# Description of Module Master of Science
# 528 Quantum Science and Technology
PO-Version 2024

FRIEDRICH-SCHILLER-UNIVERSITÄT JENA

## Contents summary

**Note :** Please note that you can find the information on examinations, courses corresponding to the examinations, and examination dates in the portal Friedolin under the menu item ‘Browse module descriptions’. After logging in, please choose your degree, your study programme, and respective module. Any immediate changes made will be displayed promptly.

| Modul **MedPhoA1.3** Physical Chemistry | |
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| Module code | MedPhoA1.3 |
| Module title (German) | Physikalische Chemie |
| Module title (English) | Physical Chemistry |
| Person responsible for the module | Michael Schmitt, Rainer Heintzmann, Jürgen Popp |
| Type of module (compulsory module, required elective module, elective module) | Required elective M.Sc. Medical Photonics,<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”adjustment” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | lectures: 4 hours per week, exercises: 2 hours per week |
| ECTS credits | 8 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 240 h<br>90 h<br>150 h |
| Content | Equilibrium thermodynamics: Properties of gases, first and second law of thermodynamics, chemical equilibrium, equilibrium electrochemistry<br>Transport phenomena: molecular motion in gases and liquids, diffusion, transport across biological membranes<br>Chemical reactions: chemical kinetics, rate laws, temperature dependence of reaction rates, relaxation methods, kinetics of complex reactions<br>Basics of quantum mechanics: wavefunctions and operators, particle in a box, harmonic oscillator, particle on a sphere, rigid rotator<br>Approximations: variational principle, Born-Oppenheimer approximation, linear combination of atomic orbitals (LCAO) method, Hartree-Fock, density functional theory (DFT) |
| Intended learning outcomes | Understanding of the fundamentals of physical chemistry.<br>Knowledge in equilibrium thermodynamics, chemical kinetics and basic molecular quantum mechanics. |
| Requirements for awarding credit points (type of examination) | written examination at the end of the semester |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFBX411** Computational Physics II | |
|---|---|
| Module code | PAFBX411 |
| Module title (German) | Computational Physics II |
| Module title (English) | Computational Physics II |
| Person responsible for the module | Prof. Dr. B. Brügmann |
| Prerequisites for admission to the module | - |
| Recommended or expected prior knowledge | Computational Physics I PAFBU311<br>Theoretische Mechanik PAFBT211<br>Elektrodynamik PAFBT311 |
| Type of module (compulsory module, required elective module, elective module) | 039 M.Sc. Geosciences, required elective module<br>128 M.Sc. Physics focus „Quantum and Gravitational Theory”<br>128 B.Sc. Physics, required elective module<br>679 B.Sc. Applied Computer Science, Application subject physics<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in summer semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 hours/week<br>Exercise: 2 hours/week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | Introduction to Unix and higher-level programming languages (e.g.: C/C++,<br>Fortran)<br>Numerical solution of partial differential equations<br>Monte Carlo method<br>Molecular dynamics methods<br>Minimization problems |
| Intended learning outcomes | Teaching the basic algorithms and practical skills for the numerical solution of complex physical problems and Visualization of large amounts of data |
| Prerequisites for admission to the module examination | - |

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| Requirements for awarding credit points (type of examination) | Written examination |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMF001** Theoretical Solid State Physics | |
|---|---|
| Module code | PAFMF001 |
| Module title (German) | Theoretische Festkörperphysik |
| Module title (English) | Theoretical Solid State Physics |
| Person responsible for the module | Prof. Dr. U. Peschel |
| Prerequisites for admission to the module | none |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc. Physics, required elective module, focus „Solid state physics / Material science"<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area "specialization" |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 4 h per week<br>Exercise: 2 h per week |
| ECTS credits | 8 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 240 h<br>90 h<br>150 h |
| Content | • Crystal structures and elastic properties of solids;<br>• Electronic properties of crystals;<br>• Approximate methods for electronic band structure;<br>• Semiconductors and defect physics;<br>• P-n junctions;<br>• Microscopic description of charge transport;<br>• Properties of alloys;<br>• Nanostructures and interfaces;<br>• Optical and dielectric properties of solids;<br>• Magnetism and superconductivity. |
| Intended learning outcomes | The course covers advanced topics of solid state physics, with a specific focus on the theoretical understanding of the properties of electrons in crystals. An effort is made to remain as rigorous as possible in the theoretical and mathematical treatment, while keeping the presentation at an accessible level through the presentation of interesting applications to experiments and advanced technology. After completion of the course the students will master the relation between electronic structure of crystalline solids and their dielectric, optical, transport, magnetic properties. |
| Prerequisites for admission to the module examination | Course exercises to be submitted; further information on the kind and scope will be given at the beginning of each semester. |

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| Requirements for awarding credit points (type of examination) | Written examination (100%) |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMF002** Electronic Structure Theory | |
|---|---|
| Module code | PAFMF002 |
| Module title (German) | Theorie der Elektronenstruktur |
| Module title (English) | Electronic Structure Theory |
| Person responsible for the module | Prof. Dr. Ulf Peschel |
| Prerequisites for admission to the module | - |
| Recommended or expected prior knowledge | - |
| Prerequisite for what other modules | - |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc. Physics: Required elective module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in summer semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 3 h per week |
| ECTS credits | 8 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 240 h<br>130 h<br>110 h |
| Content | Introduction to the many-body problem;<br>Wavefunction-based approaches for electronic structure;<br>Density functional theory;<br>Electronic excitations: beyond density functional theory. |
| Intended learning outcomes | Electronic structure theory is a successful and ever-growing field, shared by theoretical physics and theoretical chemistry, that takes advantage from the increasing availability of high-performance computers.<br>Starting only from the knowledge of the types of atoms that constitute a material (molecule, solid, nanostructure,..) students will learn how to determine without further experimental input, i.e. using only the laws of quantum physics, its structural and electronic properties.<br>The lecture will initiate the students to the state-of-the-art theoretical and computational approaches used for electronic structure calculations.<br>In the practical classes the students will learn through tutorials to use different software for electronic structure simulations. During the last month they will realize a small independent scientific project. |

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| Prerequisites for admission to the module examination | Course exercises to be submitted; Further information on the kind and scope will be given at the beginning of each semester. |
| Requirements for awarding credit points (type of examination) | Oral examination (100%) |
| Additional information on the module | 128 M.Sc.Physics: Specialization "Solid state physics / Material science". If requested by the participants and agreed on with the responsible teacher, this module can be offered on-site and/or online (hybrid). |
| Recommended reading | A list of Literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMF003** Solid State Optics | |
|---|---|
| Module code | PAFMF003 |
| Module title (German) | Solid State Optics |
| Module title (English) | Solid State Optics |
| Person responsible for the module | Prof. Dr. Heidemarie Schmidt |
| Prerequisites for admission to the module | - |
| Recommended or expected prior knowledge | - |
| Prerequisite for what other modules | - |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc. Physics: Required elective module<br>628 M.Sc. Photonics: Required elective module<br>528 M.Sc. Quantum Science and Technology: Required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in summer semester) |
| Duration of module | 2 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 8 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 240 h<br>90 h<br>150 h |
| Content | • Introduction to the many-body problem;<br>• Wavefunction-based approaches for electronic structure;<br>• Density functional theory;<br>• Electronic excitations: beyond density functional theory. |
| Intended learning outcomes | Electronic structure theory is a successful and ever-growing field, shared by theoretical physics and theoretical chemistry, that takes advantage from the increasing availability of high-performance computers.Starting only from the knowledge of the types of atoms that constitute a material (molecule, solid, nanostructure,..) we will learn how to determine without further experimental input, i.e. using only the laws of quantum physics, its structural and electronic properties.The lecture will initiate the students to the state-of-the-art theoretical and computational approaches used for electronic structure calculations.In the practical classes the students will learn through tutorials to use different software for electronic structure simulations. During the last month they will realize a small independent scientific project. |

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| Prerequisites for admission to the module examination | Course exercises to be submitted; further information on the kind and scope will be given at the beginning of each semester. |
| Requirements for awarding credit points (type of examination) | Oral examination (100%) |
| Additional information on the module | |
| Recommended reading | A list of Literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMF006** Superconductivity | |
|---|---|
| Module code | PAFMF006 |
| Module title (German) | Supraleitung |
| Module title (English) | Superconductivity |
| Person responsible for the module | Prof. Dr. P. Seidel, apl. Prof. Dr. F. Schmidl |
| Prerequisites for admission to the module | none |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc. Physics, Required elective module focus „Solid state physics / Material science",<br>177 M.Sc. Materialwissenschaften, Required elective module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area "specialization" |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in summer semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>60 h<br>60 h |
| Content | • Basic effects of superconductivity;<br>• characteristics of superconductors;<br>• Josephson effects;<br>• Superconducting materials (classes, structure, properties);<br>• fabrication (single crystals, solid material, layers, wires, ribbons);<br>• modification of the materials (doping, pinning);<br>• Applications of superconductivity. |
| Intended learning outcomes | • Understanding the basic concepts and concepts of superconductivity, superconducting materials and their application;<br>• creation of ready-to-use basic knowledge;<br>• Ability to independently re-deepen the subject.<br>• Ability to participate in a scientific discussion |
| Prerequisites for admission to the module examination | Active participation in discussions in the seminar and preparation of a term paper |
| Requirements for awarding credit points (type of examination) | Module grade: term paper and presentation (100%) |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |

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| Language of instruction | English |

| Modul **PAFMF009** Optoelectronics | |
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| Module code | PAFMF009 |
| Module title (German) | Optoelektronik |
| Module title (English) | Optoelectronics |
| Person responsible for the module | Jun.-Prof. Dr. Giancarlo Soavi |
| Prerequisites for admission to the module | - |
| Recommended or expected prior knowledge | - |
| Prerequisite for what other modules | - |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc. Physics: Required elective module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization”<br>628 M.Sc. Photonics: Required elective module |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in summer semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | • Semiconductors<br>• Optoelectronic devices<br>• Photodiodes<br>• Light emitting diodes<br>• Semiconductor optical amplifier |
| Intended learning outcomes | In this course the student will learn how to solve problems related to the fundamentals of semiconductor optical devices such as photodiodes, solar cells, LEDs, laser diodes and semiconductor optical amplifiers. |
| Prerequisites for admission to the module examination | - |
| Requirements for awarding credit points (type of examination) | Written examination (100%) |
| Additional information on the module | |
| Recommended reading | A list of Literature and materials will be provided at the beginning of the semester. |

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| Language of instruction | English |

| Modul **PAFMF016** Nanomaterials and Nanotechnology | |
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| Module code | PAFMF016 |
| Module title (German) | Nanomaterialien und Nanotechnologie |
| Module title (English) | Nanomaterials and Nanotechnology |
| Person responsible for the module | Prof. Dr. C. Ronning |
| Prerequisites for admission to the module | none |
| Type of module (compulsory module, required elective module, elective module) | Required elective module M.Sc. Physics focus „Solid state physics / Material science”<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | At irregular intervals |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | • dimension effects,<br>• Quantisation of electrons<br>• single-electron transistor,<br>• synthesis of nanomaterials,<br>• characterization of nanomaterials,<br>• Material systems: carbon nanotubes, graphene, magnetic nanomaterials, bionanomaterials,<br>• Application and technology of nanomaterials. |
| Intended learning outcomes | In-depth knowledge in the field of solid-state physics. |
| Prerequisites for admission to the module examination | Course exercises to be submitted; further information on the kind and scope will be given at the beginning of each semester. |
| Requirements for awarding credit points (type of examination) | Written or oral examination or presentation (100%)<br>The form of the exam will be announced at the beginning of the semester. |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester |
| Language of instruction | English |

| Modul **PAFMF018** Quantum Information Theory | |
|---|---|
| Module code | PAFMF018 |
| Module title (German) | Quanteninformationstheorie |
| Module title (English) | Quantum Information Theory |
| Person responsible for the module | Prof. Dr. Martin Gärttner |
| Prerequisites for admission to the module | - |
| Recommended or expected prior knowledge | Quantum mechanics, linear algebra |
| Prerequisite for what other modules | - |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc. Physics: Required elective module<br>628 M.Sc. Photonics: Required elective module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | At irregular intervals |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |

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| Content | Lecture of Drs. Eilenberger, Steinlechner<br>• Basic introduction to quantum optics;<br>• Quantum light sources;<br>• Encoding,<br>• transmission and detection of information with quantum light;<br>• Quantum communication and cryptography;<br>• Quantum communication networks;<br>• Outlook on Quantum metrology and Quantum imaging;<br><br>Lecture of Dr. Sondenheimer<br>• Open quantum systems, Density matrix formalism, Generalized measurements, Quantum channels<br>• Superdense coding, quantum teleportation<br>• Entanglement theory, Bell inequalities,<br>• CHSH inequalities<br>• Quantum circuits, universal gates<br>• Quantum error correction |
| Intended learning outcomes | <p><span dir="ltr">The course will give a basic introduction into the usage of quantum states of light for the exchange of information. It will introduce contemporary methods for the generation of quantum light and schemes that leverage these states for the exchange of information, rangingfrom fundamental concepts and experiments to state of the artimplementations for secure communication networks. The course willalso give an outlook to aspects of Quantum metrology and imaging.Afteractive participation in the course, the students will be familiarwith the basic concepts and phenomena of quantum information exchangeand some aspects related to the practical implementation thereof.They will be able to apply their knowledge in the assessment andsetup of experiments and devices for applications of quantuminformation processing.Vermittlung grundlegender Kenntnisse zur Übertragung undVerarbeitung von Information mit Hilfe von Quantensystemen als InformationsträgerInformationstheoretische Beherrschung der Verschränktheit von Quantensystemen </span> |
| Prerequisites for admission to the module examination | - |
| Requirements for awarding credit points (type of examination) | Written or oral examination or presentation (100%);<br>The selected form of the exam will be announced at the beginning of the semester. |
| Additional information on the module | |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

## Modul **PAFMF021** 2D materials

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| Module code | PAFMF021 |
| Module title (German) | Zweidimensionale Materialien |
| Module title (English) | 2D materials |
| Person responsible for the module | Jun.-Prof. Giancarlo Soavi |
| Prerequisites for admission to the module | - |
| Recommended or expected prior knowledge | - |
| Prerequisite for what other modules | - |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc. Physics: Required elective module<br>628 M.Sc. Photonics: Required elective module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | • Graphene: electrical and optical properties. Applications in electronic and optoelectronic.<br>• Semiconducting 2D materials: Coulomb screening and the concept of excitons. Optical spectroscopy of excitons. Optoelectronic applications.<br>• Heterostructures: electron and exciton interactions in layered heterostructures |
| Intended learning outcomes | • Mastering the basics and methods of two-dimensional materials<br>• Ability to work independently on problems in the field of two-dimensional materials |
| Prerequisites for admission to the module examination | - |
| Requirements for awarding credit points (type of examination) | Written or oral examination (100%) The selected form of the exam will be announced at the beginning of the semester. |
| Additional information on the module | |

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| Recommended reading | A list of Literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMO001** Fundamentals of Modern Optics | |
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| Module code | PAFMO001 |
| Module title (German) | Fundamentals of Modern Optics |
| Module title (English) | Fundamentals of Modern Optics |
| Person responsible for the module | Prof. Dr. Thomas Pertsch |
| Prerequisites for admission to the module | - |
| Recommended or expected prior knowledge | - |
| Prerequisite for what other modules | - |
| Type of module (compulsory module, required elective module, elective module) | 628 M.Sc. Photonics: Compulsory Module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”adjustment |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 4 h per week<br>Exercise: 2 h per week |
| ECTS credits | 8 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 240 h<br>90 h<br>150 h |
| Content | • Basic concepts of wave optics<br>• Dielectric function to describe light-matter interaction<br>• Propagation of beams and pulses<br>• Diffraction theory- Elements of Fourier optics<br>• Polarization of light<br>• Light in structured media<br>• Optics in crystals |
| Intended learning outcomes | The course covers the fundamentals of modern optics which are necessary for the understanding of optical phenomena in modern science and technology. The students will acquire a thorough knowledge of the most important concepts of modern optics. At the same time the importance and applications of optics in technology will be taught. This will enable students to solve advanced problems in general optics and follow more specialized courses in photonics. |
| Prerequisites for admission to the module examination | - |

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| Requirements for awarding credit points (type of examination) | Written examination (100%) |
| Additional information on the module | |
| Recommended reading | A list of Literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMO002** Structure of Matter | |
|---|---|
| Module code | PAFMO002 |
| Module title (German) | Structure of Matter |
| Module title (English) | Structure of Matter |
| Person responsible for the module | Prof. Dr. Andreas Tünnermann |
| Prerequisites for admission to the module | - |
| Recommended or expected prior knowledge | - |
| Prerequisite for what other modules | - |
| Type of module (compulsory module, required elective module, elective module) | 628 M.Sc. Photonics: Compulsory Module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 4 h per week<br>Exercise: 2 h per week |
| ECTS credits | 8 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 240 h<br>90 h<br>150 h |
| Content | • Classical interaction of light with matter<br>• Basic knowledge on quantum mechanics<br>• Einstein coefficients and Plancks formula<br>• Selection rules<br>• Hydrogen atom and helium atom<br>• Introduction to molecular spectroscopy<br>• Dielectric function and linear optical constants<br>• Kramers-Kronig-Relations<br>• Linear optical properties of crystalline and amorphous solids<br>• Basic nonlinear optical effects |
| Intended learning outcomes | The course is an introduction to the principles of the optical response of materials. |
| Prerequisites for admission to the module examination | - |
| Requirements for awarding credit points (type of examination) | Written examination (100%) |

| Additional information on the module | |
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| Recommended reading | A list of Literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMO005** Optical Metrology and Sensing | |
|---|---|
| Module code | PAFMO005 |
| Module title (German) | Optical Metrology and Sensing |
| Module title (English) | Optical Metrology and Sensing |
| Person responsible for the module | Dr. Frank Setzpfandt |
| Prerequisites for admission to the module | - |
| Recommended or expected prior knowledge | - |
| Prerequisite for what other modules | - |
| Type of module (compulsory module, required elective module, elective module) | 628 M.Sc. Photonics: compulsory module<br>128 MSc. Physics: required elective module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area "specialization" |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | • Basic principles<br>• Wave optical fundamentals<br>• Sensors<br>• Fringe projection, triangulation<br>• Interferometry and wave front sensing<br>• Holography<br>• Speckle methods and OCT<br>• Phase retrieval<br>• Metrology of aspheres and freeform surfaces<br>• Confocal methods |
| Intended learning outcomes | This course covers the main principles of optical measurements and surface metrology. |
| Prerequisites for admission to the module examination | - |
| Requirements for awarding credit points (type of examination) | Written examination (100%) |

| Additional information on the module | |
|---|---|
| Recommended reading | A list of Literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMO106** Atomic Physics at High Field Strengths | |
|---|---|
| Module code | PAFMO106 |
| Module title (German) | Atomic Physics at High Field Strengths |
| Module title (English) | Atomic Physics at High Field Strengths |
| Person responsible for the module | Prof. Dr. Thomas Stöhlker |
| Prerequisites for admission to the module | - |
| Recommended or expected prior knowledge | Basic knowledge in atomic physics |
| Prerequisite for what other modules | - |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc. Physics: Required elective module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization<br>628 M.Sc. Photonics: Required elective module |
| Frequency of offer (how often is the module offered?) | Every semester |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | • Strong field effects on the atomic structure<br>• Relativistic and QED effects on the structure of heavy ions<br>• X-ray spectroscopy of high-Z ions<br>• Application in x-ray astronomy<br>• Penetration of charged particles through matter<br>• Particle dynamics in of atoms and ions in strong laser fields<br>• Relativistic ion-atom and ion-electron collisions<br>• Fundamental interaction processes<br>• Scattering, absorption and energy loss<br>• Detection methods<br>• Particle creation |

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| Intended learning outcomes | The Module provides insight into the basic techniques and concepts in physics related to extreme electromagnetic fields. Their relevance to nowadays applications will be discussed in addition. The Module also introduces the basic interaction processes of high-energy photon and particle beams with matter, including recent developments of high intensity radiation sources, such as free electron lasers and modern particle accelerators. Experimental methods and the related theoretical description will be reviewed in great detail. |
| Prerequisites for admission to the module examination | Course exercises to be submitted; further information on the kind and scope will be given at the beginning of each semester. |
| Requirements for awarding credit points (type of examination) | Oral examination (100%) |
| Additional information on the module | |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English (German on request) |

| Modul **PAFMO151** Experimental Nonlinear Optics | |
|---|---|
| Module code | PAFMO151 |
| Module title (German) | Experimental Nonlinear Optics |
| Module title (English) | Experimental Nonlinear Optics |
| Person responsible for the module | Prof. Dr. Gerhard G. Paulus |
| Prerequisites for admission to the module | - |
| Recommended or expected prior knowledge | - |
| Prerequisite for what other modules | - |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc. Physics: Required elective module<br>628 M.Sc. Photonics: Required elective module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | • Propagation of light in crystals;<br>• Properties of the non-linear susceptibility tensor;<br>• Description of light propagation in non-linear media;<br>• Parametric effects;<br>• Second harmonic generation;<br>• Phase-matching;<br>• Propagation of ultrashort pulses;<br>• High-harmonic generation;<br>• Solitons |
| Intended learning outcomes | This course gives an introduction to optics in non-linear media and discusses the main non-linear effects. |
| Prerequisites for admission to the module examination | - |
| Requirements for awarding credit points (type of examination) | Written examination (100%) |

| Additional information on the module | |
|---|---|
| Recommended reading | A list of Literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMO183** Introduction to Nanooptics | |
|---|---|
| Module code | PAFMO183 |
| Module title (German) | Introduction to Nanooptics |
| Module title (English) | Introduction to Nanooptics |
| Person responsible for the module | Prof. Dr. I. Staude, Prof. Dr. T. Pertsch |
| Prerequisites for admission to the module | - |
| Recommended or expected prior knowledge | - |
| Prerequisite for what other modules | - |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc. Physics: Required elective module<br>628 M.Sc. Photonics: Required elective module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | • Surface-plasmon-polaritons;<br>• Plasmonics;<br>• Photonic crystals;<br>• Fabrication and optical characterization of nanostructures;<br>• Photonic nanomaterials / metamaterials / metasurfaces;<br>• Optical nanoemitters;<br>• Optical nanoantennas. |
| Intended learning outcomes | The course provides an introduction to the broad research field of nanooptics. The students will learn about different concepts which are applied to control the emission, propagation, and absorption of light at subwavelength spatial dimensions. Furthermore, they will learn how nanostructures can be used to optically interact selectively with nanoscale matter, a capability not achievable with standard diffraction limited microscopy. After successful completion of the course the students should be capable of understanding present problems of the research field and should be able to solve basic problems using advanced literature. |

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| Prerequisites for admission to the module examination | - |
| Requirements for awarding credit points (type of examination) | Module mark (100%)<br>Consists of a written examination and an oral presentation on a current research topic. |
| Additional information on the module | |
| Recommended reading | A list of Literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMO184** Integrated Optics | |
|---|---|
| Module code | PAFMO184 |
| Module title (German) | Integrated Optics |
| Module title (English) | Integrated Optics |
| Person responsible for the module | Dr. M. Gräfe, Dr. V. Gili, Prof. Dr. T. Pertsch |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc. Physics focus „Optics": Required elective module<br>628 M.Sc. Photonics: Required elective module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area "specialization" |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per weekExercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | The lecture will cover a significant part of integrated quantum photonics, which is one of the pillars of the current quantum technology development. In particular, the lecture will cover the following topics<br>• Integrated optics on a single photon level<br>• Generation and manipulation of quantum states of light using integrated waveguides<br>• Overview over integrated photonic platforms and fabrication of passive and active waveguide structures<br>• Quantum walks in linear and non-linear waveguide lattices<br>• Introduction to photonic quantum computation and simulation<br>• Measurements using superconducting nanowire single photon detectors and transition edge sensors |

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| Intended learning outcomes | The course should provide the participating students with a profound knowledge on the state of the art of integrated optics used for the realization of quantum optical devices.<br>After active participation in the course, the students will be familiar with the basic concepts and phenomena of integrated quantum photonics and will be able to develop own concepts for integrated quantum circuitry.<br>The intended learning outcome is that the students are introduced to the basics on the field of integrated quantum optics and its applications.<br>Therefore, course starts with an overview on the generation of non-classical states of light with special attention on integrated solutions.<br>Afterwards several integrated photonic platforms will be discussed ranging from fabrication to performance and useability.<br>Based on that the on-chip manipulation of non-classical states of light will be discussed. This starts with the very general concept of quantum walks and continues towards quantum simulation. It ends with an introductory to photonic quantum computing with a clear focus on practical implementation of quantum photonic gate structures.<br>The course closes with the discussion on non-classical light detection in integrated photonics. |
| Requirements for awarding credit points (type of examination) | Written or oral examination (100%)<br>The form of the exam will be announced at the beginning of the semester. |
| Additional information on the module | |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

## Modul **PAFMO185** Innovation Methods in Photonics

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|---|---|
| Module code | PAFMO185 |
| Module title (German) | Innovation Methods in Photonics |
| Module title (English) | Innovation Methods in Photonics |
| Person responsible for the module | Prof. Dr. T. Pertsch |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc. Physics focus „Optics": Required elective module<br>628 M.Sc. Photonics: Required elective module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area "specialization" |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in summer semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | • Rapid prototyping technologies in photonics<br>• Innovation management and design thinking<br>• Hands-on/practical examples of photonics prototyping<br>• Entrepreneurial skills and business modelling<br>• Basics of intellectual property rights |
| Intended learning outcomes | The students will learn how the results of their scientific research can be turned into relevant innovations as an important part of their future career. On the one hand, the course will enable students to understand and to drive innovation processes in photonics companies. On the other hand, students will develop an entrepreneurial skill set for the independent economical exploitation of scientific ideas.<br>Therefore, the course introduces the basic knowledge on innovation management, entrepreneurship, and intellectual property rights. To practice their skills, the students will also conduct their own photonics innovation project during the semester by working hands-on in small teams in the photonics makerspace Lichtwerkstatt. During this practical part, they acquire and apply a thorough knowledge of photonic rapid prototyping technologies (e.g. 3d- scanning and printing, laser cutting, microcontrollers, ...) and the most important creativity methods and project management skills. To cover this range of topics, the course will be supported by guest lecturers from different sectors (academia, industry). |

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| Requirements for awarding credit points (type of examination) | Presentation (30%), Short Project Report (30%), written examination (40%). |
| Additional information on the module | |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMO230** Nano Engineering | |
|---|---|
| Module code | PAFMO230 |
| Module title (German) | Nano Engineering |
| Module title (English) | Nano Engineering |
| Person responsible for the module | Dr. Stephanie Höppener, Prof. Dr. Ulrich S. Schubert |
| Prerequisites for admission to the module | - |
| Recommended or expected prior knowledge | - |
| Prerequisite for what other modules | - |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc. Physics: Required elective module<br>628 M.Sc. Photonics: Required elective module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area "specialization" |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | • Building with Molecules<br>• Self-organization and self-assembled coatings<br>• Chemically sensitive characterization methods<br>• Nanomaterials for optical applications<br>• Nanowires and nanoparticles<br>• Nanomaterials in optoelectronics<br>• Bottom-up synthesis strategies and nanolithography<br>• Polymers and self-healing coatings<br>• Molecular motors<br>• Controlled polymerization techniques |

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| Intended learning outcomes | A large diversity of nanomaterials can be efficiently produced by utilizing chemical synthesis strategies. The wide range of nanomaterials, i.e., nanoparticles, nanotubes, micelles, vesicles, nanostructured phase separated surface layers etc. opens on the one hand versatile possibilities to build functional systems, on the other hand also the large variety of techniques and processes to fabricate such systems is also difficult to overlook.<br>Traditionally the communication in the interdisciplinary field of nanotechnology is difficult, as expertise from different research areas is combined. This course aims on the creation of a common basic level for communication and knowledge of researchers of different research fields and to highlight interdisciplinary approaches which lead to new fabrication strategies. The course includes basic chemical synthesis strategies, molecular self-assembly processes, chemical surface structuring, nanofabrication and surface chemistry to create a pool of knowledge to be able to use molecular building blocks in future research projects. |
| Prerequisites for admission to the module examination | - |
| Requirements for awarding credit points (type of examination) | Oral examination (100%) |
| Additional information on the module | |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMO250** Particles in Strong Electromagnetic Fields | |
|---|---|
| Module code | PAFMO250 |
| Module title (German) | Particles in Strong Electromagnetic Fields |
| Module title (English) | Particles in Strong Electromagnetic Fields |
| Person responsible for the module | Prof. Dr. Matt Zepf |
| Prerequisites for admission to the module | - |
| Recommended or expected prior knowledge | <p>Fundamental knowledge on quantum mechanics und special relativity <pre id="tw-target-text" class="tw-data-text tw-ta tw-text-medium" dir="ltr" style="text-align: left;" data-placeholder="Übersetzung"><span lang="en" tabindex="0"> </span></pre> |
| Prerequisite for what other modules | - |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc. Physics: Required elective module<br>628 M.Sc. Photonics: Required elective module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area "specialization" |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in summer semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | • Electrons in constant fields<br>• Electrons in electromagnetic pulses<br>• Radiation produced by particles in extreme motion<br>• Radiation reaction<br>• QED effects in strong laser fields |

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| Intended learning outcomes | This course is devoted to the dynamics of charged particles in electromagnetic fields. Starting with motion of electrons in constant magnetic and electric fields, the course continues with the electron motion in electromagnetic pulses (i.e. laser pulses) of high strength (i.e. when laser pressure becomes dominant). Radiation produced by electrons in extreme motion will be calculated for several most important cases: synchrotron radiation, Thomson scattering, undulator radiation. Effects of radiation reaction on electron motion will be discussed. The last part of the course will briefly discuss the QED effects in strong laser fields: stochasticity in radiation reaction, pair production by focused laser pulses and QED cascades. Analytical framework will be complemented with the help of numerical calculations. |
| Prerequisites for admission to the module examination | - |
| Requirements for awarding credit points (type of examination) | Presentation or oral Exam (100%) |
| Additional information on the module | 128 M.Sc. Physics: Required elective module (Specialization in „Optics”)<br>If requested by the participants and agreed on with the responsible teacher, this module can be offered on-site and/or online (hybrid). |
| Recommended reading | A list of Literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMO260** Quantum Optics | |
|---|---|
| Module code | PAFMO260 |
| Module title (German) | Quantum Optics |
| Module title (English) | Quantum Optics |
| Person responsible for the module | Prof. Dr. T. Pertsch, Dr. F. Setzpfandt |
| Prerequisites for admission to the module | - |
| Recommended or expected prior knowledge | Fundamental knowledge on quantum theory and theoretical optics |
| Prerequisite for what other modules | - |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc. Physics: Required elective module<br>628 M.Sc. Photonics: Required elective module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in summer semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | • Basic introduction to quantum mechanics;<br>• Quantization of the free electromagnetic field;<br>• Non-classical states of light and their statistics;<br>• Experiments in quantum optics;<br>• Semi-classical and fully quantized light-matter interaction;<br>• Non-Linear optics. |
| Intended learning outcomes | The course will give a basic introduction into the theoretical description of quantized light and quantized light-matter interaction. The derived formalism is then used to examine the properties of quantized light and to understand a number of peculiar quantum optical effects.<br>After active participation in the course, the students will be familiar with the basic concepts and phenomena of quantum optics and will be able to apply the derived formalism to other problems. |
| Prerequisites for admission to the module examination | - |

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| Requirements for awarding credit points (type of examination) | Written or oral examination (100%).<br>The selected form of the exam will be announced at the beginning of the semester. |
| Additional information on the module | |
| Recommended reading | A list of Literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMO261** Quantum Computing | |
|---|---|
| Module code | PAFMO261 |
| Module title (German) | Quantum Computing |
| Module title (English) | Quantum Computing |
| Person responsible for the module | Dr. F. Steinlechner, Dr. F. Eilenberger, Prof. Dr. T. Pertsch |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc. Physics focus „Optics": Required elective module<br>628 M.Sc. Photonics: Required elective module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area "specialization" |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in summer semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | • Basic introduction to algorithms and computing<br>•The Qubit and entanglement thereof<br>• Basics of quantum algorithms<br>• Advanced quantum algorithms<br>• Implementation of QuBits and quantum computers<br>• Hands-on circuits |
| Intended learning outcomes | After active participation in the course, the students will be familiar with the basic concepts of quantum computation and the implementation of quantum algorithms. They will be able to apply their knowledge in the assessment and creation of quantum algorithms and the development of quantum information systems.<br>The intended learning outcome is to introduce the students to the basic usage of quantum bits for information processing. To provide further insight, the course will expand this concept on multipartite systems and introduce the concept of entanglement.<br>In a further step we shall see how individual quantum operations tie together to create algorithms. Important algorithms, such as the quantum Fourier transformation, the algorithms of Shor and Grover will be discussed. To relate the abstract knowledge on quantum algorithms to practical applications, real-world implementations of quantum computers will be discussed. |

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| Requirements for awarding credit points (type of examination) | written examination (100%) |
| Additional information on the module | |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMO262** Quantum Communicaton | |
|---|---|
| Module code | PAFMO262 |
| Module title (German) | Quantum Communicaton |
| Module title (English) | Quantum Communicaton |
| Person responsible for the module | Dr. F. Steinlechner, Dr. F. Eilenberger, Prof. Dr. A. Tünnermann |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc. Physics focus „Optics“: Required elective module<br>628 M.Sc. Photonics: Required elective module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in summer semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | • Basic introduction to quantum optics;<br>• Quantum light sources;<br>• Encoding, transmission and detection of information with quantum light;<br>• Quantum communication and cryptography;<br>• Quantum communication networks;<br>• Outlook on Quantum metrology and Quantum imaging; |
| Intended learning outcomes | Goals: The course will give a basic introduction into the usage of quantum states of light for the exchange of generation of quantum light and schemes that leverage these states for the exchange of information, ranging from fundamental concepts and experiments to state of the art implementations for secure communication networks. The course will also give an outlook to aspects of Quantum metrology and imaging.After active participation in the course, the students will be familiar with the basic concepts and phenomena of quantum information exchange and some aspects related to the practical implementation thereof. They will be able to apply their knowledge in the assessment and setup of experiments and devices for applications of quantum information processing. |
| Requirements for awarding credit points (type of examination) | Written or oral examination (100%)<br>The form of the exam will be announced at the beginning of the semester. |

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| Additional information on the module | If requested by the participants and agreed on with the responsible teacher, this module can be offered on-site and/or online (hybrid). |
| Recommended reading | A list of literature and further reading will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMO263** Quantum Imaging and Sensing | |
|---|---|
| Module code | PAFMO263 |
| Module title (German) | Quantum Imaging and Sensing |
| Module title (English) | Quantum Imaging and Sensing |
| Person responsible for the module | Dr. M. Gräfe, Dr. F. Setzpfandt, Prof. Dr. A. Tünnermann |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc. Physics focus „Optics": required elective module<br>628 M.Sc. Photonics: required elective module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area "specialization" |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in summer semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | • Basic introduction to relevant concepts of quantumoptics<br>• Generation of photon pairs<br>• Fundamentals of two-photon interference<br>• Applications of two-photon interference<br>• Optical quantum metrology<br>• Ghost Imaging<br>• Quantum microscopy |
| Intended learning outcomes | Goals: The course will give a basic introduction into the usage of quantum light, in particular photon pairs, for imaging and sensing. To this end, many basic concepts and applications will be introduced and discussed. Furthermore, students will learn how to mathematically describe quantum sensing schemes in order to understand and predict their propreties.<br>After active participation in the course, the students will be familiar with the basic concepts and phenomena of quantum imaging and sensing and will be able to apply the derived formalism to similar problems. |
| Requirements for awarding credit points (type of examination) | Written or oral examination (100%)<br>The form of the exam will be announced at the beginning of the semester |
| Additional information on the module | |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester |

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| Language of instruction | English |

| Modul **PAFMO265** Semiconductor Nanomaterials | |
|---|---|
| Module code | PAFMO265 |
| Module title (German) | Semiconductor Nanomaterials |
| Module title (English) | Semiconductor Nanomaterials |
| Person responsible for the module | Prof. Dr. Isabelle Staude |
| Prerequisites for admission to the module | - |
| Recommended or expected prior knowledge | Fundamental knowledge on modern optics and condensed matter physics |
| Prerequisite for what other modules | - |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc. Physics: Required elective module<br>628 M.Sc. Photonics: Required elective module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in summer semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | The course will cover the following topics:<br>• Review of fundamentals of semiconductors<br>• Optical and optoelectronic properties of semiconductors<br>• Effects of quantum confinement<br>• Photonic effects in semiconductor nanomaterials<br>• Physical implementations of semiconductor nanomaterials, including epitaxial structures, semiconductor quantum dots and quantum wires<br>• Advanced topics of current research, including 2D semiconductors and hybrid nanosystems |

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| Intended learning outcomes | This course aims to convey a fundamental understanding of the physics governing the optical and optoelectronic properties of semiconductor nanomaterials. First, the fundamental optical and optoelectronic properties of bulk semiconductors are reviewed, deepening and extending previously obtained knowledge in condensed matter physics. The students will then learn about the effects of quantum confinement in semiconductor systems in one, two or three spatial dimensions, as well as about photonic effects in nanostructured semiconductors. Finally, several relevant examples of semiconductor nanomaterial systems and their applications in photonics are discussed in detail. After successful completion of the course, the students should be capable of understanding present research directions and of solving basic problems within this field of research. |
| Prerequisites for admission to the module examination | - |
| Requirements for awarding credit points (type of examination) | Written examination at the end of the semester and oral presentation on a current research topic |
| Additional information on the module | |
| Recommended reading | A list of Literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMO270** Theory of Nonlinear Optics | |
|---|---|
| Module code | PAFMO270 |
| Module title (German) | Theory of Nonlinear Optics |
| Module title (English) | Theory of Nonlinear Optics |
| Person responsible for the module | Prof. Dr. Ulf Peschel |
| Prerequisites for admission to the module | - |
| Recommended or expected prior knowledge | - |
| Prerequisite for what other modules | - |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc. Physics: Required elective module<br>628 M.Sc. Photonics: Required elective module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in summer semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | • Types and symmetries of non-linear polarization;<br>• Non-Linear optics in waveguides;<br>• Solutions of non-linear evolution equations;<br>• Temporal and spatial solitons;<br>• Super continuum generation. |
| Intended learning outcomes | The course provides the theoretical background of non-linear optics and quantum optics. |
| Prerequisites for admission to the module examination | - |
| Requirements for awarding credit points (type of examination) | Written examination (100 %) |
| Additional information on the module | |
| Recommended reading | A list of Literature and materials will be provided at the beginning of the semester. |

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| Language of instruction | English |

## Modul **PAFMP001** Advanced Quantum Theory

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| Module code | PAFMP001 |
| Module title (German) | Fortgeschrittene Quantentheorie |
| Module title (English) | Advanced Quantum Theory |
| Person responsible for the module | Prof. Dr. S. Bernuzzi, Prof. Dr. H. Gies |
| Prerequisites for admission to the module | none |
| Type of module (compulsory module, required elective module, elective module) | Compulsory module M.Sc. Physik<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”adjustment” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 4 h per week<br>Exercise: 2 h per week |
| ECTS credits | 8 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 240 h<br>90 h<br>150 h |
| Content | • many particle systems, identical particles, non-interacting particles, Thomas-Fermi and Hartree-Fock approximations<br>• addition of angular momenta, Clebsch-Gordan coefficients, selection rules<br>• time-dependent perturbation theory, Fermis golden rule<br>• scattering theory, potential scattering, partial waves, scattering of identical particles<br>• introduction to relativistic quantum mechanics, Poincare transformations, Klein-Gordon and Dirac equations, minimal coupling, non-relativistic approximation<br>• relativistic hydrogen atom, fine structure<br>• path integrals. |
| Intended learning outcomes | The course covers relevant facts about advanced quantum mechanics which are necessary for an understanding of quantum phenomena and their relevance in all areas of modern physics. The students will learn methods for describing and modeling nonrelativistic and relativistic quantum systems. They will aquire skills to solve demanding problems and deal with complex physical systems. |
| Prerequisites for admission to the module examination | Course exercises to be submitted; further information on the kind and scope will be given at the beginning of each semester. |

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| Requirements for awarding credit points (type of examination) | Written or oral examination (100%)<br>The form of the exam will be announced at the beginning of the semester. |
| Recommended reading | e.g. F. Schwabl; W. Nolting; Straumann; K. Gottfried und T.M. Yan; C. Cohen-Tannoudji. |
| Language of instruction | German, English |

| Modul **PAFMP003** Advanced Seminar Gravitational and Quantum Physics | |
|---|---|
| Module code | PAFMP003 |
| Module title (German) | Oberseminar Gravitations- und Quantentheorie |
| Module title (English) | Advanced Seminar Gravitational and Quantum Physics |
| Person responsible for the module | Prof. Dr. B. Brügmann, Prof. Dr. H. Gies |
| Prerequisites for admission to the module | none |
| Recommended or expected prior knowledge | Basic knowledge in Gravitational and/or Quantum Theory |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc. Physics Required elective module focus „Quantum and Gravitational Theory”<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in summer semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Seminar: 2 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>30 h<br>90 h |
| Content | • Systematic development of specialized knowledge in the fields of gravitation theory and quantum theory;<br>• Presentation and discussion of current problems of gravitation theory and quantum theory. |
| Intended learning outcomes | • Familiarisation with a specific topic in gravitation or quantum theory;<br>• Independent discovery and evaluation of scientific literature;<br>• Presentation of scientific facts in form of a talk;<br>• In-depth knowledge in the fields of gravitation theory and quantum theory. |
| Prerequisites for admission to the module examination | Active participation in the seminar discussions |
| Requirements for awarding credit points (type of examination) | Scientific Talk (100%) |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMQ001** Fundamentals of Quantum information | |
|---|---|
| Module code | PAFMQ001 |
| Module title (German) | Grundlagen der Quanteninformation |
| Module title (English) | Fundamentals of Quantum information |
| Person responsible for the module | Fabian Steinlechner, Frank Setzpfandt, Martin Gärttner |
| Prerequisites for admission to the module | none |
| Recommended or expected prior knowledge | none |
| Type of module (compulsory module, required elective module, elective module) | 528 M.Sc. Quantum Science and Technology, compulsory module subject area "essentials" |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 4 h per week<br>Exercise: 2 h per week |
| ECTS credits | 8 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 240 h<br>90 h<br>150 h |
| Content | **Concepts of quantum information processing**<br>• introduction to fundamental concepts and the basic formalism<br>• entanglement<br>• application examples<br>• entanglement characterization<br><br>**Hardware for quantum information processing**<br>• brief review of key physical concepts and applications<br>• basic hardware requirements for information processing<br><br>optical qubits, gates |
| Intended learning outcomes | Understanding of fundamental properties of quantum states, their applications and how to characterize them. Knowledge about basic hardware requirements for quantum information processing and example implementations. |
| Prerequisites for admission to the module examination | Solution of exercise sheets (Scope to be announced at the beginning of the module). |
| Requirements for awarding credit points (type of examination) | Written examination |

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|---|---|
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMQ002** Advanced Quantum Information | |
|---|---|
| Module code | PAFMQ002 |
| Module title (German) | Fortgeschrittene Quanteninformationstheorie und -hardware |
| Module title (English) | Advanced Quantum Information |
| Person responsible for the module | Fabian Steinlechner, Frank Setzpfandt, Martin Gärttner |
| Recommended or expected prior knowledge | Content of ”Introduction to Quantum Information” |
| Type of module (compulsory module, required elective module, elective module) | 528 M.Sc. Quantum Science and Technology, required elective module, subject area ”essentials” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 4 h per week<br>Exercise: 2 h per week |
| ECTS credits | 8 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 240 h<br>90 h<br>150 h |
| Content | **Hardware for quantum information processing**<br>• superconducting qubits, gates, control, manipulation, readout<br>• light-matter interaction<br>• semiconductor qubits (quantum dots, defects)<br>• atoms / quantum Gases<br>• foundations of quantum sensing (sensitivity, noise, standard quantum limit)<br>• Optomechanics<br><br>**Concepts of quantum information processing**<br>• decoherence<br>• quantum error correction<br>• many-body entanglement<br><br>advanced concepts |
| Intended learning outcomes | Knowledge of all eminent concepts for implementing quantum-information systems. Understanding advanced concepts that enable treatment of non-ideal quantum systems. |
| Prerequisites for admission to the module examination | Solution of exercise sheets (Scope to be announced at the beginning of the module). |

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|---|---|
| Requirements for awarding credit points (type of examination) | Written examination. |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMQ003** Introduction to Quantum physics | |
|---|---|
| Module code | PAFMQ003 |
| Module title (German) | Einführung in die Quantenphysik |
| Module title (English) | Introduction to Quantum physics |
| Person responsible for the module | Frank Setzpfandt |
| Prerequisites for admission to the module | none |
| Recommended or expected prior knowledge | none |
| Type of module (compulsory module, required elective module, elective module) | 528 M.Sc Quantum Science and Technology: required elective module, subject area ”adjustment” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 4 h per week<br>Exercise: 2 h per week |
| ECTS credits | 8 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 240 h<br>90 h<br>150 h |
| Content | relevant core concepts of atomic and solid-state physics, basics of light-matter-interaction, basics of superconductivity, basics of quantum theory, quantum harmonic oscillator, perturbation theory, pictures of quantum mechanics |
| Intended learning outcomes | Understanding of basic concepts and methods for the description of physical systems within the framework of quantum theory.<br>Ability to independently solve simple tasks in the area of quantum physics. |
| Prerequisites for admission to the module examination | Solution of exercise sheets (Scope to be announced at the beginning of the module). |
| Requirements for awarding credit points (type of examination) | Written examination |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMQ007** Quantum Laboratory | |
|---|---|
| Module code | PAFMQ007 |
| Module title (German) | Quantum Laboratory |
| Module title (English) | Quantum Laboratory |
| Person responsible for the module | Frank Setzpfandt |
| Type of module (compulsory module, required elective module, elective module) | 528 M.Sc. Quantum Science and Technology, required elective module, subject area ”practical research training” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Practical course |
| ECTS credits | 6 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 180 h<br>60 h<br>120 h |
| Content | Practical training in experimental quantum technologies. Topics cover a broad range from quantum-state generation and characterization, the demonstration of fundamental quantum effects to applications in communication and metrology. |
| Intended learning outcomes | • Introduction to experimental techniques in quantum technologies.<br>• Planning and preparation of a scientific measuring task.<br>• Carrying out scientific lab in optics together with a research team.<br>• Preparation of a scientific report. |
| Requirements for awarding credit points (type of examination) | Lab mark (100%)<br>Consists of acceptance tests and written reports |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMQ008** Internship | |
|---|---|
| Module code | PAFMQ008 |
| Module title (German) | Internship |
| Module title (English) | Internship |
| Person responsible for the module | Frank Setzpfandt |
| Prerequisites for admission to the module | Completion of module "Quantum Laboratory" |
| Type of module (compulsory module, required elective module, elective module) | 528 M.Sc. Quantum Science and Technology, required elective module, subject area "practical research training" |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in summer semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Practical course<br>300 h<br>Depending on the topic, the workload should be distributed approximately as:<br>• 50 h introduction to research topic (literature study, ...)<br>• 190 h research work (in the lab for experimental topics, at computer, etc. for theoretical topics)<br>• 50 h preparation of the final report<br><br>10 h presentation of final results and preparation for this |
| ECTS credits | 10 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 300 h<br>- h<br>- h |
| Content | Internship in industry or a research laboratory |
| Intended learning outcomes | • Carrying out scientific work together with a research team<br>• Preparation of a written scientific report<br>• Presentation of results in an oral presentation |
| Requirements for awarding credit points (type of examination) | Lab mark (100%)<br>Consists of a written report (approximately 15-20 pages) and a final presentation (10-20 minutes) with subsequent discussion<br>The final grade will be determined based on the research performance, the final report, and the presentation. |
| Recommended reading | specifically defined by the instructor of the internship |
| Language of instruction | English |

| Modul **PAFMQ009** Research Lab | |
|---|---|
| Module code | PAFMQ009 |
| Module title (German) | Research Lab |
| Module title (English) | Research Lab |
| Person responsible for the module | Frank Setzpfandt |
| Prerequisites for admission to the module | Completion of module ”Internship” |
| Type of module (compulsory module, required elective module, elective module) | 528 M.Sc. Quantum Science and Technology, required elective module, subject area ”practical research training” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Practical course<br>540 h<br>Depending on the topic, the workload should be distributed approximately as:<br>• 150 h introduction to research topic (literature study, ...)<br>• 270 h research work (in the lab for experimental topics, at computer, etc. for theoretical topics)<br>• 100 h preparation of the final report<br><br>20 h presentation of final results and preparation for this |
| ECTS credits | 18 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 540 h<br>- h<br>- h |
| Content | Internship in a research laboratory |
| Intended learning outcomes | • Carrying out scientific work together with a research team<br>• Preparation of a written scientific report<br>• Presentation of results in an oral presentation |
| Requirements for awarding credit points (type of examination) | Lab mark (100%)<br>Consists of a written report (approximately 20-30 pages) and a final presentation (15-25 minutes) with subsequent discussion<br>The final grade will be determined based on the research performance, the final report, and the presentation |
| Recommended reading | specifically defined by the instructor of the internship |
| Language of instruction | English |

| Modul **PAFMQ100** Molecular quantum mechanics / quantum chemistry I | |
|---|---|
| Module code | PAFMQ100 |
| Module title (German) | Molecular quantum mechanics / quantum chemistry I |
| Module title (English) | Molecular quantum mechanics / quantum chemistry I |
| Person responsible for the module | Prof. Dr. Stefanie Gräfe; Dr. Alexander Croy |
| Recommended or expected prior knowledge | Module „Physical chemistry” or equivalent |
| Type of module (compulsory module, required elective module, elective module) | 528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in summer semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | 2 hour lecture, 1 hour excercise per week |
| ECTS credits | 8 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | In lecture and tutorial, students are taught basics and concepts describing the dynamics of (open) quantum systems (wave packets, density matrix, quantum master equations). Furthermore, aspects of multi-particle physics of molecules are covered, i.e. e.g. multi-electron wave functions, the Hartree-Fock approximation and the role of basis sets. |
| Intended learning outcomes | Become familiar with the fundamentals of open quantum systems and "ab initio" methods for performing quantum chemical calculations with respect to molecular and nanoscale systems. |
| Requirements for awarding credit points (type of examination) | Oral or written examination on the material taught in lecture and seminars. |
| Additional information on the module | |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMQ101** Molecular quantum mechanics / quantum chemistry II | |
|---|---|
| Module code | PAFMQ101 |
| Module title (German) | Molecular quantum mechanics / quantum chemistry II |
| Module title (English) | Molecular quantum mechanics / quantum chemistry II |
| Person responsible for the module | Prof. Dr. Stefanie Gräfe; Dr. Alexander Croy |
| Recommended or expected prior knowledge | Module ”Molecular quantum mechanics / quantum chemistry I” or equivalent |
| Type of module (compulsory module, required elective module, elective module) | 528 M.Sc. Quantum Science and Technology, required elective module,, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | 2 hour lecture, 1 hour excercise per week |
| ECTS credits | 8 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | Building on Module PAFMQ100, in-depth and advanced knowledge of advanced methods of theoretical chemistry is taught. This includes (time-dependent) density functional theory as well as an introduction to numerical methods, concepts and algorithms for the description of molecular systems that exchange energy and/or charge with their environment. |
| Intended learning outcomes | Familiarization with advanced methods and concepts, such as DFT/TDDFT. Understanding numerical methods, concepts and algorithms for describing open quantum systems and their application to molecular and nanoscale systems. |
| Requirements for awarding credit points (type of examination) | Oral or written examination on the material taught in lecture and seminars. |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMQ900** Topics of Current Research: Quantum Information I | |
|---|---|
| Module code | PAFMQ900 |
| Module title (German) | Topics of Current Research: Quantum Information I |
| Module title (English) | Topics of Current Research: Quantum Information I |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory"<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 8 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 240 h<br>90 h<br>150 h |
| Content | Advanced topics of current research in Quantum information and quantum technologies |
| Intended learning outcomes | • Introduction into a field of current research as a basis for further studyand research in this field;<br>• Independent solution of exercise problems;<br>• Ability to acquire further knowledge by independent literature studies. |
| Prerequisites for admission to the module examination | further information on the kind and scope will be given at the beginning of each semester. |
| Requirements for awarding credit points (type of examination) | Written or Oral examination (100%)<br>Will be announced at the beginning of each semester |
| Recommended reading | A list of Literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMQ901** Topics of Current Research: Quantum Information I | |
|---|---|
| Module code | PAFMQ901 |
| Module title (German) | Topics of Current Research: Quantum Information II |
| Module title (English) | Topics of Current Research: Quantum Information I |
| Person responsible for the module | Frank Setzpfandt. |
| Type of module (compulsory module, required elective module, elective module) | 528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | At irregular intervals |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 8 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | Advanced topics of current research in Quantum information and quantum technologies |
| Intended learning outcomes | • Introduction into a field of current research as a basis for further studyand research in this field;<br>• Independent solution of exercise problems;<br>• Ability to acquire further knowledge by independent literature studies. |
| Prerequisites for admission to the module examination | further information on the kind and scope will be given at the beginning of each semester. |
| Requirements for awarding credit points (type of examination) | Written or Oral examination (100%)<br>Will be announced at the beginning of each semester |
| Recommended reading | A list of Literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

## Modul **PAFMQ999** Extracurricular qualifications

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|---|---|
| Module code | PAFMQ999 |
| Module title (German) | Außerfachliche Qualifikationen |
| Module title (English) | Extracurricular qualifications |
| Person responsible for the module | Frank Setzpfandt |
| Type of module (compulsory module, required elective module, elective module) | 528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every semester |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 8 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | Knowledge and methods that build personalities beyond the field of quantum science and technologies. |
| Intended learning outcomes | • qualifications that support careers after finishing a university degree<br>• an improved ability for international students to have a successful career in Germany<br>• an awareness for other fields of research and the ability to connect them to the research field of quantum science and technology |
| Prerequisites for admission to the module examination | further information on the kind and scope will be given at the beginning of each semester. |
| Requirements for awarding credit points (type of examination) | Written or Oral examination (100%)<br>Will be announced at the beginning of each semester |
| Recommended reading | A list of Literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

## Modul **PAFMT001** General Relativity

| | |
|---|---|
| Module code | PAFMT001 |
| Module title (German) | Allgemeine Relativitätstheorie |
| Module title (English) | General Relativity |
| Person responsible for the module | Prof. Dr. B. Brügmann |
| Prerequisites for admission to the module | none |
| Recommended or expected prior knowledge | Module Relativistic Physics or equvivalent |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory"<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 4 h per week<br>Exercise: 2 h per week |
| ECTS credits | 8 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 240 h<br>90 h<br>150 h |
| Content | • Fundamentals of general relativity<br>• Einstein field equations<br>• Newtonian approximation<br>• Gravitational waves<br>• Black holes<br>• Cosmology and the big bang |
| Intended learning outcomes | • Obtain knowledge of relativistic gravitational physics<br>• Develop problem solving skills for astrophysical problems in the regime of high velocities and strong gravitational fields |
| Prerequisites for admission to the module examination | Course exercises to be submitted; further information on the kind and scope will be given at the beginning of each semester. |
| Requirements for awarding credit points (type of examination) | Written or oral examination (100%)<br>The form of the exam will be announced at the beginning of the semester. |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |

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|---|---|
| Language of instruction | English |

| Modul **PAFMT002** Particles and Fields | |
|---|---|
| Module code | PAFMT002 |
| Module title (German) | Teilchen und Felder |
| Module title (English) | Particles and Fields |
| Person responsible for the module | Prof. Dr. H. Gies |
| Prerequisites for admission to the module | none |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory"<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area "specialization" |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 2 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>60 h<br>60 h |
| Content | • Introduction: examples of classical field theories<br>• aspects of classical field theory: Lagrange and Hamilton formalism, Noether theorem and charges<br>• non-linear scalar field theories: O(N) models, spontaneous symmetry breaking, Goldstone theorem<br>• fields / particles as representations of the Lorentz group: classification of representations, spinors, construction of free theories<br>• interactive theories: Yukawa models, QED, Abelian Higgs models<br>• current aspects of field theories in particle physics |
| Intended learning outcomes | • preparation for quantum field theory in the 2nd M.Sc. Semester<br>• comprehension of concepts and methods, and acquiring technical skills for the theoretical treatment of field theories with applications in particle physics |
| Prerequisites for admission to the module examination | Course exercises to be submitted; further information on the kind and scope will be given at the beginning of each semester. |
| Requirements for awarding credit points (type of examination) | Written or oral examination or paper (100%)<br>The form of the exam will be announced at the beginning of the semester. |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |

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|---|---|
| Language of instruction | English |

| Modul **PAFMT003** Quantum Field Theory | |
|---|---|
| Module code | PAFMT003 |
| Module title (German) | Quantenfeldtheorie |
| Module title (English) | Quantum Field Theory |
| Person responsible for the module | Prof. Dr. M. Ammon |
| Prerequisites for admission to the module | none |
| Recommended or expected prior knowledge | Module Particles and Fields or equivalent |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory"<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in summer semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 4 h per week<br>Exercise: 2 h per week |
| ECTS credits | 8 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 240 h<br>90 h<br>150 h |
| Content | • Principles of relativistic quantum field theories<br>• Quantization of Klein-Gordon , Dirac , and electromagnetic fields<br>• Perturbation theory and Feynman diagrams<br>• S matrix and cross sections<br>• Functional integrals<br>• effective effects and correlation functions<br>• Regularization and renormalization |
| Intended learning outcomes | • Teaching the basic principles and structures of quantum field theories.<br>• Obtaining abilities to describe the interactions of elementary particles and to calculate important scattering and decay processes. |
| Prerequisites for admission to the module examination | Course exercises to be submitted; further information on the kind and scope will be given at the beginning of each semester. |
| Requirements for awarding credit points (type of examination) | Written or oral examination (100%)<br>The form of the exam will be announced at the beginning of the semester. |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |

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|---|---|
| Language of instruction | English |

| Modul **PAFMT010** Advanced Quantum Field Theory | |
|---|---|
| Module code | PAFMT010 |
| Module title (German) | Fortgeschrittene Quantenfeldtheorie |
| Module title (English) | Advanced Quantum Field Theory |
| Person responsible for the module | Prof. Dr. Martin Ammon |
| Prerequisites for admission to the module | none |
| Recommended or expected prior knowledge | Modules Particles and Fields and Quantum Field Theory or equivalent |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory"<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every second year (beginning in summer semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 4 h per week<br>Exercise: 2 h per week |
| ECTS credits | 8 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 240 h<br>90 h<br>150 h |
| Content | • Anomalies in Quantum Field Theory (QFT);<br>• QFT at finite temperature and density;<br>• (Quantum) Phase Transitions;<br>• Near- and non-equilibrium dynamics of QFT;<br>• Introduction to conformal field theory;<br>• Topological objects in quantum field theory. |
| Intended learning outcomes | Impart thorough knowledge of advanced methods in quantum field theory |
| Prerequisites for admission to the module examination | Will be announced in the first lecture. Usually 50 per cent of points of the examples sheets or presenting one original paper. |
| Requirements for awarding credit points (type of examination) | Will be announced in the first lecture: usually oral exam at the end of the semester |
| Language of instruction | English |
| Language of instruction | German, English |

| Modul **PAFMT011** Introduction to String Theory and AdS/CFT | |
|---|---|
| Module code | PAFMT011 |
| Module title (German) | Einführung in Stringtheorie und AdS/CFT |
| Module title (English) | Introduction to String Theory and AdS/CFT |
| Person responsible for the module | Prof. Dr. M. Ammon |
| Prerequisites for admission to the module | none |
| Recommended or expected prior knowledge | Modules Quantum Field Theory and General Relativity or equivalent |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory"<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | At irregular intervals |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 4 h per week<br>Exercise: 2 h per week |
| ECTS credits | 8 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 240 h<br>90 h<br>150 h |
| Content | Introduction to concepts of string theory and AdS/CFT correspondence, in particular:<br>• relativistic bosonic string and its quantization<br>• open strings and D-branes<br>• aspects of conformal field theory<br>• Polyakov path integral<br>• scattering of strings<br>• low energy effective action<br>• dualities in string theory<br>• compactification scenarios<br>• introduction to AdS / CFT<br>• main tests of AdS / CFT<br>• extension and application of AdS / CFT |
| Intended learning outcomes | Impart thorough knowledge of string theory and AdS/CFT duality |
| Prerequisites for admission to the module examination | Course exercises to be submitted; further information on the kind and scope will be given at the beginning of each semester. |

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|---|---|
| Requirements for awarding credit points (type of examination) | Written or oral examination (100%)<br>The form of the exam will be announced at the beginning of the semester. |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

## Modul **PAFMT012** The Standard Model of Particle Physics

| | |
|---|---|
| Module code | PAFMT012 |
| Module title (German) | Das Standardmodell der Teilchenphysik |
| Module title (English) | The Standard Model of Particle Physics |
| Person responsible for the module | Prof. Dr. A. Wipf |
| Prerequisites for admission to the module | none |
| Recommended or expected prior knowledge | Module Quantum Field Theory or equivalent |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory"<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 2 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>60 h<br>60 h |
| Content | Overview of the standard model of particle physics including:<br>• symmetries, quantum electrodynamics<br>• strong interaction<br>• the quark model and quantum chromodynamics<br>• hadrons and asymptotic freedom<br>• weak interactions and the Higgs effect<br>• scattering experiments<br>• limits of the Standard Model |
| Intended learning outcomes | Impart thorough knowledge of particle physics phenomenology and its fundamental concepts. |
| Prerequisites for admission to the module examination | Course exercises to be submitted; further information on the kind and scope will be given at the beginning of each semester. |
| Requirements for awarding credit points (type of examination) | Oral examination (100%) |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |

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|---|---|
| Language of instruction | English |

| Modul **PAFMT013** Gauge Theories | |
|---|---|
| Module code | PAFMT013 |
| Module title (German) | Eichtheorien |
| Module title (English) | Gauge Theories |
| Person responsible for the module | Prof. Dr. H. Gies |
| Prerequisites for admission to the module | none |
| Recommended or expected prior knowledge | Module Quantum Field Theory or equivalent |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory"<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | At irregular intervals |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 2 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>60 h<br>60 h |
| Content | • gauge symmetry<br>• classical Yang-Mills theory<br>• quantization of gauge theories / BRST formalism / Gribov problem<br>• perturbation theory<br>• semiclassical expansions<br>• topological configurations<br>• confinement criteria and scenarios |
| Intended learning outcomes | Comprehension of concepts and methods, and acquiring technical skills for the theoretical treatment of gauge theories with applications in particle physics |
| Prerequisites for admission to the module examination | Course exercises to be submitted; further information on the kind and scope will be given at the beginning of each semester or term paper |
| Requirements for awarding credit points (type of examination) | Written or oral examination (100%)<br>The form of the exam will be announced at the beginning of the semester. |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |

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|---|---|
| Language of instruction | German, English |

| Modul **PAFMT014** Lattice Field Theory | |
|---|---|
| Module code | PAFMT014 |
| Module title (German) | Quantenfeldtheorien auf dem Gitter |
| Module title (English) | Lattice Field Theory |
| Person responsible for the module | Prof. Dr. A. Wipf |
| Prerequisites for admission to the module | none |
| Recommended or expected prior knowledge | Module Quantum Field Theory or equivalent |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory"<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | At irregular intervals |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 4 h per week<br>Exercise: 2 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>135 h |
| Content | • Path integral for quantum field theories<br>• Euclidean formulation and quantum field theories in thermal equilibrium<br>• Lattice field theory as spin models in Statistical Physics<br>• rigorous results and approximations<br>• stochastic methods, Monte Carlo simulations<br>• renormalization group, critical phenomena<br>• gauge theories on a space-time grid<br>• Quantumchromodynamic on a lattice |
| Intended learning outcomes | • The course covers theoretical concepts and methods necessary to understand (discretized) Quantum Field Theories.<br>• The students will learn stochastical and numerical methods to simulate spin models and lattice field theories.<br>• They will aquire skills to independently develop numerical algorithms to calculate observables in Elementary Particle Physics, Quantum Field Theory and Statistical Physics. |
| Prerequisites for admission to the module examination | Course exercises to be submitted; further information on the kind and scope will be given at the beginning of each semester. |

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|---|---|
| Requirements for awarding credit points (type of examination) | Written or oral examination (100%)<br>The form of the exam will be announced at the beginning of the semester. |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMT015** Computational Quantum Physics | |
|---|---|
| Module code | PAFMT015 |
| Module title (German) | Quantenphysik mit dem Rechner |
| Module title (English) | Computational Quantum Physics |
| Person responsible for the module | Prof. Dr. S. Fritzsche |
| Prerequisites for admission to the module | none |
| Recommended or expected prior knowledge | Module Theoretical Mechanics, Electrodynamics and Quantum Theory or equivalent |
| Type of module (compulsory module, required elective module, elective module) | 128 B.Sc. Physics, Required elective module<br>128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory"<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | At irregular intervals |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 2 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>60 h<br>60 h |
| Content | • Coulomb problem;<br>• particles with spin;<br>• qubits, quantum registers and quantum gates;<br>• representation of pure and mixed states (Bloch sphere);<br>• composite systems, indistinguishable particles;<br>• Hartree-Fock method;<br>• Coupling of angular momenta. |
| Intended learning outcomes | • Learning computer algebraic and numerical methods in the description of simple quantum models;<br>• Ability to independently solve simple models and tasks, formulate pseudo-code and deal with computer algebra systems more efficiently. |
| Prerequisites for admission to the module examination | Course exercises to be submitted; further information on the kind and scope will be given at the beginning of each semester. |

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|---|---|
| Requirements for awarding credit points (type of examination) | Written examination or paper (100%)<br>The form of the exam will be announced at the beginning of the semester. |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | German, English |

| Modul **PAFMT016** Symmetries in Physics | |
|---|---|
| Module code | PAFMT016 |
| Module title (German) | Symmetrien in der Physik |
| Module title (English) | Symmetries in Physics |
| Person responsible for the module | Prof. Dr. A. Wipf |
| Prerequisites for admission to the module | none |
| Recommended or expected prior knowledge | Modules Theoretical Mechanics und Quantum Mechanics or equivalent |
| Type of module (compulsory module, required elective module, elective module) | 128 B.Sc. Physics Required elective module<br>128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory"<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every second year (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 2 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>60 h<br>60 h |
| Content | • symmetries and groups<br>• space and space-time symmetries<br>• conserved currents and charges<br>• discrete groups and continuous Lie-groups<br>• representations of groups, theory of characters, reductions of representation<br>• invariant integration on Lie-Groups<br>• Lie-algebras and their representations<br>• classification of semi-simple Lie-algebras<br>• selected application of group theory and representation theory in solid state physics, atomic and molecular physics, quantum field theory and particle physics. |

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| Intended learning outcomes | • The course covers theoretical concepts of discrete and continuous groups, Lie-algebras and their representations with relevant applications in physics<br>• The students will learn how to exploit symmetry principles to simplify or even solve problems in all branches of physics where symmetry principles play a role |
| Prerequisites for admission to the module examination | Course exercises to be submitted; further information on the kind and scope will be given at the beginning of each semester. |
| Requirements for awarding credit points (type of examination) | Written or oral examination (100%)<br>The form of the exam will be announced at the beginning of the semester. |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | German, English |

| Modul **PAFMT017** Atomic Theory | |
|---|---|
| Module code | PAFMT017 |
| Module title (German) | Theoretische Atomphysik |
| Module title (English) | Atomic Theory |
| Person responsible for the module | Prof. Dr. S. Fritzsche |
| Prerequisites for admission to the module | none |
| Recommended or expected prior knowledge | Module Quantum Theory or equivalent |
| Type of module (compulsory module, required elective module, elective module) | 128 B.Sc. Physics Required elective module<br>128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory"<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | At irregular intervals |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 4 h per week<br>Exercise: 2 h per week |
| ECTS credits | 8 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 240 h<br>90 h<br>150 h |
| Content | • Short review of hydrogenic atoms<br>• Independent-particle model & Hartree-Fock theory<br>• Interaction with the radiation field<br>• Correlated many-body theory<br>• Atomic collision theory<br>• Basics of the density matrix theory<br>• Atoms and forces in (intense) light fields<br>• Laser cooling and trapping; ions traps<br>• Rotating-wave approximation |
| Intended learning outcomes | Learning the basics of atomic structure and atomic collision processes. |
| Prerequisites for admission to the module examination | Course exercises to be submitted; further information on the kind and scope will be given at the beginning of each semester. |
| Requirements for awarding credit points (type of examination) | Written or oral examination (100%)<br>The form of the exam will be announced at the beginning of the semester. |

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| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMT018** Physics of the Quantum Vacuum in Strong Fields | |
|---|---|
| Module code | PAFMT018 |
| Module title (German) | Physik des Quantenvakuums in starken Feldern |
| Module title (English) | Physics of the Quantum Vacuum in Strong Fields |
| Person responsible for the module | Prof. Dr. H. Gies |
| Prerequisites for admission to the module | none |
| Recommended or expected prior knowledge | Module Quantum Field Theory or equivalent |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory"<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | At irregular intervals |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 2 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>60 h<br>60 h |
| Content | • Theoretical foundations of quantum electrodynamics (QED) in strong electromagnetic fields;<br>• Derivation of elementary signatures of the strong field QED;<br>• Discussion of proposals for their demonstration with current experimental methods. |
| Intended learning outcomes | Imparting concepts and methods and gaining the skills to deal with quantum electrodynamics issues in strong electromagnetic fields. |
| Prerequisites for admission to the module examination | Course exercises to be submitted; further information on the kind and scope will be given at the beginning of each semester. or term paper |
| Requirements for awarding credit points (type of examination) | Written or oral examination (100%)<br>The form of the exam will be announced at the beginning of the semester. |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMT019** Supersymmetry | |
|---|---|
| Module code | PAFMT019 |
| Module title (German) | Supersymmetrie |
| Module title (English) | Supersymmetry |
| Person responsible for the module | Prof. Dr. A. Wipf |
| Prerequisites for admission to the module | none |
| Recommended or expected prior knowledge | Module Quantum Field Theory or equvivalent |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory"<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | At irregular intervals |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 2 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>60 h<br>60 h |
| Content | • Supersymmetric quantum mechanics<br>• symmetries and spinors<br>• Wess Zumino models<br>• Supersymmetry algebra and representations<br>• Superspace and superfields<br>• supersymmetric Yang-Mills theories |
| Intended learning outcomes | • The students will learn the structure and properties of supersymmetric theories and the basics for understanding developments in particle physics and string theory.<br>• They will aquire skills to calculate simple processes in supersymmetric theories. |
| Prerequisites for admission to the module examination | Course exercises to be submitted; further information on the kind and scope will be given at the beginning of each semester. |
| Requirements for awarding credit points (type of examination) | Written or oral examination (100%)<br>The form of the exam will be announced at the beginning of the semester. |

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| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMT099** Topics of Current Research: Quantum Field Theory | |
|---|---|
| Module code | PAFMT099 |
| Module title (German) | Themen der aktuellen Forschung: Gravitations- und Quantenfeldtheorie I |
| Module title (English) | Topics of Current Research: Quantum Field Theory |
| Person responsible for the module | Prof. Dr. M. Ammon |
| Prerequisites for admission to the module | none |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory"<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | At irregular intervals |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 2 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>60 h<br>60 h |
| Content | • Further, in-depth topics in the field of quantum field theory;<br>• Topics from current areas of research. |
| Intended learning outcomes | • specialisation in a special field of quantum field theory;<br>• Independent handling of exercises;<br>• Ability of literature review. |
| Prerequisites for admission to the module examination | Course exercises to be submitted; further information on the kind and scope will be given at the beginning of each semester. |
| Requirements for awarding credit points (type of examination) | Written or oral examination (100%)<br>The form of the exam will be announced at the beginning of the semester. |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMT202** Computational Physics III | |
|---|---|
| Module code | PAFMT202 |
| Module title (German) | Computational Physics III |
| Module title (English) | Computational Physics III |
| Person responsible for the module | Prof. Dr. B. Brügmann |
| Prerequisites for admission to the module | none |
| Recommended or expected prior knowledge | Module Computational Physics or equivalent |
| Prerequisite for what other modules | |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory"<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | Partial Differential Equations:<br>• Fundamentals of differential equations<br>• Introduction to elliptic, parabolic and hyperbolic differential equations<br>• explicit and implicit procedures, stability analysis<br>• Poisson equation, diffusion equation, advection equation, wave equation,<br>• shocks;<br>• difference method,<br>• pseudo spectral methods,<br>• multiple grids |
| Intended learning outcomes | • Mastering the basics and methods of partial differential equations and machine learning in physics<br>• Ability to work independently on a numerical project |
| Prerequisites for admission to the module examination | Course exercises to be submitted; further information on the kind and scope will be given at the beginning of each semester. |

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| Requirements for awarding credit points (type of examination) | Written or oral examination or project (100%)<br>The form of the exam will be announced at the beginning of the semester. |
| Additional information on the module | |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMT206** Computational Physics IV | |
|---|---|
| Module code | PAFMT206 |
| Module title (German) | Computational Physics IV |
| Module title (English) | Computational Physics IV |
| Person responsible for the module | Prof. Dr. Bernd Bruegmann |
| Prerequisites for admission to the module | none |
| Recommended or expected prior knowledge | Modules Computational Physics I and II or equivalent |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc.Physics, Required elective module<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | At irregular intervals |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | • Machine Learning in Physics<br>• Basics of Machine Learning, Neural Networks and Deep Learning<br>• Sample Applications in Physics, Pattern Recognition, Time Series Analysis, Monte Carlo Methods |
| Intended learning outcomes | • Mastering the basics and methods of machine learning in physics<br>• Ability to work independently on a numerical project |
| Prerequisites for admission to the module examination | Processing of exercise sheets (kind and extend will be announced at the beginning of the semester) |
| Requirements for awarding credit points (type of examination) | Numerical project or written exam (100%); to be announced at the beginning of term |
| Recommended reading | A list of literature and materials will be provided at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMT299** Topics of Current Research: Gravitational Theory | |
|---|---|
| Module code | PAFMT299 |
| Module title (German) | Themen der aktuellen Forschung: Gravitations- und Quantentheorie II |
| Module title (English) | Topics of Current Research: Gravitational Theory |
| Person responsible for the module | Prof. Dr. B. Brügmann |
| Prerequisites for admission to the module | none |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory"<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | At irregular intervals |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 2 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>60 h<br>60 h |
| Content | • Further, in-depth topics in the field of gravitation theory;<br>• Topics from current areas of research. |
| Intended learning outcomes | • specialization in the special field of gravitation theory;<br>• Independent handling of exercises;<br>• Ability of literature review. |
| Prerequisites for admission to the module examination | Course exercises to be submitted; further information on the kind and scope will be given at the beginning of each semester. |
| Requirements for awarding credit points (type of examination) | Written or oral examination (100%)<br>The form of the exam will be announced at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMT300** Topics of Current Research: Gravitation- and Quantum Theory III | |
|---|---|
| Module code | PAFMT300 |
| Module title (German) | Themen der aktuellen Forschung: Gravitations- und Quantentheorie III |
| Module title (English) | Topics of Current Research: Gravitation- and Quantum Theory III |
| Person responsible for the module | Prof. Dr. M. Ammon, Prof. Dr. H. Gies, Prof. Dr. S. Flörchinger |
| Prerequisites for admission to the module | none |
| Recommended or expected prior knowledge | Module General Relativity PAFMT001 or equivalent |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory"<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in winter semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | The lecture will cover topics in the foundations of quantum mechanics and with relevance to the interplay between quantum physics and gravity with a focus on nonrelativistic laboratory quantum systems, specifically including topics of current research. In particular, the lecture will cover all or a selection of the following topics:<br>• Quantum systems in the gravitational field of the earth, experiments and relativistic generalisation<br>• Decoherence from spacetime fluctuations<br>• The equivalence principle for quantum matter<br>• Theoretical treatment of classically gravitating quantum systems and experimental distinction from a quantised gravitational field<br>• Interpretations of quantum mechanics, the measurement problem, and the potential role of gravity in quantum wave function reduction |

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| Intended learning outcomes | The course should provide the participating students with a profound knowledge on the state of the art of the foundations of quantum mechanics and experimentally established facts on the interplay between gravitational and quantum physics. It should provide them with an overview of different ideas and approaches how to merge the theoretical description of quantum systems with the principles of general relativity, including obstacles and caveats.<br>The advanced level course is ideally taken by Master students who already have some knowledge of general relativity but is open to interested students at all levels with a basic knowledge in quantum mechanics. |
| Prerequisites for admission to the module examination | None |
| Requirements for awarding credit points (type of examination) | Oral examination (100%) |
| Language of instruction | English |

| Modul **PAFMT301** Topics of Current Research: Gravitation- and Quantum Theory IV | |
|---|---|
| Module code | PAFMT301 |
| Module title (German) | Themen der aktuellen Forschung: Gravitations- und Quantentheorie IV |
| Module title (English) | Topics of Current Research: Gravitation- and Quantum Theory IV |
| Person responsible for the module | Prof. Dr. S. Bernuzzi |
| Recommended or expected prior knowledge | Module General Relativity PAFMT001 or equivalent |
| Type of module (compulsory module, required elective module, elective module) | 128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory"<br>528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization” |
| Frequency of offer (how often is the module offered?) | Every second semester (beginning in summer semester) |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Lecture: 2 h per week<br>Exercise: 1 h per week |
| ECTS credits | 4 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 120 h<br>45 h<br>75 h |
| Content | • Newtonian and Relativistic hydrodynamics Radiation hydrodynamics<br>• Hyperbolic PDEs<br>• Finite volume methods<br>• Riemann problem and solvers<br>• Conservative finite-differencing<br>• Limiters<br>• Galerking methods |
| Intended learning outcomes | This course covers the development of numerical techniques required to solve the nonlinear equations<br>that arise in the study of Fluid Dynamics. It also covers the analytical background that governs the solutions of these equations. By the end of the course the students will have learned the techniques required to write numerical codes to solve problems in fluid dynamics and relativistic hydrodynamics |
| Prerequisites for admission to the module examination | None |
| Requirements for awarding credit points (type of examination) | Written examination (100%)<br>The form of the exam will be announced at the beginning of the semester. |
| Language of instruction | English |

| Modul **PAFMQ099** Master thesis | |
|---|---|
| Module code | PAFMQ099 |
| Module title (German) | Master thesis |
| Module title (English) | Master thesis |
| Person responsible for the module | Frank Setzpfandt |
| Prerequisites for admission to the module | Completion of module Research Lab, 72 ECTS according to the Study- and Examination Regulations |
| Prerequisite for what other modules | |
| Type of module (compulsory module, required elective module, elective module) | 528 M.Sc. Quantum Science and Technology, compulsory module |
| Frequency of offer (how often is the module offered?) | Every semester |
| Duration of module | 1 semester |
| Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...) | Practical course /<br>900 h<br>Depending on the topic, the workload should be distributed approximately as:<br>• 225 h introduction to research topic (literature study, ...)<br>• 450 h research work (in the lab for experimental topics, at computer, etc. for theoretical topics)<br>• 200 h preparation of the final report<br>25 h presentation of final results and preparation for this |
| ECTS credits | 30 CP |
| Work load:<br>- In-class studying<br>- Independent studying<br>(incl. preparations for examination) | 900 h<br>0 h<br>900 h |
| Content | Internship in a research laboratory |
| Intended learning outcomes | • Carrying out advanced scientific work together with a research team<br>• Preparation of the workflow to obtain researchresults<br>• Analysis of research results<br>• Preparation of a written scientific report (Master Thesis)<br>Presentation of results in an oral presentation |
| Requirements for awarding credit points (type of examination) | The mark consists of a written report – Master's Thesis (66%), presentation (33%)<br>The Master's Thesis should contain approximately 40-60 pages. The results of the Master's Thesis are presented by the candidate in a 20-30minute talk, and then discussed. The final grade is determined accordingto the Rules of Examination (in German: ”Prüfungsordnung”). |
| Recommended reading | specifically defined by the instructor |
| Language of instruction | English |

# Abbrevations:

Abbrevations of lectures

| | |
|---|---|
| IL.... | Inaugural lecture |
| WG.... | Working group |
| AM.... | Advanced module |
| Exh.... | Exhibition |
| BM.... | Basic module |
| BzPS.... | Begleitveranstaltung zum Praxissemester |
| C.... | Consulting |
| To.... | Tour |
| M.... | Meeting |
| Blo.... | Blockage |
| BC.... | Block course |
| DV.... | Slide show |
| IN.... | Introductory session |
| RS.... | Registrations |
| EC.... | Exam course |
| EX.... | Excursion |
| Exp.... | Experiment/survey |
| FE.... | Celebration/festivity |
| MS.... | Movie screening |
| FEx.... | Field exercise |
| BC.... | Basic course |
| MaS.... | Main seminar |
| MS/ BC.... | Main seminar/block course |
| MaS/ Ex.... | Main seminar/exercise |
| Inf.... | Information session |
| IDS/E.... | Interdisciplinary main seminar/ exercise |
| E.... | Exam |
| E/T.... | Exam/test |
| C.... | Colloquium |
| C/I.... | Colloquium/practical work |
| CS.... | Conference/symposium |
| kV.... | Kulturelle Veranstaltung |
| Cu.... | Course |

Abbrevations of lectures

| | |
|---|---|
| Co.... | Course |
| Lag.... | Lagerung |
| TRP.... | Training research project |
| RC.... | Reading course |
| M.... | Module |
| ME.... | Musical event |
| AS.... | Advanced seminar |
| OnS.... | Online seminar |
| OnL.... | Online lecture |
| P.... | Practical work |
| I/S.... | Practical work/seminar |
| PM.... | Practice module |
| Sa.... | Sample |
| PJ.... | Project |
| PPD.... | Propaedeutic |
| PS.... | Proseminar |
| EPr.... | Exam preparation |
| CSA.... | Cross-sectional area |
| RE.... | Revision course |
| LS.... | Lecture Series |
| TC.... | Training course |
| S.... | Seminar |
| S/E.... | Seminar/Excursion |
| S/E.... | Seminar/Exercise |
| ST.... | Service time |
| SI.... | Conference |
| SuSch.... | Summer school |
| MISC.... | Miscellaneous |
| OE.... | Other event |
| LC.... | Language course |
| Con.... | Convention |
| TT.... | Teleteaching |
| MN.... | Meeting |
| Tu.... | Tutorial |
| T.... | Tutorial |
| E.... | Exercise |
| E/BC.... | Exercise/block course |
| E.... | Exercises |
| E/I.... | Exercise/interdisciplinary |
| E/I.... | Exercise/practical work |

Abbrevations of lectures

| | |
|---|---|
| E/T.... | Exercise/tutorial |
| Conf.... | Conference |
| ViCo.... | Video conference |
| L.... | Lecture |
| L/C.... | Lecture with colloquium |
| L/I.... | Lecture/practical work |
| L/S.... | Lecture/seminar |
| L/E.... | Lecture/exercise |
| Sp.... | Speech |
| TK.... | Talk |
| OS.... | Optional seminar |
| OL.... | Optional lecture |
| Tr.... | Training |
| Wo.... | Workshop |
| WOS.... | Workshop |
| CAC.... | Certificate award ceremony |

Other Abbrevations

| | |
|---|---|
| Anm..... | Anmerkung |
| ASQ.... | Allgemeine Schlüsselqualifikationen |
| AT.... | Altes Testament |
| E.... | Essay |
| FSQ.... | Fachspezifische Schlüsselqualifikationen |
| FSV.... | Fakultät für Sozial- und Verhaltenswissenschaften |
| GK.... | Grundkurs |
| IAW.... | Institut für Altertumswissenschaften |
| LP.... | Leistungspunkte |
| NT.... | Neues Testament |
| SQ.... | Schlüsselqualifikationen |
| SS.... | Sommersemester |
| SWS.... | Semesterwochenstunden |
| TE.... | Teilnahme |
| TP.... | Thesenpublikation |
| ThULB.... | Thüringer Universitäts- und Landesbibliothek |
| VVZ.... | Vorlesungsverzeichnis |
| WS.... | Wintersemester |