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	
Module code	MedPhoA1.3
Module title (German)	Physical Chemistry
Module title (English)	Physical Chemistry
Person responsible for the module	Jürgen POPP, Michael SCHMITT, Rainer HEINTZMANN
Prerequisites for admission to the module	none
Recommended or expected prior knowledge	--
Prerequisite for what other modules	This module is part of the block „Adjustment" of the 1st semester.
Type of module (compulsory module, required elective module, elective module)	The module is mandatory for students not having a Bachelor degree in chemistry or physics. Students of chemistry or physics having passed the corresponding modules during their studies do not need to participate in this course.
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: 4h/week exercises: 2h/week
ECTS credits	8 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	240 h 90 h 150 h
Content	• Equilibrium thermodynamics: Properties of gases, first and second law of thermodynamics, chemical equilibrium, equilibrium electrochemistry • Transport phenomena: molecular motion in gases and liquids, diffusion, transport across biological membranes • Chemical reactions: chemical kinetics, rate laws, temperature dependence of reaction rates, relaxation methods, kinetics of complex reactions • Basics of quantum mechanics: wavefunctions and operators, particle in a box, harmonic oscillator, particle on a sphere, rigid rotator • Approximations: variational principle, Born-Oppenheimer approximation, linear combination of atomic orbitals (LCAO) method, Hartree-Fock, density functional theory (DFT)
Intended learning outcomes	This module provides an introduction into the fundamentals of physical chemistry. Topics include equilibrium thermodynamics, chemical kinetics and an introduction into molecular quantum mechanics (techniques of approximation).

Prerequisites for admission to the module examination	none
Requirements for awarding credit points (type of examination)	written examination at the end of the semester
Additional information on the module	Used media: blackboard, beamer, overhead projector, written supplementary material
Recommended reading	• Textbooks on physical chemistry: o P.W. Atkins, J. de Paula: Physical Chemistry. 9th ed., OUP Oxford 2009. • Textbooks on molecular quantum mechanics: o P.W. Atkins, R.S. Friedman: Molecular quantum mechanics. 5th ed., Oxford University Press 2010.
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 Theoretische Mechanik PAFBT211 Elektrodynamik PAFBT311
Type of module (compulsory module, required elective module, elective module)	039 M.Sc. Geosciences, required elective module 128 M.Sc. Physics focus „Quantum and Gravitational Theory" 128 B.Sc. Physics, required elective module 679 B.Sc. Applied Computer Science, Application subject physics 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 Exercise: 2 hours/week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h
Content	Introduction to Unix and higher-level programming languages (e.g.: C/C+ +, Fortran) Numerical solution of partial differential equations Monte Carlo method Molecular dynamics methods 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	-

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" 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 Exercise: 2 h per week
ECTS credits	8 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	240 h 90 h 150 h
Content	• Crystal structures and elastic properties of solids; • Electronic properties of crystals; • Approximate methods for electronic band structure; • Semiconductors and defect physics; • P-n junctions; • Microscopic description of charge transport; • Properties of alloys; • Nanostructures and interfaces; • Optical and dielectric properties of solids; • 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.

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. U. 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 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 Exercise: 3 h per week
ECTS credits	8 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	240 h 75 h 165 h
Content	Introduction to the many-body problem; Wavefunction-based approaches for electronic structure; Density functional theory; 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,..) students 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.

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. H. Krüger
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 628 M.Sc. Photonics: Required 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	2 semester
Module Components/Types of courses (lecture, practical course, lab, tutorial, exercise, seminar, internship, ...)	Lecture: 2 h per week Exercise: 1 h per week
ECTS credits	8 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	240 h 90 h 150 h
Content	• Introduction to the many-body problem; • Wavefunction-based approaches for electronic structure; • Density functional theory; • 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.

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	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", 177 M.Sc. Materialwissenschaften, Required 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, ...)	Lecture: 2 h per week Exercise: 1 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 60 h 60 h
Content	• Basic effects of superconductivity; • characteristics of superconductors; • Josephson effects; • Superconducting materials (classes, structure, properties); • fabrication (single crystals, solid material, layers, wires, ribbons); • modification of the materials (doping, pinning); • Applications of superconductivity.
Intended learning outcomes	• Unterstanding the basic concepts and concepts of superconductivity, superconducting materials and their application; • creation of ready-to-use basic knowledge; • Ability to independently re-deepen the subject. • 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.

Language of instruction	English

Modul **PAFMF009** Optoelectronics	
Module code	PAFMF009
Module title (German)	Optoelektronik
Module title (English)	Optoelectronics
Person responsible for the module	Prof. Dr. G. 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 528 M.Sc. Quantum Science and Technology, required elective module, subject area "specialization" 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 Exercise: 1 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h
Content	• Semiconductors • Optoelectronic devices • Photodiodes • Light emitting diodes • 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.

Language of instruction	English

Modul **PAFMF012** Materials Informatics	
Module code	PAFMF012
Module title (German)	Materialinformatik
Module title (English)	Materials Informatics
Person responsible for the module	Prof. Dr. J. George
Type of module (compulsory module, required elective module, elective module)	128 MSc. Physics specialization solid-state physics/material science: required elective module 528 MSc. Quantum Science & Technology: 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 SWS Exercises: 2 SWS
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 60 h 60 h
Content	Object-oriented programming and data science with Python, data sources and access to material data, automation of data generation (e.g. using density functional theory or machine-learned interatomic potentials), typical descriptors for materials (representation of the composition of crystalline or amorphous solids or the structure of crystalline solids), general principles of machine learning, classification and regression, supervised and unsupervised learning, clustering, kernel methods, neural networks (different architectures), current examples from materials informatics.
Intended learning outcomes	Students are familiar with the fundamental problems in materials informatics (focus on inorganic solid-state materials). They know basic concepts from the field of data science and machine learning and can apply methods from these fields to topics relating to materials and their data.
Prerequisites for admission to the module examination	Completion of the exercises (exact extend will be announced at the beginning of the module)
Requirements for awarding credit points (type of examination)	Oral examination or homework and presentation
Additional information on the module	Basic knowledge in Python is required
Recommended reading	Literature will be announced at the beginning of the semester
Language of instruction	English

Modul **PAFMF016** Nanomaterials and Nanotechnology	
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” 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 Exercise: 1 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h
Content	• dimension effects, • Quantisation of electrons • single-electron transistor, • synthesis of nanomaterials, • characterization of nanomaterials, • Material systems: carbon nanotubes, graphene, magnetic nanomaterials, bionanomaterials, • 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%) 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. M. 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 specialization "Quantum and Gravitational Theory" 628 M.Sc. Photonics: Required 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 Exercise: 1 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h

Content	Lecture of Drs. Eilenberger, Steinlechner • Basic introduction to quantum optics; • Quantum light sources; • Encoding, • transmission and detection of information with quantum light; • Quantum communication and cryptography; • Quantum communication networks; • Outlook on Quantum metrology and Quantum imaging; Lecture of Dr. Sondenheimer • Open quantum systems, Density matrix formalism, Generalized measurements, Quantum channels • Superdense coding, quantum teleportation • Entanglement theory, Bell inequalities, • CHSH inequalities • Quantum circuits, universal gates • Quantum error correction
Intended learning outcomes	<p>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.
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	
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	
Module code	PAFMF021
Module title (German)	Zweidimensionale Materialien
Module title (English)	2D materials
Person responsible for the module	Prof. Dr. G. 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 628 M.Sc. Photonics: Required 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, ...)	Lecture: 2 h per week Exercise: 1 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h
Content	• Graphene: electrical and optical properties. Applications in electronic and optoelectronic. • Semiconducting 2D materials: Coulomb screening and the concept of excitons. Optical spectroscopy of excitons. Optoelectronic applications. • Heterostructures: electron and exciton interactions in layered heterostructures
Intended learning outcomes	• Mastering the basics and methods of two-dimensional materials • 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	

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	
Module code	PAFMO001
Module title (German)	Fundamentals of Modern Optics
Module title (English)	Fundamentals of Modern Optics
Person responsible for the module	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)	628 M.Sc. Photonics: Compulsory 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 Exercise: 2 h per week
ECTS credits	8 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	240 h 90 h 150 h
Content	• Basic concepts of wave optics • Dielectric function to describe light-matter interaction • Propagation of beams and pulses • Diffraction theory- Elements of Fourier optics • Polarization of light • Light in structured media • 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	-

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. A. Tünnermann (FSU), Dr. O. Stenzel (FSU)
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)	828 MSc. Photon Science and Technology: Required Elective Module Adjustment 628 M.Sc. Photonics: Compulsory 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, ...)	Lecture: 4 h per week Exercise: 2 h per week
ECTS credits	8 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	240 h 90 h 150 h
Content	• Classical interaction of light with matter • Basic knowledge on quantum mechanics • Einstein coefficients and Plancks formula • Selection rules • Hydrogen atom and helium atom • Introduction to molecular spectroscopy • Dielectric function and linear optical constants • Kramers-Kronig-Relations • Linear optical properties of crystalline and amorphous solids • Basic nonlinear optical effects

Intended learning outcomes	The students • understand the classical interaction of light with matter and basic quantum mechanics • can apply Einstein coefficients, Planck's formula, and selection rules • have a solid understanding of the hydrogen and helium atoms • can analyze molecular spectroscopy data and optical properties of materials • understand the dielectric function, Kramers-Kronig relations, and basic nonlinear optical 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	Demtröder, ”Experimental physics II” Demtröder, ”Experimental physics III – atoms, molecules and solids” R. Feynman, ”Feynman lectures on physics III quantum mechanics” Jackson, ”Classical ElectrodynamicsE. Hecht, ”Optics”
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	Prof. Dr. Isabelle Staude (FSU)
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)	828 MSc. Photon Science and Technology: Required Elective Course Specialization 628 M.Sc. Photonics: compulsory module 128 MSc. Physics: required 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, ...)	Lecture 2 SWS and exercise 1 SWS
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h
Content	• Basic principles • Wave optical fundamentals • Sensors • Fringe projection, triangulation • Interferometry and wave front sensing • Holography • Speckle methods and OCT • Phase retrieval • Metrology of aspheres and freeform surfaces • Confocal methods

Intended learning outcomes	The students understand the basic principles and wave optical fundamentals of optical metrology are familiar with key sensor technologies and measurement techniques can apply interferometry, holography, and speckle methods for precise measurements understand phase retrieval and its role in optical metrology can analyze and compare metrology techniques for aspheres, freeform surfaces, and confocal methods
Prerequisites for admission to the module examination	-
Requirements for awarding credit points (type of examination)	90 min written exam
Additional information on the module	
Recommended reading	
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. T. 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 528 M.Sc. Quantum Science and Technology, required elective module, subject area ”specialization 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 Exercise: 1 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h
Content	• Strong field effects on the atomic structure • Relativistic and QED effects on the structure of heavy ions • X-ray spectroscopy of high-Z ions • Application in x-ray astronomy • Penetration of charged particles through matter • Particle dynamics in of atoms and ions in strong laser fields • Relativistic ion-atom and ion-electron collisions • Fundamental interaction processes • Scattering, absorption and energy loss • Detection methods • Particle creation

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. G. G. Paulus (FSU)
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)	828 MSc. Photon Science and Technology: Required Elective Course Specialization 128 M.Sc. Physics: Required elective module 628 M.Sc. Photonics: Required 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, …)	Lecture 2 SWS and exercise 1 SWS
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h
Content	• Propagation of light in crystals; • Properties of the non-linear susceptibility tensor; • Description of light propagation in non-linear media; • Parametric effects; • Second harmonic generation; • Phase-matching; • Propagation of ultrashort pulses; • High-harmonic generation; • Solitons

Intended learning outcomes	The students understand light propagation in nonlinear media and the role of the nonlinear susceptibility tensor can describe and analyze parametric effects and second harmonic generation grasp the concept of phase-matching and its importance in nonlinear optical processes are familiar with ultrashort pulse propagation and high-harmonic generation can explain soliton formation and its relevance in nonlinear optics
Prerequisites for admission to the module examination	-
Requirements for awarding credit points (type of examination)	90 min written exam
Additional information on the module	128 M.Sc. Physics: Required elective module (Specialization in „Optics”)
Recommended reading	
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 (FSU), Prof. Dr. T. Pertsch (FSU)
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)	828 MSc. Photon Science and Technology: Required Elective Course Specialization 128 M.Sc. Physics: Required elective module 628 M.Sc. Photonics: Required 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, ...)	Lecture 2 SWS and exercise 1 SWS
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h
Content	• Surface-plasmon-polaritons; • Plasmonics; • Photonic crystals; • Fabrication and optical characterization of nanostructures; • Photonic nanomaterials / metamaterials / metasurfaces; • Optical nanoemitters; • 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.
Prerequisites for admission to the module examination	-
Requirements for awarding credit points (type of examination)	90 min written exam
Additional information on the module	
Recommended reading	L. Novotny and B. Hecht, Principles of Nano-Optics, Cambridge 2006; P. Prasad, Nanophotonics, Wiley 2004; J. D. Joannopoulos, S. G. Johnson, J. N. Winn, R. D. Meade, Photonic Crystals – Molding the Flow of Light, Princeton University Press (2008) list of selected journal publications given during the lecture.
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 (FSU), Dr. V. Gili (FSU), Prof. Dr. T. Pertsch (FSU)
Type of module (compulsory module, required elective module, elective module)	828 MSc. Photon Science and Technology: Required Elective Course Specialization 128 M.Sc. Physics focus „Optics": Required elective module 628 M.Sc. Photonics: Required 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, ...)	Lecture 2 SWS and exercise 1 SWS
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 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 • Integrated optics on a single photon level • Generation and manipulation of quantum states of light using integrated waveguides • Overview over integrated photonic platforms and fabrication of passive and active waveguide structures • Quantum walks in linear and non-linear waveguide lattices • Introduction to photonic quantum computation and simulation • Measurements using superconducting nanowire single photon detectors and transition edge sensors

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. 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. The intended learning outcome is that the students are introduced to the basics on the field of integrated quantum optics and its applications. Therefore, course starts with an overview on the generation of non-classical states of light with special attention on integrated solutions. Afterwards several integrated photonic platforms will be discussed ranging from fabrication to performance and useability. 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. The course closes with the discussion on non-classical light detection in integrated photonics.
Requirements for awarding credit points (type of examination)	90 min written exam
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	
Module code	PAFMO185
Module title (German)	Innovation Methods in Photonics
Module title (English)	Innovation Methods in Photonics
Person responsible for the module	Dr. M. Gräfe (FSU), Dr. V. Gili (FSU), Prof. Dr. T. Pertsch (FSU)
Type of module (compulsory module, required elective module, elective module)	828 MSc. Photon Science and Technology: Required Elective Course Specialization 128 M.Sc. Physics focus „Optics": Required elective module 628 M.Sc. Photonics: Required 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, ...)	Lecture: 2 h per week Exercise: 1 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h
Content	• Rapid prototyping technologies in photonics • Innovation management and design thinking • Hands-on/practical examples of photonics prototyping • Entrepreneurial skills and business modelling • 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. 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).
Requirements for awarding credit points (type of examination)	90 min written exam
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 **PAFMO187** Ion traps and precision experiments	
Module code	PAFMO187
Module title (German)	Ionenfallen und Präzisionsexperimente
Module title (English)	Ion traps and precision experiments
Person responsible for the module	Jun.-Prof. Dr. P. Micke
Recommended or expected prior knowledge	Basics in electrodynamics, quantum mechanics, and atomic physics
Type of module (compulsory module, required elective module, elective module)	128 M.Sc. Physics specialization ”Optics”: Required elective module 128 LA Gymnasium Physik: Required elective module 528 M.Sc. Quantum Science and Technology: Required elective module, subject area ”specialization” 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 Exercise: 1 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h
Content	Basics of ion trap physics; Paul and Penning traps; Cooling techniques, in particular laser cooling methods; Coherent manipulation of electronic and motional states; detection techniques; Application of ion traps for precision experiments: optical clocks, quantum logic spectroscopy, ion traps as a platform for quantum computing, high-resolution mass spectrometry, measurements of g-factors and magnetic moments
Intended learning outcomes	Understanding the concepts of Paul and Penning traps as well as the applied techniques; knowledge of the discussed precision experiments; ability to deepen knowledge independently through latest scientific literature
Prerequisites for admission to the module examination	50% of the points of the exercise sheets; active participation in the exercises by presenting own solutions and discussing content
Requirements for awarding credit points (type of examination)	Oral examination (100%)
Recommended reading	An up-to-date literature list will be announced at the beginning of the semester.
Language of instruction	English

Modul **PAFMO210** Machine Learning for Quantum Science	
Module code	PAFMO210
Module title (German)	Machine Learning for Quantum Science
Module title (English)	Machine Learning for Quantum Science
Person responsible for the module	Dr. X. Gu
Prerequisites for admission to the module	None
Recommended or expected prior knowledge	
Type of module (compulsory module, required elective module, elective module)	528 M.Sc. Quantum Science and Technology: required elective module 128 M.Sc. Physics focus ”Optics”: required elective module 628 M.Sc. Photonics: required elective module
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 Tutorial: 2 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 60 h 60 h
Content	Artificial intelligence has become as a powerful tool in quantum science, enabling researchers to simulate complex systems, optimize experimental procedures, and discover new ideas and experiments. This course introduces the principles and practice of applying artificial intelligence (AI) and machine learning (ML) techniques to quantum physics, providing students with both theoretical foundations and hands-on computational skills. Topics include: • Basic AI/ML techniques for physicists • Differentiable programming • Generative models and reinforcement learning • Quantum circuit optimization and design • Quantum parameter estimation and measurement strategies • Quantum experiments design and discovery • Interpretable AI in quantum physics

Intended learning outcomes	This course introduces and deepens students' understanding of artificial intelligence techniques applied to quantum information science. By actively participating in this course, students will: • Develop both theoretical understanding and practical skills at the intersection of quantum science and artificial intelligence. • Understand how artificial intelligence and machine learning can address challenges in quantum physics, such as quantum state estimation and experimental design. • Gain hands-on experience implementing AI/ML methods in Python (using frameworks like PyTorch and JAX). • Engage with current research literature to identify open questions and design AI systems for quantum tasks.
Prerequisites for admission to the module examination	none
Requirements for awarding credit points (type of examination)	Oral examination (100%)
Additional information on the module	
Recommended reading	Students are encouraged to explore the following papers relevant to the course topics: • Krenn, M. et al., Computer-inspired quantum experiments. Nat Rev Phys 2, 649–661 (2020) • Krenn, M. et al., Artificial intelligence and machine learning for quantum technologies, Phys. Rev. A 107, 010101 (2023) • Dawid, A. et al., Modern applications of machine learning in quantum sciences, arXiv:2204.04198 (2022) • Acampora, G. et al., Quantum computing and artificial intelligence: status and perspectives, arXiv:2505.23860 (2025) A more detailed and regularly updated list of supplementary literature and resources will be provided at the beginning of the semester and throughout the course.
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. S. Höppener, Prof. Dr. U. 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 628 M.Sc. Photonics: Required 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, ...)	Lecture: 2 h per week Exercise: 1 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h
Content	• Building with Molecules • Self-organization and self-assembled coatings • Chemically sensitive characterization methods • Nanomaterials for optical applications • Nanowires and nanoparticles • Nanomaterials in optoelectronics • Bottom-up synthesis strategies and nanolithography • Polymers and self-healing coatings • Molecular motors • Controlled polymerization techniques

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. 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. M. Zepf
Prerequisites for admission to the module	-
Recommended or expected prior knowledge	Fundamental knowledge on quantum mechanics und special relativity
Prerequisite for what other modules	-
Type of module (compulsory module, required elective module, elective module)	128 M.Sc. Physics: Required elective module 628 M.Sc. Photonics: Required 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, ...)	Lecture: 2 h per week Exercise: 1 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h
Content	• Electrons in constant fields • Electrons in electromagnetic pulses • Radiation produced by particles in extreme motion • Radiation reaction • QED effects in strong laser fields
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”) 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 (FSU), Dr. F. Setzpfandt (FSU)
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)	828 MSc. Photon Science and Technology: Required Elective Course Specialization 128 M.Sc. Physics: Required elective module 628 M.Sc. Photonics: Required 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, ...)	Lecture: 2 h per week Exercise: 1 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h
Content	• Basic introduction to quantum mechanics; • Quantization of the free electromagnetic field; • Non-classical states of light and their statistics; • Experiments in quantum optics; • Semi-classical and fully quantized light-matter interaction; • 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. 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	-
Requirements for awarding credit points (type of examination)	90 min written exam
Additional information on the module	
Recommended reading	Grynberg / Aspect / Fabre "Introduction to Quantum Optics";Garrison / Chiao "Quantum Optics"; Fox "Quantum Optics – An Introduction"; Loudon "The Quantum Theory of Light"; Bachor / Ralph "A Guide to Experiments in Quantum Optics".
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 (FSU), Dr. F. Eilenberger (FSU), Prof. Dr. T. Pertsch (FSU)
Type of module (compulsory module, required elective module, elective module)	828 MSc. Photon Science and Technology: Required Elective Course Specialization 128 M.Sc. Physics focus „Optics": Required elective module 628 M.Sc. Photonics: Required 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, ...)	Lecture: 2 h per week Exercise: 1 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h
Content	• Basic introduction to algorithms and computing •The Qubit and entanglement thereof • Basics of quantum algorithms • Advanced quantum algorithms • Implementation of QuBits and quantum computers • 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. 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. 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.
Requirements for awarding credit points (type of examination)	90 min written exam
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 (FSU), Dr. F. Eilenberger (FSU), Prof. Dr. A. Tünnermann (FSU)
Type of module (compulsory module, required elective module, elective module)	828 MSc. Photon Science and Technology: Required Elective Course Specialization 128 M.Sc. Physics focus „Optics": Required elective module 628 M.Sc. Photonics: Required 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, ...)	Lecture: 2 h per week Exercise: 1 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h
Content	• Basic introduction to quantum optics; • Quantum light sources; • Encoding, transmission and detection of information with quantum light; • Quantum communication and cryptography; • Quantum communication networks; • 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%) The form of the exam will be announced at the beginning of the semester.
Additional information on the module	
Recommended reading	
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 (FSU), Dr. F. Setzpfandt (FSU), Prof. Dr. A. Tünnermann (FSU)
Type of module (compulsory module, required elective module, elective module)	828 MSc. Photon Science and Technology: Required Elective Course Specialization 128 M.Sc. Physics focus „Optics": required elective module 628 M.Sc. Photonics: required 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, ...)	Lecture: 2 h per week Exercise: 1 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h
Content	• Basic introduction to relevant concepts of quantumoptics • Generation of photon pairs • Fundamentals of two-photon interference • Applications of two-photon interference • Optical quantum metrology • Ghost Imaging • 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. 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%) 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 **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 (FSU)
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)	828 MSc. Photon Science and Technology: Required Elective Course Specialization 128 M.Sc. Physics: Required elective module 628 M.Sc. Photonics: Required 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, ...)	Lecture: 2 h per week Exercise: 1 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h
Content	The course will cover the following topics: • Review of fundamentals of semiconductors • Optical and optoelectronic properties of semiconductors • Effects of quantum confinement • Photonic effects in semiconductor nanomaterials • Physical implementations of semiconductor nanomaterials, including epitaxial structures, semiconductor quantum dots and quantum wires • Advanced topics of current research, including 2D semiconductors and hybrid nanosystems

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	P. Y. Yu and M. Cardona, Fundamentals of Semiconductors, Springer 2010 C. F. Klingshirn, Semiconductor Optics, Springer 1995 M. Fox, Quantum Optics – An Introduction, Oxford University Press 2006
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. U. Peschel (FSU)
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)	828 MSc. Photon Science and Technology: Required Elective Course Specialization 128 M.Sc. Physics: Required elective module 628 M.Sc. Photonics: Required 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, ...)	Lecture: 2 h per week Exercise: 1 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h
Content	• Types and symmetries of non-linear polarization; • Non-Linear optics in waveguides; • Solutions of non-linear evolution equations; • Temporal and spatial solitons; • 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 %). Written examination (100 %). The final grade will be determined by the exercise performance (25%)and an oral exam (75%).
Additional information on the module	

Recommended reading	• Agrawal, Govind P.: Contemporary non-linear optics; • Moloney, Jerome V., Newell Alan C.: Non-Linear Optics ; • Sutherland, Richard Lee: Handbook of non-linear optics.
Language of instruction	English

Modul **PAFMP001** Advanced Quantum Theory	
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 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 Exercise: 2 h per week
ECTS credits	8 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	240 h 90 h 150 h
Content	• many particle systems, identical particles, non-interacting particles, Thomas-Fermi and Hartree-Fock approximations • addition of angular momenta, Clebsch-Gordan coefficients, selection rules • time-dependent perturbation theory, Fermis golden rule • scattering theory, potential scattering, partial waves, scattering of identical particles • introduction to relativistic quantum mechanics, Poincare transformations, Klein-Gordon and Dirac equations, minimal coupling, non-relativistic approximation • relativistic hydrogen atom, fine structure • 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.

Requirements for awarding credit points (type of examination)	Written or oral examination (100%) 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” 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: - In-class studying - Independent studying (incl. preparations for examination)	120 h 30 h 90 h
Content	• Systematic development of specialized knowledge in the fields of gravitation theory and quantum theory; • 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; • Independent discovery and evaluation of scientific literature; • Presentation of scientific facts in form of a talk; • 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	Prof. Dr. F. Steinlechner, PD Dr. F. Setzpfandt, Prof. Dr. M. 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 ("essentials") 128 M.Sc. Physics: required elective module spezialisation "optics" 628 M.Sc. Photonics: required elective module
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 Exercise: 2 h per week
ECTS credits	8 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	240 h 90 h 150 h
Content	**Concepts of quantum information processing** • introduction to fundamental concepts and the basic formalism • entanglement • application examples • entanglement characterization **Hardware for quantum information processing** • brief review of key physical concepts and applications • basic hardware requirements for information processing 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
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	Prof. Dr. F. Steinlechner, PD Dr. F. Setzpfandt, Prof. Dr. M. 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” 128 M.Sc. Physics: required elective module spezialization "optics" 628 M.Sc. Photonics: required elective module
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 Exercise: 2 h per week
ECTS credits	8 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	240 h 90 h 150 h
Content	**Hardware for quantum information processing** • superconducting qubits, gates, control, manipulation, readout • light-matter interaction • semiconductor qubits (quantum dots, defects) • atoms / quantum Gases • foundations of quantum sensing (sensitivity, noise, standard quantum limit) • Optomechanics **Concepts of quantum information processing** • decoherence • quantum error correction • many-body entanglement 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).

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	PD Dr. F. 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 Exercise: 2 h per week
ECTS credits	8 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	240 h 90 h 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. 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	PD Dr. F. 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” 128 M.Sc. Physics: requied elective module
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: - In-class studying - Independent studying (incl. preparations for examination)	180 h 60 h 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. • Planning and preparation of a scientific measuring task. • Carrying out scientific lab in optics together with a research team. • Preparation of a scientific report.
Requirements for awarding credit points (type of examination)	Lab mark (100%) 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	PD Dr. F. 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 300 h Depending on the topic, the workload should be distributed approximately as: • 50 h introduction to research topic (literature study, ...) • 190 h research work (in the lab for experimental topics, at computer, etc. for theoretical topics) • 50 h preparation of the final report 10 h presentation of final results and preparation for this
ECTS credits	10 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	300 h - h - h
Content	Internship in industry or a research laboratory
Intended learning outcomes	• Carrying out scientific work together with a research team • Preparation of a written scientific report • Presentation of results in an oral presentation
Requirements for awarding credit points (type of examination)	Lab mark (100%) Consists of a written report (approximately 15-20 pages) and a final presentation (10-20 minutes) with subsequent discussion 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 Project	
Module code	PAFMQ009
Module title (German)	Research Project
Module title (English)	Research Project
Person responsible for the module	PD Dr. F. 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 540 h Depending on the topic, the workload should be distributed approximately as: • 150 h introduction to research topic (literature study, …) • 270 h research work (in the lab for experimental topics, at computer, etc. for theoretical topics) • 100 h preparation of the final report 20 h presentation of final results and preparation for this
ECTS credits	18 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	540 h - h - h
Content	Internship in a research laboratory
Intended learning outcomes	• Carrying out scientific work together with a research team • Preparation of a written scientific report • Presentation of results in an oral presentation
Requirements for awarding credit points (type of examination)	Lab mark (100%) Consists of a written report (approximately 20-30 pages) and a final presentation (15-25 minutes) with subsequent discussion 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. S. Gräfe, Dr. A. 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: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 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. S. Gräfe; Dr. A. 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” 128 M.Sc. Physics: required elective module
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: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 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
Person responsible for the module	PD Dr. F. Setzpfandt
Type of module (compulsory module, required elective module, elective module)	128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory" 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 Exercise: 1 h per week
ECTS credits	8 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	240 h 90 h 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; • Independent solution of exercise problems; • 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%) 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	PD Dr. F. 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 Exercise: 1 h per week
ECTS credits	8 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 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; • Independent solution of exercise problems; • 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%) 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	
Module code	PAFMQ999
Module title (German)	Außerfachliche Qualifikationen
Module title (English)	Extracurricular qualifications
Person responsible for the module	PD Dr. F. 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 Exercise: 1 h per week
ECTS credits	8 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 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 • an improved ability for international students to have a successful career in Germany • 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%) 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" 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 Exercise: 2 h per week
ECTS credits	8 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	240 h 90 h 150 h
Content	• Fundamentals of general relativity • Einstein field equations • Newtonian approximation • Gravitational waves • Black holes • Cosmology and the big bang
Intended learning outcomes	• Obtain knowledge of relativistic gravitational physics • 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%) 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 **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" 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 Exercise: 2 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 60 h 60 h
Content	• Introduction: examples of classical field theories • aspects of classical field theory: Lagrange and Hamilton formalism, Noether theorem and charges • non-linear scalar field theories: O(N) models, spontaneous symmetry breaking, Goldstone theorem • fields / particles as representations of the Lorentz group: classification of representations, spinors, construction of free theories • interactive theories: Yukawa models, QED, Abelian Higgs models • current aspects of field theories in particle physics
Intended learning outcomes	• preparation for quantum field theory in the 2nd M.Sc. Semester • 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%) 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 **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" 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 Exercise: 2 h per week
ECTS credits	8 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	240 h 90 h 150 h
Content	• Principles of relativistic quantum field theories • Quantization of Klein-Gordon , Dirac , and electromagnetic fields • Perturbation theory and Feynman diagrams • S matrix and cross sections • Functional integrals • effective effects and correlation functions • Regularization and renormalization
Intended learning outcomes	• Teaching the basic principles and structures of quantum field theories. • 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%) 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 **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. M. 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" 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 Exercise: 2 h per week
ECTS credits	8 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	240 h 90 h 150 h
Content	• Anomalies in Quantum Field Theory (QFT); • QFT at finite temperature and density; • (Quantum) Phase Transitions; • Near- and non-equilibrium dynamics of QFT; • Introduction to conformal field theory; • 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" 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 Exercise: 2 h per week
ECTS credits	8 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	240 h 90 h 150 h
Content	Introduction to concepts of string theory and AdS/CFT correspondence, in particular: • relativistic bosonic string and its quantization • open strings and D-branes • aspects of conformal field theory • Polyakov path integral • scattering of strings • low energy effective action • dualities in string theory • compactification scenarios • introduction to AdS / CFT • main tests of AdS / CFT • 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.

Requirements for awarding credit points (type of examination)	Written or oral examination (100%) 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" 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 Exercise: 2 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 60 h 60 h
Content	Overview of the standard model of particle physics including: • symmetries, quantum electrodynamics • strong interaction • the quark model and quantum chromodynamics • hadrons and asymptotic freedom • weak interactions and the Higgs effect • scattering experiments • 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.

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" 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 Exercise: 2 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 60 h 60 h
Content	• gauge symmetry • classical Yang-Mills theory • quantization of gauge theories / BRST formalism / Gribov problem • perturbation theory • semiclassical expansions • topological configurations • 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%) 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 **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" 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 Exercise: 2 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 135 h
Content	• Path integral for quantum field theories • Euclidean formulation and quantum field theories in thermal equilibrium • Lattice field theory as spin models in Statistical Physics • rigorous results and approximations • stochastic methods, Monte Carlo simulations • renormalization group, critical phenomena • gauge theories on a space-time grid • Quantumchromodynamic on a lattice
Intended learning outcomes	• The course covers theoretical concepts and methods necessary to understand (discretized) Quantum Field Theories. • The students will learn stochastical and numerical methods to simulate spin models and lattice field theories. • 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.

Requirements for awarding credit points (type of examination)	Written or oral examination (100%) 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 128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory" 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 Exercise: 2 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 60 h 60 h
Content	• Coulomb problem; • particles with spin; • qubits, quantum registers and quantum gates; • representation of pure and mixed states (Bloch sphere); • composite systems, indistinguishable particles; • Hartree-Fock method; • Coupling of angular momenta.
Intended learning outcomes	• Learning computer algebraic and numerical methods in the description of simple quantum models; • 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.

Requirements for awarding credit points (type of examination)	Written examination or paper (100%) 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 128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory" 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 Exercise: 2 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 60 h 60 h
Content	• symmetries and groups • space and space-time symmetries • conserved currents and charges • discrete groups and continuous Lie-groups • representations of groups, theory of characters, reductions of representation • invariant integration on Lie-Groups • Lie-algebras and their representations • classification of semi-simple Lie-algebras • selected application of group theory and representation theory in solid state physics, atomic and molecular physics, quantum field theory and particle physics.

Intended learning outcomes	• The course covers theoretical concepts of discrete and continuous groups, Lie-algebras and their representations with relevant applications in physics • 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%) 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 128 M.Sc.Physics, Required elective module specialization "Gravitation and Quantum Theory" 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 Exercise: 2 h per week
ECTS credits	8 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	240 h 90 h 150 h
Content	• Short review of hydrogenic atoms • Independent-particle model & Hartree-Fock theory • Interaction with the radiation field • Correlated many-body theory • Atomic collision theory • Basics of the density matrix theory • Atoms and forces in (intense) light fields • Laser cooling and trapping; ions traps • 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%) 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 **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" 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 Exercise: 2 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 60 h 60 h
Content	• Theoretical foundations of quantum electrodynamics (QED) in strong electromagnetic fields; • Derivation of elementary signatures of the strong field QED; • 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%) 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" 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 Exercise: 2 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 60 h 60 h
Content	• Supersymmetric quantum mechanics • symmetries and spinors • Wess Zumino models • Supersymmetry algebra and representations • Superspace and superfields • 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. • 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%) 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 **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" 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 Exercise: 2 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 60 h 60 h
Content	• Further, in-depth topics in the field of quantum field theory; • Topics from current areas of research.
Intended learning outcomes	• specialisation in a special field of quantum field theory; • Independent handling of exercises; • 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%) 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" 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 Exercise: 1 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h
Content	Partial Differential Equations: • Fundamentals of differential equations • Introduction to elliptic, parabolic and hyperbolic differential equations • explicit and implicit procedures, stability analysis • Poisson equation, diffusion equation, advection equation, wave equation, • shocks; • difference method, • pseudo spectral methods, • multiple grids
Intended learning outcomes	• Mastering the basics and methods of partial differential equations and machine learning in physics • 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.

Requirements for awarding credit points (type of examination)	Written or oral examination or project (100%) 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. B. Brügmann
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 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 Exercise: 1 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h
Content	• Machine Learning in Physics • Basics of Machine Learning, Neural Networks and Deep Learning • 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 • 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" 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 Exercise: 2 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 60 h 60 h
Content	• Further, in-depth topics in the field of gravitation theory; • Topics from current areas of research.
Intended learning outcomes	• specialization in the special field of gravitation theory; • Independent handling of exercises; • 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%) 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" 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 Exercise: 1 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 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: • Quantum systems in the gravitational field of the earth, experiments and relativistic generalisation • Decoherence from spacetime fluctuations • The equivalence principle for quantum matter • Theoretical treatment of classically gravitating quantum systems and experimental distinction from a quantised gravitational field • Interpretations of quantum mechanics, the measurement problem, and the potential role of gravity in quantum wave function reduction

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. 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" 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 Exercise: 1 h per week
ECTS credits	4 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	120 h 45 h 75 h
Content	• Newtonian and Relativistic hydrodynamics Radiation hydrodynamics • Hyperbolic PDEs • Finite volume methods • Riemann problem and solvers • Conservative finite-differencing • Limiters • Galerking methods
Intended learning outcomes	This course covers the development of numerical techniques required to solve the nonlinear equations 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%) 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	PD Dr. F. 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 / 900 h Depending on the topic, the workload should be distributed approximately as: • 225 h introduction to research topic (literature study, ...) • 450 h research work (in the lab for experimental topics, at computer, etc. for theoretical topics) • 200 h preparation of the final report 25 h presentation of final results and preparation for this
ECTS credits	30 CP
Work load: - In-class studying - Independent studying (incl. preparations for examination)	900 h 0 h 900 h
Content	Internship in a research laboratory
Intended learning outcomes	• Carrying out advanced scientific work together with a research team • Preparation of the workflow to obtain researchresults • Analysis of research results • Preparation of a written scientific report (Master Thesis) 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%) 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
KS/ PR....	Klausur/Prüfung
C....	Colloquium
C/I....	Colloquium/practical work
CS....	Conference/symposium
kV....	Kulturelle Veranstaltung

Abbrevations of lectures

Cu....	Course
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
E/T....	Exam/test
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

Abbrevations of lectures

E/I....	Exercise/interdisciplinary
E/I....	Exercise/practical work
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