, weight if applicable:** | | Type of Course | Status | CH (SWS) | CP | Type of Exam | Duration of Exam | Grading | Weight for Grade | | | |
| | Practical course | P | o | 4 | 6 | A | -- | ng | -- | | | |
| **Transfer** | The module can be also used for following studies:<br>- BSc in Physics (Vertiefungsfach, 4th year) | | | | | | | | | | | |
| **Prerequisites** | | | | | | | | | | | | |
| **Responsible** | Andreas Günter, Jozsef Fortagh | | | | | | | | | | | |

| **Module Code:** AQP211 | **Module Title:** Mathematical Quantum Theory | | **Type of Module:** Elective |
|---|---|---|---|
| **CP (ECTS Credits)** | 9 | | |
| **Workload:**<br>**- Time in Class**<br>**- Self-Study** | Total Workload:<br>270 h | Time in Class:<br>90 h / 6 SWS | Self-Study:<br>180 h |
| **Duration** | 1 Semester | | |
| **Frequency** | Winter semester | | |
| **Language of Instruction:** | English | | |
| **Forms of Teaching and Learning** | Theoretical lecture with exercises, homework assignments | | |
| **Exam** | The module is by default examined in an oral or written exam, depending on the number of participants. In this case it cannot be chosen for module AQP105 “Discussing Comprehensive Problems of Quantum Science”. In case that students choose this module for AQP105, the exam can be suspended and replaced by the oral exam of module AQP105. | | |
| **Content** | The module provides an introduction to mathematical methods that play an essential role in the formulation and analysis of quantum theories. Topics include the Fourier transform, distributions, Hilbert spaces, unitary groups and their generators, spectral theory of self-adjacent operators, spectral theorem, tensor products, POVMs, spectral measures, and trace class operators. In addition, basic ideas from more specific methods such as Rayleigh-Schrödinger perturbation theory, Hartree resp. Hartree-Fock theory, the Fock space formalism, scattering theory, adiabatic theory or semiclassical analysis can be discussed. The mentioned mathematical methods and areas are motivated in the lecture from quantum theory and applied to examples from quantum theory. | | |
| **Objectives** | Students know and understand the terms and methods mentioned above and can use them to analyse known and new questions from quantum theory. They are able to understand and explain the statements and proofs of the lecture. Furthermore, they link physical problems and their mathematical modelling and are able to question the relevance and adequacy of mathematical modelling and the mathematical results derived from it. Through homework assignments and exercise classes students develop a confident, precise, and independent acquaintance with the notions, statements, and methods explained in the lectures. They learn how to transfer these methods to new problems, to analyse them and to develop solution strategies on their own and within a group. They are able to present their solutions and to stand for them in a critical discourse if necessary. | | |

**Requirements for Obtaining Credit, Grading, weight if applicable:**

| | Type of Course | Status | CH (SWS) | CP | Type of Exam | Duration of Exam in minutes | Grading | Weight for Grade |
|---|---|---|---|---|---|---|---|---|
| Lecture | L | o | 4 | 6 | O or W | 90-180 or 20-30 | ng | -- |
| Exercise | E | o | 2 | 3 | | | | |

| | |
|---|---|
| **Transfer** | The module can also be used for following studies:<br>- BSc Physics, (Vertiefungsfach, 4th year)<br>- MSc Mathematics<br>- MSc Mathematical Physics |
| **Prerequisites** | The module requires basic knowledge of mathematical concepts and quantum mechanics. |
| **Responsible** | Stefan Teufel |

| **Module Code:** AQP212 | **Module Title:** Quantum Information Theory | | **Type of Module:** Elective |
|---|---|---|---|
| **CP (ECTS Credits)** | 9 | | |
| **Workload:** **- Time in Class** **- Self-Study** | Total Workload: 270 h | Time in Class: 90 h / 6 SWS | Self-Study: 180 h |
| **Duration** | 1 Semester | | |
| **Frequency** | Summer semester | | |
| **Language of Instruction:** | English | | |
| **Forms of Teaching and Learning** | Theoretical lecture with exercises, homework assignments | | |
| **Exam** | The exam consists of the delivery of solutions to weekly task sheets and presenting the solution of exercises in the exercise group. For passing the exam, the number of omitted task sheets may not exceed two, the total amount of points reached in the task sheets must exceed 2/3 of all points, and the solution of at least two complete exercises must be presented in the group. | | |
| **Content** | 1. Universal quantum computers: Toffoli gates, single and multiple Qubit gates, controlled gates, Quantum circuits, …<br>2. Quantum algorithms: Deutsch-Josza algorithm, Shor's factorization algorithm and applications, Grover's search algorithm, …<br>3. Quantum communication: No cloning theorem, Quantum teleportation, Quantum key distribution, …<br>4. Physical Realizations: DiVincenzo criteria, Cirac Zoller quantum computer, Circuit QED, …<br>5. Decoherence and open quantum systems: Stochastic operations, POVM measurements, single Qubit quantum channels, …<br>6. Quantum error correction: Simple Q correction codes, General theory of quantum error correction, Fault tolerant quantum computing, ...<br>7. Alternative quantum computing models: One-way quantum computer, Adiabatic quantum computation, …<br>8. Introduction to the theory of entanglement: Definition, criteria and measurement of entanglement, multipartite entanglement, … | | |
| **Objectives** | Students will learn the basic concepts and theoretical tools in quantum information processing. They will understand the concept of quantum algorithms and quantum circuits, learn to program a quantum computer, understand the functioning of important quantum algorithms, learn how to describe quantum channels and the principles of quantum error correction and entanglement theory. They will understand the most advanced concepts of physical realizations of quantum computers. | | |

**Requirements for Obtaining Credit, Grading, weight if applicable:**

| | Type of Course | Status | CH (SWS) | CP | Type of Exam | Duration of Exam | Grading | Weight for Grade |
|---|---|---|---|---|---|---|---|---|
| Lecture | L | o | 4 | 6 | A | 30 | ng | -- |
| Exercise | E | o | 2 | 3 | | | | |

| | |
|---|---|
| **Transfer** | The module can can also be also used for following studies:<br>- BSc in Physics (Vertiefungsfach, 4th year) |
| **Prerequisites** | Quantum mechanics |
| **Responsible** | Daniel Braun |

<table>
<tr><td>Module Code:<br>AQP213</td><td colspan="5">Module Title:<br>Theory of Open Quantum Systems</td><td colspan="4">Type of Module:<br>Elective</td></tr>
<tr><td>CP (ECTS Credits)</td><td colspan="9">6</td></tr>
<tr><td>Workload:<br>- Time in Class<br>- Self-Study</td><td>Total Workload:<br>270 h</td><td colspan="4">Time in Class:<br>90 h / 6 SWS</td><td colspan="4">Self-Study:<br>180 h</td></tr>
<tr><td>Duration</td><td colspan="9">1 Semester</td></tr>
<tr><td>Frequency</td><td colspan="9">Summer semester</td></tr>
<tr><td>Language of Instruction:</td><td colspan="9">English</td></tr>
<tr><td>Forms of Teaching and Learning</td><td colspan="9">Theoretical lecture with exercises, homework assignments. The basic principles will be conveyed in the lecture. Exercises will be used to support the lectures, i.e. to deepen certain aspects and make the students engage as much as possible with the lecture contents.</td></tr>
<tr><td>Exam</td><td colspan="9">The exam consists of the delivery of solutions to weekly task sheets and presenting the solutions in the exercise class. For passing the exam, each student must have presented solutions to at least two problems in front of the class.</td></tr>
<tr><td>Content</td><td colspan="9">The lecture will teach the basic principles of open quantum systems. Starting with fundamental aspects of quantum mechanics, such as the density matrix formalism and the measurement process, the lecture will continue with the discussion of quantum systems coupled to an environment. This will culminate in the so-called Lindblad master equation, which will be – among other things – used to introduce and study quantum jump trajectories. Besides the development of a consistent theoretical framework, the lecture focusses on practically and experimentally relevant problems, such as spontaneous decay of atoms or the photon counting statistics of laser-excited atoms.</td></tr>
<tr><td>Objectives</td><td colspan="9">The students will get familiar with the density matrix formalism applied to open quantum systems. They will understand the origin of dephasing and decoherence in quantum systems coupled to an environment. They will be able to solve and analyse the quantum dynamics of simple settings, such as the laser-driven two-level atom in the presence of spontaneous decay. The students will be able to contrast the deterministic evolution under the quantum master equation with the description of an open system dynamics via a stochastic unravelling, using so-called quantum jump trajectories.</td></tr>
<tr><td rowspan="3">Requirements for Obtaining Credit, Grading, weight if applicable:</td><td></td><td>Type of Course</td><td>Status</td><td>CH (SWS)</td><td>CP</td><td>Type of Exam</td><td>Duration of Exam</td><td>Grading</td><td>Weight for Grade</td></tr>
<tr><td>Lecture</td><td>L</td><td>o</td><td>2</td><td>3</td><td rowspan="2">A</td><td rowspan="2">30</td><td rowspan="2">ng</td><td rowspan="2">--</td></tr>
<tr><td>Exercise</td><td>E</td><td>o</td><td>2</td><td>3</td></tr>
<tr><td>Transfer</td><td colspan="9">The module can be also used for following studies:<br>- BSc in Physics (Vertiefungsfach, 4th year)</td></tr>
<tr><td>Prerequisites</td><td colspan="9">Quantum mechanics</td></tr>
<tr><td>Responsible</td><td colspan="9">Igor Lesanovsky, Daniel Braun</td></tr>
</table>

| **Module Code:** AQP214 | **Module Title:** Many-body Quantum Optics | | | | | | **Type of Module:** Elective | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **CP (ECTS Credits)** | 6 | | | | | | | | | |
| **Workload: - Time in Class - Self-Study** | Total Workload: 180 h | Time in Class: 60 h / 4 SWS | | | | | Self-Study: 120 h | | | |
| **Duration** | 1 Semester | | | | | | | | | |
| **Frequency** | winter semester | | | | | | | | | |
| **Language of Instruction:** | English | | | | | | | | | |
| **Forms of Teaching and Learning** | Theoretical lecture with seminar, homework assignments | | | | | | | | | |
| **Exam** | Presentation of a related topic to the class | | | | | | | | | |
| **Content** | The module deals with the formalism in second quantization, Green's functions, diagrammatic many-body theory, random-phase approximation, response functions and electronic correlations, Landau theory of Fermi liquids, Hubbard model, and high-temperature superconductivity. | | | | | | | | | |
| **Objectives** | The students know various theoretical approaches to solve quantum many-body problems. They can apply these approaches in current research activities. | | | | | | | | | |
| **Requirements for Obtaining Credit, Grading, weight if applicable:** | | Type of Course | Status | CH (SWS) | CP | Type of Exam | Duration of Exam | Grading | Weight for Grade | |
| | Lecture | L | o | 2 | 3 | P | 60 | ng | -- | |
| | Seminar | S | o | 2 | 3 | | | | | |
| **Transfer** | The module can be also used for following studies:<br>- BSc in Physics (Vertiefungsfach, 4th year) | | | | | | | | | |
| **Prerequisites** | Quantum mechanics | | | | | | | | | |
| **Responsible** | Beatriz Olmos Sanchez | | | | | | | | | |

<table>
<tr><td>Module Code:<br>AQP221</td><td colspan="9">Module Title:<br>Basics of Superconductivity</td><td colspan="4">Type of Module:<br>Elective</td></tr>
<tr><td>CP (ECTS Credits)</td><td colspan="13">3</td></tr>
<tr><td>Workload:<br>- Time in Class<br>- Self-Study</td><td colspan="5">Total Workload:<br>90 h</td><td colspan="4">Time in Class:<br>30 h / 2 SWS</td><td colspan="4">Self-Study:<br>60 h</td></tr>
<tr><td>Duration</td><td colspan="13">1 Semester</td></tr>
<tr><td>Frequency</td><td colspan="13">Summer semester and winter semester</td></tr>
<tr><td>Language of Instruction:</td><td colspan="13">English</td></tr>
<tr><td>Forms of Teaching and Learning</td><td colspan="13">Experimental lecture</td></tr>
<tr><td>Exam</td><td colspan="13">The module is by default examined in an oral exam. In this case it cannot be chosen for module AQP105 “Discussing Comprehensive Problems of Quantum Science”. In case that students like to choose this module for AQP105, the exam can be suspended and replaced by the oral exam of module AQP105.</td></tr>
<tr><td>Content</td><td colspan="13">Introduction – some history, cooling methods<br>Basic properties of superconductor (R=0,ideal diamagnetism, flux quanta, Type I and Type II superconductors)<br>The macroscopic wave function<br>Quantum interference<br>The BCS theory for „conventional“ superconductors<br>Properties of some superconducting materials<br>Unconventional superconductivity<br>Thermodynamic properties, Ginzburg-Landau theory<br>Critical currents<br>Josephson junctions<br>Outlook: Applications of superconductors</td></tr>
<tr><td>Objectives</td><td colspan="13">Students understand the basic concepts in superconductivity. They also know the properties of relevant superconducting materials, and understand low temperature techniques and experimental methods to grow, pattern and characterize superconductors. This will allow students to participate in more advanced (experimental) research activities in superconductivity.</td></tr>
<tr><td rowspan="2">Requirements for Obtaining Credit, Grading, weight if applicable:</td><td colspan="5"></td><td>Type of Course</td><td>Status</td><td>CH (SWS)</td><td>CP</td><td>Type of Exam</td><td>Duration of Exam</td><td>Grading</td><td>Weight for Grade</td></tr>
<tr><td colspan="5">Lecture</td><td>L</td><td>o</td><td>2</td><td>3</td><td>O</td><td>30</td><td>ng</td><td>--</td></tr>
<tr><td>Transfer</td><td colspan="13">The module can be also used for following studies:<br>- BSc in Physics (Vertiefungsfach, 4th year)</td></tr>
<tr><td>Prerequisites</td><td colspan="13">Quantum mechanics, solid state physics.</td></tr>
<tr><td>Responsible</td><td colspan="13">Reinhold Kleiner</td></tr>
</table>

| **Module Code:** AQP222 | **Module Title:** Macroscopic Quantum Phenomena in Josephson Junctions and Related Systems | **Type of Module:** Elective |
|---|---|---|
| **CP (ECTS Credits)** | 3 | |
| **Workload:**<br>**- Time in Class**<br>**- Self-Study** | Total Workload: 90 h<br>Time in Class: 30 h / 2 SWS | Self-Study: 60 h |
| **Duration** | 1 Semester | |
| **Frequency** | Summer semester and winter semester | |
| **Language of Instruction:** | English | |
| **Forms of Teaching and Learning** | Experimental lecture | |
| **Exam** | The module is by default examined in an oral exam. In this case it cannot be chosen for module AQP105 "Discussing Comprehensive Problems of Quantum Science". In case that students like to choose this module for AQP105, the exam can be suspended and replaced by the oral exam of module AQP105. | |
| **Content** | *Towards artificial atoms:*<br>„Short" Josephson junctions: classical dynamics; „Short" Josephson junctions as macroscopic quantum systems; SQUIDs classic; SQUIDs quantum; Charge Qubits; Circuit QED; More complex superconducting qubits and improved readouts<br>*Josephson junctions with internal degrees of freedom: Fluxons and other macroscopic quantum objects:*<br>Long Josephson junctions: classical dynamics; Long Josephson junctions as macroscop. quantum systems; Fractional Vortices in long 0- $\pi$- Josephson junctions; Quantum properties of fractional vortices; $\varphi$-Josephson junctions<br>Alternative realizations of macroscopic quantum systems | |
| **Objectives** | The students understand the basic concepts of using superconducting devices and circuits as artificial atoms for quantum computing. Knowledge of the state-of-the-art and of specific challenges will enable students to actively participate in the ongoing research in this emerging field. | |

**Requirements for Obtaining Credit, Grading, weight if applicable:**

| | Type of Course | Status | CH (SWS) | CP | Type of Exam | Duration of Exam | Grading | Weight for Grade |
|---|---|---|---|---|---|---|---|---|
| Lecture<br>Seminar | L | o | 2 | 3 | O | 30 | ng | -- |

| | |
|---|---|
| **Transfer** | The module can be also used for following studies:<br>- BSc in Physics (Vertiefungsfach, 4th year) |
| **Prerequisites** | Quantum mechanics, superconductivity |
| **Responsible** | Reinhold Kleiner |

<table>
<tr><td>Module Code:<br>AQP223</td><td colspan="2">Module Title:<br>Applications of Superconductivity</td><td>Type of Module:<br>Elective</td></tr>
<tr><td>CP (ECTS Credits)</td><td colspan="3">3</td></tr>
<tr><td>Workload:<br>- Time in Class<br>- Self-Study</td><td>Total Workload:<br>90 h</td><td>Time in Class:<br>30 h / 2 SWS</td><td>Self-Study:<br>60 h</td></tr>
<tr><td>Duration</td><td colspan="3">1 Semester</td></tr>
<tr><td>Frequency</td><td colspan="3">Summer semester and winter semester</td></tr>
<tr><td>Language of In-struction:</td><td colspan="3">English</td></tr>
<tr><td>Forms of Teaching and Learning</td><td colspan="3">Experimental lecture</td></tr>
<tr><td>Exam</td><td colspan="3">The module is by default examined in an oral exam. In this case it cannot be chosen for module AQP105 “Discussing Comprehensive Problems of Quantum Science”. In case that students choose this module for AQP105, the exam can be suspended and replaced by the oral exam of module AQP105.</td></tr>
<tr><td>Content</td><td colspan="3">Introduction<br>Superconducting cables and magnets<br>Resonators and filters<br>Superconducting detectors of radiation: Bolometers, Calorimeters, Detection and generation of electromagnetic waves<br>Superconducting quantum interferometers (SQUIDs)<br>Superconductors in Microelectronics: Voltage standards and digital electronics</td></tr>
<tr><td>Objectives</td><td colspan="3">The students get familiarized with established and potential applications of super-conductors. For each application they know the state-of-the-art and understand ad-vantages of using superconductors. They get acquainted to challenges in applied superconductivity and learn about strategies to overcome them.<br>The module will enable students to actively participate in research and development in applications of superconductivity.</td></tr>
<tr><td>Requirements for Obtaining Credit, Grading, weight if applicable:</td><td colspan="3"><table><tr><td></td><td>Type of Course</td><td>Status</td><td>CH (SWS)</td><td>CP</td><td>Type of Exam</td><td>Duration of Exam</td><td>Grading</td><td>Weight for Grade</td></tr><tr><td>Lecture<br>Seminar</td><td>L</td><td>o</td><td>2</td><td>3</td><td>O</td><td>30</td><td>ng</td><td>--</td></tr></table></td></tr>
<tr><td>Transfer</td><td colspan="3">The module can be also used for following studies:<br>- BSc in Physics (Vertiefungsfach, 4th year)</td></tr>
<tr><td>Prerequisites</td><td colspan="3">Quantum mechanics, superconductivity.</td></tr>
<tr><td>Responsible</td><td colspan="3">Reinhold Kleiner, Dieter Kölle</td></tr>
</table>

<table>
<tr><td>Module Code:<br>AQP301</td><td colspan="2">Module Title:<br>Module from neighbouring field</td><td>Type of Module:<br>Obligatory</td></tr>
<tr><td>CP (ECTS Credits)</td><td colspan="3">6 (at minimum)</td></tr>
<tr><td>Workload:<br>- Time in Class<br>- Self-Study</td><td>Total Workload:<br>180 h</td><td>Time in Class:<br>60 h / 4 SWS</td><td>Self-Study:<br>120 h</td></tr>
<tr><td>Duration</td><td colspan="3">1 Semester</td></tr>
<tr><td>Frequency</td><td colspan="3">Winter or summer semester</td></tr>
<tr><td>Language of In-struction:</td><td colspan="3">English</td></tr>
<tr><td>Forms of Teaching and Learning</td><td colspan="3">Lecture, possibly with exercises</td></tr>
<tr><td>Exam</td><td colspan="3">No exam necessary</td></tr>
<tr><td>Content</td><td colspan="3">The module can to be taken from a neighboring field, e.g. advanced courses from Mathematics or other fields of Physics that are not covered by the modules of this Master Programme.<br>A second option are modules that prepare the student for a later work as project leader in industry. We recommend courses in management or organization devel-opment.<br>A third option is an internship at an industrial company. Ask your tutor for more in-formation.</td></tr>
<tr><td>Objectives</td><td colspan="3">The students will acquire knowledge, methods and skills in related scientific areas. They are able to cooperate with other disciplines and find joint solutions and are able to apply scientific expertise from other fields in Advanced Quantum Physics.</td></tr>
<tr><td>Requirements for Obtaining Credit, Grading, weight if applicable:</td><td colspan="3">
<table>
<tr><th></th><th>Type of Course</th><th>Status</th><th>CH (SWS)</th><th>CP</th><th>Type of Exam</th><th>Duration of Exam</th><th>Grading</th><th>Weight for Grade</th></tr>
<tr><td>Lecture</td><td>L</td><td>e</td><td>2</td><td>3</td><td rowspan="2">--</td><td rowspan="2">--</td><td rowspan="2">ne</td><td rowspan="2">--</td></tr>
<tr><td>Exercise</td><td>E</td><td>e</td><td>2</td><td>3</td></tr>
</table>
</td></tr>
<tr><td>Transfer</td><td colspan="3">--</td></tr>
<tr><td>Prerequisites</td><td colspan="3">--</td></tr>
<tr><td>Responsible</td><td colspan="3">--</td></tr>
</table>

| **Module Code:** AQP401 | **Module Title:** Methods and Project Planning | | | | | | | | **Type of Module:** Obligatory |
|---|---|---|---|---|---|---|---|---|---|
| **CP (ECTS Credits)** | 15 | | | | | | | | |
| **Workload: - Time in Class - Self-Study** | Total Workload: 450 h | Contact Time: variable depending on the activity | | | | Self-Study: variable depending on the activity | | | |
| **Duration** | 1 Semester | | | | | | | | |
| **Frequency** | Every semester, the student can start any time in the 2nd year | | | | | | | | |
| **Language of Instruction:** | English | | | | | | | | |
| **Forms of Teaching and Learning** | Advising the student to scientific methods and project planning | | | | | | | | |
| **Exam** | -- | | | | | | | | |
| **Content** | The module serves to teach the student methods of project management. The formulation, presentation and discussion of the project plan for the own research project will be done together with the supervisor. The project will be done in the research group in which the Master Thesis will be prepared. At the beginning of the module the supervisor will present the topic of the Thesis. | | | | | | | | |
| **Objectives** | The students are able to prepare independently (albeit under the supervision of an adviser) a larger research project and to present it in an appropriate fashion. They critically evaluate secondary sources and situate their project within current scholarly discourses. They are able to demonstrate that they have acquired general knowledge and can critically discuss special topics of their choice against this background. | | | | | | | | |
| **Requirements for Obtaining Credit, Grading, weight if applicable:** | | Type of Course | Status | CH (SWS) | CP | Type of Exam | Duration of Exam | Grading | Weight for Grade |
| | Project related research | PR | o | -- | 15 | -- | -- | ne | -- |
| **Transfer** | The module prepares for the research in the subject of the Master Thesis. Can be used for the MSc in Physics | | | | | | | | |
| **Prerequisites** | Completion of modules with 60 CP in the Advanced Quantum Physics master program, in particular: Completion of modules AQP101, AQP102, AQP103 or AQP104, AQP105, and AQP301. | | | | | | | | |
| **Responsible** | Advisor in the research group, where the Master thesis will be prepared | | | | | | | | |

<table>
<tr><td>Module Code:<br>AQP402</td><td colspan="4">Module Title:<br>Scientific Specialisation in Thesis Topic</td><td colspan="4">Type of Module:<br>Obligatory</td></tr>
<tr><td>CP (ECTS Credits)</td><td colspan="8">15</td></tr>
<tr><td>Workload:<br>- Time in Class<br>- Self-Study</td><td>Total Workload:<br>450 h</td><td colspan="4">Contact Time: 30 h / 2 SWS for the seminar, otherwise variable depending on the activity</td><td colspan="4">Self-Study: 60 h for the lecture, otherwise variable depending on the activity</td></tr>
<tr><td>Duration</td><td colspan="8">1 Semester</td></tr>
<tr><td>Frequency</td><td colspan="8">Every semester, the student can start any time in the 2nd year</td></tr>
<tr><td>Language of Instruction:</td><td colspan="8">English</td></tr>
<tr><td>Forms of Teaching and Learning</td><td colspan="8">Advising the students to perform independent scientific research which includes the participation in the group seminars.</td></tr>
<tr><td>Exam</td><td colspan="8">--</td></tr>
<tr><td>Content</td><td colspan="8">The module serves to define a specific scientific project in theoretical or experimental quantum physics. To prepare the Master Thesis the student will specialize in a research group of the Center for Quantum Science in which she/he will prepare the Thesis.</td></tr>
<tr><td>Objectives</td><td colspan="8">The students are able to formulate independently an own research project and situate it within current scholarly debates. They are capable of developing own solution methods and present them in an appropriate manner. They can react appropriately to the feedback of peers and faculty, and they are also able to understand and provide feedback on other students' projects.</td></tr>
<tr><td rowspan="3">Requirements for Obtaining Credit, Grading, weight if applicable:</td><td></td><td>Type of Course</td><td>Status</td><td>CH (SWS)</td><td>CP</td><td>Type of Exam</td><td>Duration of Exam</td><td>Grading</td><td>Weight for Grade</td></tr>
<tr><td>Project related work</td><td>PR</td><td>o</td><td></td><td>12</td><td rowspan="2">--</td><td rowspan="2">--</td><td rowspan="2">ne</td><td rowspan="2">--</td></tr>
<tr><td>Exercise</td><td>S</td><td>o</td><td>2</td><td>3</td></tr>
<tr><td>Transfer</td><td colspan="8">The module prepares for the research in the subject of the Master Thesis. Can be used for the MSc in Physics</td></tr>
<tr><td>Prerequisites</td><td colspan="8">Completion of modules with 60 CP in the Advanced Quantum Physics master program, in particular: Completion of modules AQP101, AQP102, AQP103 or AQP104, AQP105, and AQP301.</td></tr>
<tr><td>Responsible</td><td colspan="8">Advisor in the research group, where the Master thesis will be prepared</td></tr>
</table>

| **Module Code:** AQP403 | **Module Title:** Master-Thesis | | | | | | | **Type of Module:** Obligatory | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **CP (ECTS Credits)** | 30 | | | | | | | | | |
| **Workload:** **- Time in Class** **- Self-Study** | Total Workload: 900 h | Contact Time: variable depending on the activity | | | | Self-Study: variable depending on the activity | | | | |
| **Duration** | 1 Semester | | | | | | | | | |
| **Frequency** | Every semester, the student can start any time in the 2nd year | | | | | | | | | |
| **Language of Instruction:** | English | | | | | | | | | |
| **Forms of Teaching and Learning** | Independent research project under supervision (100%) | | | | | | | | | |
| **Exam** | Delivery of Master-Thesis essay and oral scientific presentation of the content. | | | | | | | | | |
| **Content** | Scientific research, method developments, and/or laboratory tasks, preparation of a scientific essay | | | | | | | | | |
| **Objectives** | After successful completion of the Master Thesis, students have acquired profound skills in state-of-the art methods in Advanced Quantum Physics. They are acquainted with the current scientific questions and recent publications in their research field. They are trained in compiling and analyzing scientific data and writing a scientific report. In addition to scientific expertise, students will acquire soft skills, such as time and project management, working in international, interdisciplinary teams, English communication and writing skills, and rules of responsible conduct of research. Overall, with successful completion of the Master Thesis, students proof their scientific competence and demonstrate that they are well prepared to tackle demanding research projects such as, for example, a doctoral thesis. | | | | | | | | | |
| **Requirements for Obtaining Credit, Grading, weight if applicable:** | | Type of Course | Status | CH (SWS) | CP | Type of Exam | Duration of Presentation | Grading | Weight for Grade | |
| | Project related research | PR | o | -- | 30 | A/P | 30 | g | 1.0 | |
| **Transfer** | The module is the final one of the Master programme. It can be used for the MSc in Physics | | | | | | | | | |
| **Prerequisites** | Completion of modules with 90 CP in the Advanced Quantum Physics master program, in particular: Completion of modules AQP101, AQP102, AQP103 or AQP104, AQP 105, AQP301, AQP401, and AQP402 | | | | | | | | | |
| **Responsible** | Advisor in the research group, where the Master thesis will be prepared | | | | | | | | | |