QuanTEEM
ERASMUS MUNDUS MASTER
QUANTUM TECHNOLOGIES
AND ENGINEERING

European Commission
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Erasmus Mundus Master QuanTEEM

Syllabus

This document is intended to prospective students interested in the QuanTEEM master's program. It provides a detailed description of the curriculum offered during the master.

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1. Semester 1 – Core Courses – UBFC

Module name	Professor(s)	Number of ECTS
Quantum Physics	S. Guérin, D. Sugny, H. Jauslin, V. Boudon	6 ETCS
Quantum Technologies	S. Guérin, F. Holweck	5 ECTS
Numerical methods for physics	A. Dereux, M. Sala	4 ECTS
Signal Processing	A. Coillet, B. Sinardet	4 ECTS
Solid-state physics and soft matter	A. Dereux, P. Senet	5 ECTS
Industry seminars	J.-R. Dumas	1,5 ECTS
Soft Skills	R. Chamberlain	1,5 ECTS
French Language & Culture	C. Rodriguez	1,5 ECTS
Interdisciplinary Winter School	Invited Professors and scientists	1,5 ECTS

1.1. Quantum Physics

Content Summary

This course covers the principles and concepts of non-relativistic quantum physics, including:

- quantisation,
- superposition,
- wave-particle duality,
- tunneling,
- entanglement and composite systems,
- addition of angular momenta,
- spin,
- identical particles,
- time-dependent problems,

and their advanced modern applications relevant to QT, focusing on:

- atomic & molecular physics & spectroscopy,
- introduction to quantum optics,
- introduction to open quantum systems & quantum dissipation,
- introduction to quantum control & optimal control.

We will use numerical tools to solve various problems relevant for QT applications such as quantum control and spectroscopy.

Main learning outcomes

- General knowledge of non-relativistic quantum physics relevant for applications to QT.
- Experience using mathematical tools to construct approximate quantum mechanical models.
- Translating a theoretical problem of quantum physics into a model and its associated computer code (using the Matlab programming language), including the graphical representations of the results.

- Solve time-dependent and time-independent Schrödinger equation for key potentials relevant for QT.
- Apply the variational method, time-independent perturbation theory and time-dependent perturbation theory to solve key problems of QT.
- Understand and analyse spectra of atoms.
- Describe and understand the principles of quantum electrodynamics
- Describe and understand single photons in cavity and in free space
- Describe and understand the quantum dissipative systems by master equations, such as Lindblad equation
- Implement numerically strategies of quantum control.
- Understand and analyze spectra of atoms and molecules

1.2. Quantum Technologies

Content Summary

This course covers the basic concepts and techniques of quantum technologies, how the quantum physics principles are translated into quantum information processing:

- Classical and quantum information, bits and quantum bits, entangled states;
- Quantum information, principles and applications: quantum cryptography, quantum teleportation, quantum compression, von Neumann entropy, quantum information by single photons, quantum no-cloning theorem, Bell's inequalities;
- Quantum computation: quantum gates, quantum algorithms, principles of the state-of-the-art platforms, quantum supremacy.

Practical works using educational QuTools' kits and IBM's quantum computers (via the IBM Quantum Experience platform and the associated software Qiskit):

- entanglement demonstration by polarised single photons,
- quantum sensing by diamond magnetometer,
- quantum cryptography and quantum key distribution,
- implementation of quantum logical gates and quantum algorithms (Fourier transform, Quantum phase estimation algorithm, Grover's algorithm, Shor's algorithm) on IBM quantum computers.

Main learning outcomes

- Knowledge of the main concepts of quantum technologies, from theory to experimental demonstrations of key effects.
- Describe and understand how information can be represented, stored and conveyed through quantum mechanical phenomena, such as entanglement.
- Describe and understand quantum computation and the quantum circuit model, including quantum logical gates, and quantum algorithms.
- Describe, understand and implement on a quantum computer key algorithms for quantum computation.
- Describe and understand quantum compression.
- Describe and understand error-correction coding.
- Describe, understand and implement protocols for quantum cryptography.

- Describe the platforms of QT.
- Describe the principles of quantum sensing and its applications.

1.3. Numerical methods for physics

Content summary

The module provides the students with a suite of numerical tools for solving problems relevant to QT, including the modelling of quantum systems, data analysis such as linear and nonlinear fits to data sets, applications of high-performance computing, visualisation techniques, and methods of machine learning:

- numerical linear algebra for QT,
- numerical integration,
- modelling: interpolation, curve fitting, optimisation,
- differential equations,
- introduction to machine learning, including deep learning techniques,
- symbolic computation.

The programming languages used are Matlab or Python. The examples of applications will be overlapping the topics of the other courses with emphasis on the applications of the course on quantum condensed matter and statistical physics.

Main learning outcomes

The students will acquire the necessary knowledge in numerical analysis, computer programming and numerical computation relevant to advanced topics in QT. More generally, it provides an essential skill-set for students who wish to pursue their studies in academic or industrial oriented programmes at doctoral level, or to integrate the job market as engineer in the research and development sector. More specific learning outcomes include:

- Identify modern programming methods and describe their extent and limitations;
- Identify and describe the characteristics of various numerical methods;
- Independently program computers using leading-edge tools;
- Formulate and computationally solve a selection of QT problems, use the tools methodologies, language and conventions to test and communicate ideas and explanations.

1.4. Signal Processing

Content summary

The aim of this course is to give the students the basic and advanced tools needed for an efficient data acquisition, interpretation, and transformation, all relevant for quantum information processing. Control process and data acquisition automation are realised through LabVIEW software and specific practical exercises. The content summarises as:

- analysis of a signal using the tool of Fourier transform,
- solving differential equation by Fourier transform,
- convolution filters and correlation operations,
- discrete Fourier transform & fast Fourier transform algorithm for signal processing,

- heterodyne detection and frequency mixing,
- advanced processing techniques with Laplace and wavelet transforms,
- LabVIEW: The development environment (programming tools, creating application by example),
- data acquisition (interfaces, drivers, measurement automation eXplorer, data acquisition by integrated ports, by GPIB link, by input/output cards and NIDAQ).

Main learning outcomes

- Define and characterise a given signal.
- Manipulate the Fourier transform and Fourier series.
- Use the Fourier transform to solve differential equations.
- Use convolution filters and correlations to extract the desired information from a signal.
- Understand the experimental advantages of heterodyne detection and its link to Fourier transforms.
- Manipulate numerical signals with a programming language and especially with the Fast Fourier Transform algorithm.
- Programme data acquisition with LabVIEW according to internationally recognised standards.

1.5. Solid-state physics and soft matter

Content summary

The first part of this course (Prof. P. Senet) focusses on the quantum description of electrons in crystals (quasielectrons) in order to master the quantum description of the electrical conductivity which is a ubiquitous concept of technologies at the nanoscale. In a second part, the course presents an introduction to statistical physics of complex molecular systems (as biopolymers) with applications in nanosciences:

- partition functions, free-energy, potential of mean force, free-energy landscape;
- Brownian motion, Smoluchowski equation, linear response functions, self-avoiding random walks;
- statistical properties of simple models of polymers: freely jointed chain model, continuum elastic model, Zimm model, Go model;
- flexible chain under an external field, singlebiomolecule experiments, confinement in nanopores;
- advanced applications. Unsupervised learning methods for molecular time series data (protein folding).

The second part of this course (Prof. A. Dereux) is devoted to the quantum description of electron transport in metals, semiconductors as well as in junctions and heterostructures :

- Describe and understand the many-body problem of electrons in crystals using the one-electron approximation and the concept of quasiparticles in reciprocal space using the Sommerfeld and Bloch models.
- In-depth understanding of the Bloch electron dynamics (Bloch wave packets, effective mass, etc).
- Classification of metals, semiconductors and insulators.

- Describe and understand the Boltzmann equation in the 6D phase space to describe the electrical conductivity and thermo-electric effects.
- Compute the electron band structure of semiconductors.
- Physics of electron transport in various junction exploiting quantum effects (metal-metal, metal-semiconductor, semiconductor featuring different doping, semiconductor heterostructures)

Main learning outcomes

- Knowledge of the main concepts and modern tools of statistical physics
- Describe applications of statistical physics to complex molecular systems.
- Describe and understand the concept of free-energy and entropy at the molecular level.
- Describe and understand the Brownian motion and the linear response theory (fluctuations-dissipation theorem).
- Describe and understand statistical properties of flexible chains, the scaling properties and limits of simple models.
- Describe and understand the physics of singlemolecule experiments (AFM, nanoconfinement, translocation) and numerical simulation of the experiments.
- Knowledge of the principles of statistical analysis driven by machine learning in complex molecular systems. Numerical applications.
- Mastering the concept of an electron viewed as a quasiparticle in various experimental circumstances.
- Ability to decide which model of metal a(mong Drude, Sommerfeld, and Bloch models) is most appropriate depending on experimental circumstances.
- Understanding the concepts of empirical pseudopotential, Bloch wavepacket, electron group velocity, holes, Bloch oscillation.
- Understanding the relation between the quantum description of Bloch electrons and the macroscopic property of electrical conductivity as well as the roles of impurities, of electron-electron interactions and electron-phonon interactions.
- Mastering the concepts of work function, contact bias, Schottky model of polarization charges at interfaces as well as the modelling of electric current flowing through junctions.
- Understanding the quantum effects driving microelectronic and nanoelectronic devices.
- Capacity to translate elaborated chapters of theoretical physics into numerical applications that have a sound physical meaning by a rigorous link to units of experimental data. This goal will be achieved by a strong overlapping with the course and practical exercices on advanced numerical methods.

1.6. Industry seminars

Main learning outcome

From focusing on technical project management to mastering the innovation process and beyond, there is a large body of competencies, soft-skills and knowledge one has to learn in order to understand, take part in and manage modern businesses. This course is an open window on those subjects, focusing on innovation management, project management and high-tech companies and research labs interaction and inner workings, with a specific focus on the ethics and understanding of the quantum technologies' impact on our society:

- innovation and innovation management,
- intellectual property,
- transfer of technology,
- creativity for innovation,
- project management,
- oral communication: credibility, conviction, clarity,
- business models,
- start-up and spin-off creation and financing,
- ethics and impact of quantum technologies on our society.

Main learning outcomes

- Innovation management: understand the principles and process of innovation, understand how market value can be assessed and influenced, know and anticipate the process of diffusion / adoption of a new product.
- Project management: define a project's scope, breakdown the deliverable and work, plan and schedule tasks and resources, identify and prioritise risks, understand the balance and sources of finances, report and deliver.
- Understand how creativity for innovation works, how it can be channelled and how creative ideas can be leveraged to build innovative projects.
- Intellectual property and transfer of technology: know the main principles and tools of intellectual property and whether to use them, prepare for the negotiations around industrial property, understand the advantages and steps of technology transfer, know the main stakeholders and anticipate the transfer for a company or a research laboratory.
- Business and start-ups: know the definition of a company and the differences with other kinds of organisations, find and refine a business idea, build a business model, know the main financing steps of a tech company.
- Take into account sociological and methodological points, to analyse and question quantum technologies' impact: social acceptability (collective dynamics, psychometric scales, promotion, monitoring), science popularisation (communication, outreach, line of argument) and ethics (debate and awareness, legal ethical framework).

1.7. Soft Skills

Content summary

The aim of this module is to equip students from a scientific background with the necessary competencies in order to confidently enter into the competitive job market. The course covers several subjects concerning self-confidence, presentation and communication skills, using techniques from transactional analysis, neuro-linguistic programming and non-violent communication.

Main learning outcomes

- Build a future project, imagine the future career, based on each students' values and personal objectives.
- Communication skills: the importance of assertiveness in communication.
- Understand how to create win-win relations.
- Speak in public: build a strong and efficient presentation and give a credible and convincing speech.

- Anticipate and resolve conflict in a team.
- Gain self confidence in order to venture out of the comfort zone.
- Prepare skills for job interview situations.

1.8. French Language & Culture

Content summary

French Language and Culture course is organised to improve the individual skill of French as a foreign language, providing different levels from A1 (beginners) to C1 (expert), depending on the initial level of the students. The course will address all aspects: oral and written comprehension, oral and written expression (EO) with particular emphasis on phonetic and phonological aspects especially for beginners. For native French speakers, an alternative language course will be proposed (such as advanced English or German). Discussions targeting science & technology and global challenges related to environment and health will be organised. Cultural outings & activities, such as visit to museums and excursions in Dijon and Beaune will be offered.

Main learning outcomes

- Improve the skills of French language
- Knowledge of French culture.

1.9. Interdisciplinary Winter School

An interdisciplinary Winter School is organized each year after the exams of the S1. The ai mis to open the mind of the students to a broad range of topics related to Quantum Technologies. Possible topics include:

- Secure quantum communications
- Quantum machine learning and applications
- Quantum sensing for healthcare
- Green quantum chemistry
- Quantum computer & molecular simulation for molecular design
- Multidisciplinary research with graphene

2. Semester 2 – Specialization 1: Photonics, Nanophotonics and enabling Technologies – UBFC

Module name	Professor(s)	Number of ECTS
Lasers	O. Faucher	5 ETCS
Non-linear Optics	F. Chaussard , P. Mathey	4 ECTS
Opto-electronics and optical communications	P. Grelu, P. Tchofo-Dinda	4 ECTS
Nano-Optics	G. Colas des Francs, A. Dereux	4 ECTS
Guided Optics and laser technologies	P. Tchofo-Dinda	4 ECTS
Micro Nano Fabrication & clean-room	L. Markey	3 ECTS
Research Project	Dept. Of Physics	6 ECTS

2.1. Lasers

Content summary

The purpose of this course is to present a semi- classical model providing a good understanding of the laser operating principles and a description of the main features of the coherent light emission as for instance laser power, laser frequency, spectral bandwidth, and spatial modes structure. The first part of the course covers the description of the amplifying medium, the optical pumping system, the optical cavity, the spectral broadening sources, and single-mode or multimode operation. The seconds part is dedicated to the spatial structure of laser waves and their propagation. Two main families of Gaussian propagation modes, associated to rectangular and cylindrical geometries of the laser cavity, are derived as particular solutions of Maxwell's equations. The presented model describes the transverse distribution of energy and the wave front properties as a function of the propagation distance. Finally, ABCD law is introduced in order to describe the modification of the Gaussian mode when a laser beam propagates though diverse optical elements.

Main learning outcomes

- Derive the optical Bloch equations.
- Solve the steady-state Bloch-Maxwell solutions and understand the laser operating in a continuous wave regime.
- Describe the linear and nonlinear gain of the laser amplifier.
- Calculate the laser output intensity and describe the mode pulling effect.
- Derive the pumping rate equations for different laser systems.
- Derive the paraxial wave propagation equation.
- Describe and understand fundamental and higher-order Gaussian modes.
- Understand the transfer matrix formalism.
- Solve the transformation of Gaussian beams with ABCD law.

2.2. Non-linear Optics

Content summary

Nonlinear optical phenomena such as optical frequency conversion or Raman scattering have become commonplace in optical devices and materials thanks to the technological advancements in lasers producing intense fields with ultrashort pulses. This course introduces the concepts underlying nonlinear optics and aims at giving essential ingredients to understand its origins, consequences and applications. It is complemented by a course of materials for nonlinear optics, designed to provide students with developments in crystalline and glassy media involved in linear and nonlinear phenomena and their applications. The course covers:

- description of the origin of nonlinearities through a standard model based on the classical anharmonic oscillator and an introduction to nonlinear susceptibility formalism,
- derivation of the nonlinear wave propagation equation,
- propagation in anisotropic materials and the derivation of solutions regarding phasematching conditions,
- study of optical processes: second harmonic generation (SHG) or frequency doubling, sum and difference frequency generation (SFGDFG), optical parametric amplification and oscillation (OPA – OPO),
- optical Kerr effect, Stimulated Raman scattering,
- Faraday effect,
- electro-optic properties of Crystals,
- optical Phase Conjugation.

Main learning outcomes

- Manipulate the nonlinear susceptibility tensor components.
- Calculate the components of nonlinear polarisation vector.
- Derive the phase matching conditions.
- Solve the nonlinear equation for a given nonlinear interaction even under the undepleted pump approximation in the case of SHG.
- Describe and understand the classical microscopic model of Faraday effect.
- Describe and understand the technology of optical isolator.
- Describe and understand the linear electro-optic effect (Pockels effect) and the quadratic electro-optic effect (Kerr effect) in crystals and the consequences of the different crystal symmetries.
- Describe and understand the optical phase conjugation as a technique for the automatic correction of distorted laser beams.
- Describe nonlinear optical effects producing the phase-conjugate wave and the performance of several nonlinear crystals.

2.3. Opto-electronics and optical communications

Content summary

The objective of this module is to provide students with a rationale introduction to modern optical communications, explaining their possibilities, current limitations, and some of their prospects. The long-haul high-bit-rate optical communication link is a central figure of this presentation. The optoelectronics technological building blocks are presented and explained: laser diodes, photodiodes, passive and doped optical fibers, fiber integrated components. Modulations formats and methods to measure the quality of optical digital transmissions (eye diagram, Q-factor) are presented, leading to an overview of the design of optical telecom systems. Content:

- Introduction to optical fiber communications.
- Wave optics mathematical tools survey: Gaussian beams and pulses.
- Semiconductor Light Emitters LED/LD/VCSEL. PIN Photodiodes.
- Fiber integrated devices.
- Fiber amplifiers and lasers.
- Dispersion limitations and dispersion management.
- Modulation formats.
- SNR in optical communications. Eye diagram, Q-factor.
- Design of optical telecom systems.
- Nonlinearity impairments and other physical limitations in optical communication systems.

Several important aspects of the course are illustrated in lab classes: Fiber amplifier and fiber laser; Optical fiber reflectometry; Fiber integrated components and application to chromatic dispersion measurement; Optical polarisation control and application to optical telecom; Propagation effects in optical telecom (software); Design of an optical transmission line (software).

Main learning outcomes

- Knowledge of the key enabling technologies for optical communications.
- Understanding the physical principles of semiconductor emitters and receivers.
- Understanding linear propagation effects: diffraction, dispersion, polarisation.
- Knowledge of the functional properties of optical fibers, nonlinearity impairments and other physical limitations in optical communication systems.
- Knowledge of major fiber integrated components: couplers, multiplexers, isolators etc.
- Knowledge of switching and multiplexing for highcapacity transmission lines.
- Description of major fiber-based architectures: fiber amplifiers, fiber lasers, fiber sensors, optical transmission lines and passive optical networks (GPON, XG-PON, NG-PON, FTTH).
- Knowledge of the main modulation formats used to encode binary messages (RZ, NRZ, ASK, PSK, FSK, DQSK).
- Understanding the principles of measurements of optical transmission fidelity, such as the eye-diagram and Q-factor. Application to the design of long-distance communication lines.
- Learning methods to design a backbone long-distance optical transmission line with power budget, dispersion management and data rate optimisation.
- Acquisition of concepts on communication protocols in computer and telecom networks (OSI Model, TCP -IP, Frame Relay, ATM, etc.).

2.4. Nano-Optics

Content summary

Nano-optics is the study of optical phenomena near or beyond the diffraction limit. In this course, we present light propagation in submicronic optical waveguides for nanophotonics and discuss micro-optical cavities as a key concept for efficient light-matter interaction. Next, we introduce the effect of electronic confinement on the optical properties of semi-conductor (quantum dots). The final part concerns plasmonics, i.e. optics of metal at the nanoscale, relying on the specific modes (surface

plasmon polaritons) sustained by metallic nanoparticles to control the light at a subwavelength scale.
Content:

- Background on the measurement of electromagnetic fields associated to optical fields : Lorentz point of view, time-average versus volume average of electromagentic fields, concept of so-called macroscopic field, Heisenberg uncertainties involving electric and magnetic field strengths.
- Dielectric response of matter, most general concept of dielectric function, application to the optical regime. Limit of application of the dielectric function. Modelling dielectric functions from the static regime to UV frequencies in the cases of insulators, semiconductors and metals. Optical properties of these material.
- Concepts of volume, surface and interface polaritons : applications to phonon-polaritons and to plasmon polaritons, surface phonon-polariton, surface plasmon-polariton, Fuchs-Kliewer modes of thin films, interface modes in heterostructures. How all these modes appear in experimental contexts : reflectance, attenuated total reflection, electron energy loss spectroscopy, Raman spectroscopy, scanning near fiel optical microscopes.
- Light scattering by small particles : the various regimes of Mie scattering, Ewald-Oseen theorem, localized phonon-polariton and plasmon-polariton of micro- and nanoparticles.
- Light scattering by small particles deposited on surfaces.
- Unified framework based on Green’s dyadics leading to the concepof optical density of staes and optical local density of states.
- Correct interpretation of near-field optical images.
- Fundamentals of integrated photonics (dispersion relation, density of guided modes, mode profile, nanophotonics devices).
- Optical micro-cavities (photonic crystal, enhanced light matter interaction and Purcell factor, applications).
- Optical nanosources : semi-conductor nanocrystal (quantum dots) , dipolar emission, applications (biolabelling, display, quantum cryptography).
- Key concepts for modelling nano-optical systems.
- Delocalised/localised plasmons and applications: surface enhanced spectroscopies, biosensing, integrated photonics devices, optical nanoantennas.

Practical works:

- Surface plasmon waves
- Optical tweezers
- Whispering gallery mode resonators

Main learning outcomes

- Casting optical experiments in reciprocal space (dispersion relations) for a variety of situations : bulk samples, plane surfaces and interfaces between several media from the static regime to UV frequencies.
- Mastering the light scattering effects by small particles (micro- and nano-particles)
- Casting optical experiments in reciprocal space (dispersion relations) for a variety of situations of samml particles deposited on surfaces or embeddd in a thin film or a waveguide (from the static regime to UV frequencies).
- Computing accurate optical properties from the static regime to the UV frrequencies.
- Establishing accurate dispersion relations. Mastering the transition from the ideal damping-free dispersion relations to the experimental situation including damping.
- Recognining the pitfalls relatd to subwavelength measurements of optical fields.
- Knowledge of the main concepts of nanophotonics and plasmonics from theory to experimental demonstrations of key effects.

- Describe and understand light confinement near and below the diffraction limits and applications.
- Describe and understand light-matter interaction at the nanoscale in insulator, semi-conductor and metal.
- Describe and understand near-field and far-field behavior.
- Describe the principles and discuss applications of optical microcavities.

2.5. Guided Optics and laser technologies

Content summary

Guided optics is the set of concepts and principles for confining light and guiding its propagation from its source to its destination. It has been a rapidly developing topic since the invention of lasers and fiber optics. Currently, guided optics abundantly irrigates the field of telecoms and laser sources, with a host of innovative components (passive and active optical fibers, Bragg gratings, couplers, multiplexers, splitters, attenuators, isolators, etc.) which make up the physical layer of Telecoms networks such as MAN, WAN, and the Internet.
Content:

- Introduction to waveguides.
- Planar dielectric waveguides.
- Step-index optical fiber.
- Functional properties of optical fibers (Numerical aperture, Attenuation, Dispersion, kerr effect).
- Mode coupling in optical waveguides.
- Mode coupling based devices (directional coupler, grating coupler, multiplexers).
- Fibered and/or integrated optical components.
- Microstructured waveguides.

Main learning outcomes

- Understand the physical principles of guiding light waves.
- Knowledge of the main waveguide architectures (Buried-, strip-loaded-, ridge-, rib- WG, etc).
- Describe the mode structure in planar dielectric waveguides.
- Knowledge of the mode structure in step-index optical fiber.
- Knowledge of the functional properties of optical fibers.
- Knowledge of the trigger conditions for mode coupling and the negative and positive aspects of this phenomenon.
- Knowledge of device design techniques based on mode coupling (directional coupler, grating coupler, splitters, multiplexers, etc.).
- Understand the physical principle of integrated optical components and micro-structured waveguides.

2.6. Micro Nano Fabrication & clean-room

Content summary

Micro-Nano-Fabrication covers the experimental techniques used to fabricate integrated circuits or to integrate nano-objects onto a substrate (wafer, chip). These techniques are mainly based on the

heritage of the microelectronics semiconductor sector and its fantastic development since the early sixties, but have also evolved in the past two decades towards more diversified techniques developed for an increased amount of applications, including for example on-chip photonics for data communication or biosensing. Micro-Nano-Fabrication techniques are nowadays used for a very large number of applications. This UE proposes laboratory work on thin film deposition, lithography and plasma etching which are the core techniques in this field.
Content:

- General introduction to nanotechnologies
- Micro-nano-fabrication general process flows
- Thin film deposition
- Optical Lithography (UV)
- e-beam lithography
- resist processes
- recent and non-conventional patterning techniques
- plasma etching, (RIE =Reactive ion Etching), wet etching
- Clean room

Main learning outcomes

- Get familiar with clean room environment and all the classical tools and materials used in micro-nano-fabrication
- Knowledge of lithography and other patterning techniques
- Knowledge of the performances of the lithography tools (resolution, throughput, etc.)
- Knowledge of plasma etching (RIE) and wet etching techniques
- Knowledge of the performances of RIE (directivity, selectivity, etc.)
- Knowledge of thin film deposition techniques (mainly physical vapour deposition)
- Understand how a fabrication process flow is built.

2.7. Research Project

Content summary

The laboratory project is a research internship supervised by one of the professors of the master at UBFC in the topics of quantum technology, or in the area of the specialisation at UBFC.

Main learning outcomes

- Skills to conduct research.
- Professional attitude.
- Autonomy.
- Critical thinking.
- Write a research report.
- Oral presentations.

3. Semester 2 – Specialization 2: Integrated Quantum Optics – RPTU

The semester starts with an optional one-month long Orientation Course including **German language courses**. QuanTEEM students are highly encouraged to attend the Orientation Course.

Specialized courses are not offered every year.

Module name	Professor(s)	Number of ECTS
Quantum Optics I + II	A. Pelster	8 ETCS
Quantum Field Theory I + II	H. C. Schneider	8 ECTS
Solid State Theory (specialized)	W. Hübner	8 ECTS
Quantum Physics Tutorial (specialized)	A. Widera	0 ECTS
Advanced Photonics II (specialized)	C. Jörg	4 ECTS
Magnonics (specialized)	B. Hillbrands, A. Serga	8 ECTS
Quantum Gases I (specialized)	A. Widera	4 ECTS
Cryptography (elective)	M. Horn	6 ECTS
Digital signal processing: algorithms and their implementation (elective)	A. Potchinkov	3 ECTS
Functional programming (elective)	R. Hinze	8 ECTS
Machine Learning I - Foundations (elective)	M. Kloft	8 ECTS
Real-Time Systems I (elective)	G. Fohler	4 ECTS

3.1. Quantum Optics I+II

Content summary

1) Quantization of Maxwell field:

   a) Canonical field quantization
   b) Quantum fluctuations effects: electric field vacuum correlations, Casimir effect, Lamb shift

2) Quantum states of radiation field:

   a) Fock, coherent, squeezed, and thermal states
   b) Density operator, quasi-probability distribution in phase space

3) Emission and absorption of light by matter:

   a) Non-relativistic matter
   b) Perturbative treatment: Einstein processes
   c) Rabi model: classical light-matter interaction
   d) Jaynes-Cummings model: quantum mechanical light-matter interaction

4) Quantum mechanical equations of light field and atoms:

a) Without and with coupling to environment providing losses/pumping
b) Semiclassical and quantum mechanical laser theory

5) Theory of photon Bose-Einstein condensation:

a) Experimental set-up and results
b) Paraxial approximation in microcavity
c) Kerr interaction
d) Thermo-optic interaction

Main learning outcomes

- Understanding of the fundamental concepts, methods and approaches of quantum optics and optical technologies.
- Understanding of the close interaction between theoretical predictions and experiments in (quantum) optics, and the importance of this close interaction for developing technological applications.
- Awareness for how quantum optics theory and optical technologies were developed historically and how they have contributed to the development of the fundamental concepts of modern physics in general.

3.2. Quantum Field Theory I + II

Content Summary

- Classical field theory
- canonical field quantization
- Poincare group
- Klein-Gordon field
- Noether theorem
- Maxwell field
- Dirac field
- quantum electrodynamics
- perturbation theory
- Feyman diagrams
- scattering processes
- cross section

Main learning outcomes

- Understanding of the core concepts of general field theory and in particular quantum field theory.
- Awareness for the implications of the field theoretical description of quantum mechanics.

3.3. Solid State Theory (specialized)

Content Summary

- Many-body description of electron bandstructure and phonons
- Theory of electron-phonon and electron-electron interaction
- Basics of many-particle quantum mechanics
- Superconductivity

Main learning outcomes

Students will:

- Acquire a theoretical foundation of advanced solid state theory
- Relate concepts of solid state theory to their quantum mechanical principles

3.4. Quantum Physics Tutorial (specialized)

Content Summary

Tutorial covering the lectures "Quantum Technology", "Quantum Optics", and "Ultracold Quantum Gases"

Main learning outcomes

Deepen the understanding an finding the links between the covered subjects.

3.5. Advanced Photonics II (specialized)

Content Summary

This lecture continues the lecture Advanced Photonics I. It focusses onto metallic materials. Hence, we will discuss:

- foundations of plasmonics
- metamaterials
- transformation optics
- Outlook: dielectric metamaterials and topological photonics.

Main learning outcomes

After this lecture students will be able to:

- Explain of the core concepts of photonics in metalic materials
- Outline the importance of metamaterials and plasmonics for metal based photonics
- Appreciate the role of photonics for state of the art quantum technology

3.6. Magnonics (specialized)

Content summary

- fundamentals of spin waves in confined structures
- basic elements of magnonics
- parametric and nonlinear phenomena
- advanced properties and applications

Main learning outcomes

- Understand and apply spin wave in research and industry
- Appreciate the potential of magnonics for quantum technology

3.7. Quantum Gases I (specialized)

Content Summary

- Making and probing ultracold quantum gases
- Bose-Einstein condensation
- Properties of Bose-Einstein condensates
- Solitons
- Vortices
- Ultracold Fermi gases
- BEC-BCS crossover

3.8. Cryptography (elective)

Content summary

This course covers methods and implementations of modern cryptography. It includes:

- Symmetric cryptosystems: Stream and block ciphers, Frequency analysis, Modern ciphers;
- Asymmetric cryptosystems: Factorisation problem of large numbers, RSA, Prime number tests, Discrete logarithm, DiffieHellman key exchange, El-Gamal encryption, Hash functions, Signature, Cryptography on elliptic curves (ECC), Attacks on the discrete logarithm problem, Factorisation algorithms (e.g., quadratic sieve, Pollard ρ, Lenstra).

Main learning outcome

- Understand how basic results of algebra and number theory are applied in modern cryptography.
- How these results can be implemented in algorithms.
- Critically evaluate the possibilities and limitations of the algorithms.

3.9. Digital signal processing: algorithms and their implementation (elective)

Content summary

Digital Signal Processing (DSP) is the branch of engineering that has enabled unprecedented levels of interpersonal communication and of on-demand entertainment. By reworking the principles of electronics, telecommunication and computer science into a unifying paradigm, DSP is at the heart of the digital revolution. This course covers:

- State-finite Typical DSP algorithms (signal delay chain with taps, FIR and IIR filters, time domain averaging, exponential smoothing, adaptive filters, digital sine generators, FFT, random numbers, function approximation with polynomials and Newton's method, signal generation with lookup table and interpolation, AlphaMaxBetaMin);
- DSP number formats (integers and real numbers with their number ranges, fixed-point arithmetic, single and double precision, floating-point arithmetic, precision and dynamics, overflow, rounding and truncation characteristics);
- Architecture of typical DSPs (DSP architectures of Analog-Devices, TexasInstruments and Motorola, modified Harvard architecture, CISC-RISC-DSP, instruction pipelining);
- Motorola DSP56300 family (data ALU with register set, word representations, saturation arithmetic, convergent rounding, scaling, addressing modes, interrupt processing, instruction set, development tools);
- DSP systems (external memory, bus timing (mixed speed expansion, data input and output, parallel host port, serial host port, audio interfaces);
- DSP algorithms (DSP suitable implementation of the above mentioned typical DSP algorithms).

Main learning outcomes

- Knowledge of DSP structures (Digital Signal Processors), DSP families.
- In-depth knowledge of typical DSV algorithms.
- In-depth knowledge of the implementation of DSV algorithms, basic techniques in numerical mathematics.

3.10. Functional programming (elective)

Content summary

This course covers the aspects of functional programming, as the process of building software by composing pure functions, avoiding shared state, mutable data, and side-effects. It includes:

- Programming with expressions and values
- Types and polymorphism
- Lists and list-processing functions
- Algebraic data types
- Higher order functions
- Type classes
- Proofs and program synthesis
- Demand evaluation
- Imperative Programming
- Applicative functors and monads

- Extensions of the type and class system
- Generic Programming

Main learning outcomes

- Solve typical tasks in the Haskell programming language.
- Describe the benefits of basic features of Haskell such as value orientation.
- Apply concepts such as recursive data types, higher order functions, polymorphism, and type classes.
- Explain and apply applicative functors and monads for integrating effects.

3.11. Machine Learning I – Foundations (elective)

Content summary

- Introduction and Overview
- Linear classifiers
- Support vector machines
- Optimization Kernel methods
- Deep learning
- Regularization and Overfitting
- Regression
- Clustering
- Dimensionality reduction
- Random forests

Main learning outcome

After successfully completing the module, students will be able to:

- recognize machine-learning problems in their everyday life or work day
- find and implement solutions to ML problems understand the inner workings of ML algorithms
- describe concepts and formalisms of Machine Learning as a generic approach to a variety of disciplines, including image processing, robotics, computational linguistics and software engineering

3.12. Real-Time Systems I (elective)

Content summary

- Real-time (RT) issues and challenges
- types and properties of real-time systems
- RT operating systems
- Scheduling
- worst case execution times
- RT networks
- RT mediaprocessing and streaming
- RT in inhome entertainment networks

Main learning outcomes

Basic understanding of real-time issues and solutions.

4. Semester 3 – Specialization 3: Many-Body Quantum Physics – RPTU

The semester starts with an optional one-month long Orientation Course including **German language courses**. QuanTEEM students are highly encouraged to attend the Orientation Course.

Module name	Professor(s)	Number of ECTS
Advanced Quantum Theory II	W. Hübner, H.C. Schneider	8 ETCS
Advanced Laboratory Course	C. Ziegler, C. Döring	8 ECTS
Research project	Dept. Of Physics	6 ECTS
Processor architecture (elective)	K. Schneider	4 ECTS
Foundations of Software Engineering (elective)	J. Dörr, R. Hinze	4 ECTS
Digital Systems Architecture (elective)	W. Kunz	4 ECTS
Advanced Automata Theory	D. Neider, A.-K. Schmuck	4 ECTS
Operating Systems (elective)	G. Fohler	4 ECTS
System Theory	M. Pandit	4 ECTS

4.1. Advanced quantum theory II

Content summary

This course is a continuation of the advanced quantum theory I course at UBFC (S1). It includes:

- Discrete groups, including application to eigenvalue spectra
- Continuous (Lie) groups, including application to electron spin and other elementary particle properties quantum mechanics of open systems;
- Scattering theory;
- Relativistic quantum mechanics: Klein-Gordon and Dirac equations, nonrelativistic limit;
- Many-body theory of quantum liquids;
- Finite temperatures;
- Elementary quantum field theory: quantisation of the electromagnetic field.

Main learning outcomes

- Knowledge and understanding of the special concepts, methods and approaches of modern quantum mechanics.
- Ability to apply the essential working strategies and paradigms that are specific to quanutm mechanics, in order to recognise and solve typical problems involving quantum particles
- Ability to approach quanutm mechanical problems using state of the art theoretical mehtods.

4.2. Advanced Laboratory Course

Content summary

Complex experiments are performed and analysed, dealing with fundamental phenomena and techniques of modern physics, particularly in the field of quantum optics. A total of two experiments are to be performed successfully.

Main learning outcomes

- Acquaint themselves rapidly with special subjects and techniques.
- Work in a scientific team.
- Set up and operate complex modern measurement apparatus.
- Plan and perform experiments.
- Analyse and critically evaluate experimental results.
- Present scientific results graphically, orally, and in written reports, according to good scientific practice.

4.3. Research Project

Content summary

A guided research project in one of the department's experimental or theoretical research groups is organised individually for each student. An introduction to the ongoing research and the employed methods will be given. The students will be assigned a small research task and will present their results to the group members in a seminar.

Main learning outcomes

- Overview of current research topics and methodology in theoretical and experimental quantum physics.
- Ability to apply fundamental scientific methods, such as induction, model construction, and experimental testing, to solve scientific problems and develop new scientific insights, especially in the context of quantum science and technology.

4.4. Processor Architecture (elective)

Content summary

The course covers the fundamentals of classical and modern processor design:

- Computer arithmetic for parallel instruction execution;
- Generalisation of pipelined processing;
- Processors with dynamic scheduling (superscalarity);
- Processors with static scheduling (VLIW/DSP);
- vector computers and vectorisation of code;
- application specific processors.

Main learning outcomes

- Explain the microarchitecture of current processor architectures.
- Explain the interaction of their components.
- Explain the interaction of processors and compilers.
- Explain the parallelisation of sequential programs at the instruction level, and classify new developments of application-specific processors.

4.5. Foundations of Software Engineering (elective)

Content summary

Fundamental software engineering techniques and methodologies commonly used during software development are covered in this course:

- Principles of software engineering
- Existing empic considerations and laws;
- Basic knowledge (specification, architecture, verification, testing, process modeling, measurement, experimentation);
- Process integration / traceability (UML, Java);
- Component engineering;
- Development of large systems;
- Application engineering;
- Project management.

Main learning outcomes

Students have in-depth knowledge of principles,reference models, techniques, methods and tools for the development of large software systems. The main focus is on "Quality Software Engineering".

4.6. Digital Systems Architecture (elective)

Content summary

This course introduces students to computer architecture and the design of efficient computing and memory systems, covering:

- Data representation: signed and unsigned fixed point numbers, floating point numbers, IEEE 754 standard;
- Computer arithmetic: algorithms, sequential and parallel hardware implementations;
- Instruction set and machine language: instruction set categories, addressing modes, assembler programming;
- Data path and control: hardware implementation of a processor, control unit design, microprogramming, exceptions;
- Instruction-level parallelism: pipelining, superscalar and VLIW processors, dynamic scheduling;
- Memory hierarchy: caches, virtual memory, page tables, TLB.

Main learning outcomes

- Identify and describe a RISC instruction set architecture (ISA) for embedded processors.
- Explain the purpose, working principles and interrelation of the components of an embedded processor core. • Relate features of the ISA to internal structures of the processor hardware.
- Classify and explain principles of instruction level parallelism.
- Explain the working principles, general architecture of a processor's memory hierarchy.
- Devise the general hardware for embedded processors at the block diagram level.

4.7. Operating Systems (elective)

Content summary

This course introduces students to modern operating systems, covering:

- Processes and threads;
- Synchronisation;
- mutual exclusion;
- deadlock;
- scheduling;
- Security;
- Storage and file management;
- Drivers and network

Main learning outcomes

Understand the basic concepts and services of operating systems.

5. Semester 3 – Specialization 4: Platforms for Quantum Technologies – AU

In addition to the courses mentionned below, additional elective courses covering various topics are offered. Students will be guided in their choice of elective courses.

Module name	Professor(s)	Number of ECTS
Engineering of complex quantum systems	J. Arlt, M. Drewsen, G. Bruun	5 ECTS
Methods and platforms of quantum technology	J. Arlt, M. Drewsen	5 ECTS
Physics and Astronomy Student Colloquium	M. Drewsen	5 ECTS
Danish language and Nordic culture	TBD	2 ECTS
Individual Project - Physics C (elective)	Department of Physics and Astronomy	5 ECTS
Advanced Statistical Physics (elective)	A. Imparato	5 ECTS
Surface and semiconductor physics (elective)	J.V. Lauritsen	10 ECTS
Electronics and data acquisition (elective)	H.B. Pedersen	10 ECTS
Atomic, molecular and optical physics II (elective)	L.B. Madsen, P. Balling, L.H. Andersen	10 ECTS
General relativity (elective)	D. Fedorov	5 ECTS
Particle Physics II (elective)	N. Thomas Zinner, S. E. Rasmussen	10 ECTS
Quantum Mechanics II (elective)	T. Pohl, A. Imparato	10 ECTS
Space Missions and Space Technology (elective)	H. Kjeldsen, S. Albrecht	5 ECTS
Advanced MR Methods (elective)	M. S. Vinding, S. Ringgaard, B. Hansen, I. K. Mikkelsen, S. Jespersen, S. F. Eskildsen, E. Hansen, C. Laustsen	5 ECTS
Quantum Information Processing (elective)	I. B. Damgård, S. Srinivasan	10 ECTS
Photonic Devices (elective)	N. Volet	10 ECTS

5.1. Engineering of complex quantum systems

Content summary

Techniques to trap and cool atoms in order to study and use their quantum mechanical properties are described. We focus both on techniques used for ions and for neutral atomic gases. Various quantum optical experiments with single or few ions will be analysed including quantum jumps and sub-/super-radiation, as well as quantum logical units, which can be used for quantum computers. We will discuss Coulomb crystals formed by collections of ions at low temperatures. Scattering theory for cold atoms in neutral quantum gases will be discussed. We will then analyse Bose-Einstein condensation within a mean-field description, and we derive the so-called Gross-Pitaevskii equation. The experimental realisation of this equation is explained and we discuss the elementary excitations of the condensate using Bogoliubov theory.

Main learning outcomes

- Describe the techniques to trap and cool neutral atoms and ions.
- Explain the properties of small and large ion Coulomb crystals.
- Discuss quantum optical experiments with atomic and molecular ions.
- Analyse quantum optical experiments with large Coulomb crystals.
- Describe the low energy interaction between cold atoms.
- Analyse the mean-field theory for Bose-Einstein condensation.
- Describe the experimental realisation of Bose-Einstein condensation.
- Discuss new experiments with Bose-Einstein condensates and optical lattices.

5.2. Methods and platforms of quantum technology

Content summary

This course will discuss a broad scope of current and emerging technological approaches to quantum technology. This will include the different atomic, solid state and photonic platforms for quantum communication, quantum computing, quantum metrology and quantum simulation. The course will have particular focus on techniques beyond the immediate scope of university research. It will include presentations by internationally known scientists and industry leaders.

Main learning outcomes

- Describe the available platforms in quantum technology.
- Apply the methods from advanced quantum mechanics to investigate the strengths of quantum technology.
- Discuss the advantage of the platforms for different purposes in quantum technology.
- Address the validity of experimental approaches in the fields of quantum technology.
- Discuss the components necessary for a future quantum computing infrastructure.

5.3. Physics and Astronomy Student Colloquium

Content summary

The course starts with a 45 min introduction where the purpose of the course is presented, and lectures on how to give a good presentation are given. At the same time, the schedule for the students' own colloquia is agreed upon.

Each student chooses a subject from physics or astronomy, for example inspired by a recent scientific paper published in a major journal. A supervisor is chosen to help the student with the scientific content of the colloquium. The student then acquaints herself with relevant literature and prepares a 45 min talk on the subject, based on a power point presentation. The talk addresses an audience which has passed the second year of the bachelor study in physics. The student prepares an abstract to announce her colloquium. Approximately one week before the colloquium, the student gives a test colloquium to the supervisor and the person responsible for this course. The student gives her/his presentation to the audience, and answers any questions. The student participates in five other student colloquia during the same semester.

Main learning outcomes

- Learn how to master a given research topic based on the relevant literature
- Learn how to give a good presentation of a highly technical research topic to a non-specialist audience
- Learn to set up an attractive set of slides for the presentation

5.4. Danish language and Nordic culture

Content summary

The Danish course is intended to introduce students to a basic understanding of the Danish language and Nordic cultures. If necessary different levels of Danish will be offered. For native Danish speakers, an alternative language course (such as scientific English) will be offered. Discussions on political issues in the Nordic countries will be included to create awareness of the cultural background. Cultural excursions and activities will be offered.

Main learning outcomes

- Allow for basic understanding of Danish written language
- Knowledge of Nordic cultures

5.5. Individual Project - Physics C (elective)

Content summary

Depends on the particular project.

Main learning outcomes

The purpose of the project is to enable the student to study special topics in experimental or theoretical physics. The topics are chosen in cooperation with a project supervisor, and the project is described by a short title. Through the work on the project the student will be given an understanding of the techiques, results and concepts of the chosen topic.

At the end of the project, and within its topics, the student should be able to:

- formulate problems within a limited subtopic
- analyse the problems
- work on the problems
- convey the results found.

5.6. Advanced Statistical Physics (elective)

Content summary

Review of equilibrium thermodynamics: first law and equilibrium, second law, thermal equilibrium and temperature, phase transitions.

Review of the principles of statistical mechanics: microcanonical ensemble, canonical ensemble, grand canonical ensemble. Maximum entropy principle.

Phase transitions: Ising model, lattice gas, broken symmetry and range of correlations, Ising model in one dimension, mean field theory, Landau theory of phase transitions, critical exponents, scaling, renormalization group theory, Ising model in two dimensions.

Statistical mechanics of non-equilibrium systems: systems close to equilibrium, Onsager's regression hypothesis and time correlation functions, fluctuation-dissipation theorem, response function, Brownian motion, Langevin Equation, Fokker-Planck equation, master equation and detailed balance, systems far from equilibrium, the concepts of work and heat revisited, the fluctuation theorems.

Main learning outcomes

Advanced Statistical Physics is a senior graduate/graduate course requiring the introductory course in statistical physics. The aim of the course, is to give the student an introduction and an understanding of essential methods and points of view, which together with a knowledge of the phenomena leads to an understanding of statistical physics.

In the course of her/his studies the student will encounter examples in fundamental research where statistical physics plays an essential role. By working with theoretical models the student will learn, how to construct and use physical models as a mean for the qualitative and quantitative explanation and understanding of various phenomena and processes. The student will work with texts and reflect on the content and argumentation with the purpose of putting statistical physics into perspective. After completion of the course, the students are expected to be able to:

- define and discuss the basic concepts and physics of statistical mechanics.
- apply statistical physics to predict the mechanical and dynamical properties and to explain phase behavior of physical systems.
- use simple physical models to illustrate the fundamental ideas of thermodynamics and statistical mechanics.

- reflect on the universal behaviour of different systems in the field of statistical physics communicate a topic in statistical physics and put the scientific issues into perspective.
- analyze and reason about scientific literature in the field.

5.7. Surface and semiconductor physics (elective)

Content summary

The course covers the physics of surfaces, low-dimensional systems and semiconductors. It is designed to provide the student with a fundamental understanding of surface applications and important solid-state nanotechnologies together with a detailed account of semiconductor properties and how these are exploited in selected micro- and nano-electronic components.

Main learning outcomes

- Explain the fundamental structural and electronic features pertaining to surfaces and relate these to systems composed of interfaces and nanostructures.
- Account for the basic fundamental chemical concepts of bonding to surfaces based on experimental observations and theoretical modelling
- Explain typical models for nucleation and growth on surfaces and build on this insight to account for selfassembly phenomena on surfaces.
- Establish the physics behind common surface analysis techniques, demonstrate the working principles of the instrumentation in surface science experiments, and account for the structure of experimental data extracted from typical experiments discussed in the lectures.
- Analyse and conclude from data from surface characterisation tools and compare how complementary information obtained from spectroscopy, microscopy and diffraction techniques are used to solve surface structures.
- Derive the physics of semiconductors in equilibrium statistics.
- Derive the non-equilibrium dynamics and transport properties of charge carriers in semiconductors.
- Analyse the electrical properties of selected semiconductor devices, such as a metal-oxidesemiconductor field-effect transistor (MOSFET) and a solar cell.

5.8. Electronics and data acquisition (elective)

Content summary

The course gives an advanced description to experimental work on electronics and data acquisition. General skills within circuit design and analysis as well as instrument communication via the LabVIEW software are acquired through specific practical exercises. Additionally, the course includes two time periods where the students apply the acquired skills to conduct independently formulated projects.

Main learning outcomes

- Describe simple analog and digital circuits.
- Analyse and do calculations on electrical circuits.
- Evaluate and select components for a specific circuit.
- Design and communicate electronic diagrams.

- Build up and test circuits.
- Apply generators, oscilloscopes, and multi-meters to investigate circuits.
- Describe different types of communication with external devices, including Serial, GPIB, and Ethernet.
- Compare and discuss choices of communication methods in actual examples.
- Build Labview Instrument drivers for communication with specific instruments.
- Apply LabVIEW to solve complete problems within control and data acquisition.

5.9. Atomic, molecular and optical physics II (elective)

Content summary

The course elaborates on atomic and molecular structure and dynamics. For molecules, group theory is introduced as an efficient tool to provide symmetry orbitals and selection rules for electronic transitions. The discussion of atomic structure focusses on electron-electron correlation effects, including autoionisation. The interaction of manyelectron atoms with electromagnetic radiation, including laser spectroscopy, coherent processes and ultrafast dynamics is described. Furthermore, we study the dynamics of atoms and small molecules and examine the basic scattering theory, also in a time-dependent formulation.

Main learning outcomes

- Make and use a wide range of models as a qualitative and quantitative explanation of pheno-mena in atomic, molecular and optical (AMO) physics.
- Describe selected experimental approaches to AMO physics.
- Discuss the application range of the models.
- Identify the most important elements in articles or books on AMO physics.
- Assess the validity of the reasoning in articles or books on AMO physics.

5.10. General relativity (elective)

Content summary

- Short reiteration of classical field theory and special relativity;
- Equivalence principle and elementary Riemann-geometry;
- Einstein's equation;
- Experimental tests: bending of light, gravitational red shift, perihelion precession;
- Newtonian limit, gravitational waves;
- Schwarzchild metric, black holes;
- Relativistic cosmology (Friedman-Lemaitre metric).

Main learning outcomes

The course gives an introduction to the General theory of relativity. After finishing the course, the students are expected to be able to:

- Reproduce the basic elements and results of general relativity;
- Analyse simple relativistic problems using the correct relativistic terminology and symbolic language:

- Apply the basic methods of general relativity to solve simple relativistic problems;
- Explain the basic relativistic phenomena and consequences.

5.11. Particle Physics II (elective)

Content summary

- Classical and quantum field theories.
- Fermions, bosons, and interactions.
- Symmetries and conservation laws.
- Local gauge theories.
- Spontaneous symmetry breaking and the Higgs mechanism.
- Electroweak theory and the standard model of particle physics.
- Physics beyond the standard model.

Main learning outcomes

This course continues the particle physics started in the introductory course "Nuclear/Particle Physics". The course also introduces the techniques of quantum field theory and how to apply it to physical systems with focus on those of relevance for particle physics.

The aim is to give the student a phenomenological understanding of quantum field theory and the standard model of particle physics, which is the most fundamental theory of matter and interactions we know today, as well as quantitative methods for calculating cross-sections and decay rates.

When the course is finished, the participant is expected to be able to:

- Formulate and describe models for quantitative and qualitative description of phenomena in Particle Physics including Feynman diagrams using the technical tools of quantum field theory.
- Apply methods for calculating processes in particle physics.
- Formulate and describe local gauge theories and spontaneous symmetry breaking.
- Structure and relate phenomena related to the weak interaction including symmetry properties and the Higgs mechanism.
- Formulate problems in quantum field theory in the context of particle physics and the standard model and discuss existing proposals for the solution of these problems.

5.12. Quantum Mechanics II (elective)

Content summary

The main topics are:

- Time-dependent quantum mechanics.
- Angular momentum and spin.
- Symmetries.
- Dirac equation.
- Scattering Theory.
- Quantum theory of electromagnetic radiation.

Main learning outcomes

The aim of the course is to further develop the methods and concepts presented in the introductory course in quantum mechanics. The course gives the students familiarity with the essential methods in quantum mechanics and a deeper understanding of quantum physics.

At the end of the course the students are expected to be able to:

- Reproduce the fundamental results of advanced quantum mechanics;
- Analyse advanced quantum mechanical problems using the correct quantum terminology and symbolic language;
- Apply the fundamental methods and results of advanced quantum mechanics to solve quantum mechanical problems;
- Explain the fundamental quantum mechanical phenomena and consequences.

5.13. Space Missions and Space Technology (elective)

Content summary

The course will provide an introduction to spacecrafts, space systems, and payloads. We will establish the background to understand Celestial Mechanics, Mission Analysis, and the space environment. In addition, the course will give an overview over satellite communications, telemetry and data handling. We will discuss Spacecraft System Engineering with focus on Small Satellite Engineering and Applications. Finally we will give an overview about scientific techniques that can be applied to Earth and Space observations (e.g. Earth remote sensing, Solar System in situ research, astronomical observations).

The practical part of the course will consist of designing a space mission and presenting it.

Main learning outcomes

The aim of the course is to analyse, describe and explainlearn the basic concepts of space missions and space technology. The delphini-1 space mission will be used as a practical example throughout the course.

When the course is finished the student is expected to be able to:

- Discuss and understand the background and content of the theoretical and practical parts of space missions and space communication.
- Discuss Celestial Mechanics and Mission Analysis
- Discuss and model the space environment (e.g. microgravity radiation, temperature, …).
- Discuss satellite communications.
- Discuss different techniques for Earth Observations (remote sensing) and astronomy and perform simple data analyses.
- Search for relevant scientific literature.
- Design a space mission (e.g. with the aim of doing remote sensing, astronomy, monitoring signals of airplanes, etc…).
- Collaborate in smaller groups with the aim of producing a scientific analysis.
- Present the results as a small talk at a final workshop day.

5.14. Advanced MR Methods (elective)

Content summary

Hyperpolarization, spectroscopy, flow and angiography, cardiac MR, perfusion, diffusion, high-field MR, sequence programming, digital image processing and more.

Main learning outcomes

The course will enhance the participants' knowledge on various advanced methods of magnetic resonance. This includes hyperpolarization, spectroscopy, flow and angiography, cardiac MR, perfusion, diffusion, high-field MR, sequence programming, digital image processing and more.

After the course the students should be able to:

- Understand and explain principles of the included methods.
- Understand and explain application of the methods for clinical and research use.

5.15. Quantum Information Processing (elective)

Content summary

The idea of quantum computing arose in part from the difficulty of simulating quantum systems on a standard computer. In the 1980s, some physicists suggested using the quantum system itself as a computational device! The system could clearly simulate itself, but what else could it do? This led to theoretical definitions of a quantum computer.

In the 1990s, many interesting algorithmic applications of quantum computers were found. In particular, Peter Shor found an efficient quantum algorithm for factoring large numbers (opening up the potential for quantum computers to break current-day cryptosystems) and Lov Grover found a quantum algorithm to speed up unstructured search. At the same time, applications of quantum computing that helped in cryptography were also discovered.

In recent years, these theoretical models of quantum computing devices are getting closer to reality, as companies spend vast amounts of resources on building quantum computers.

This course will introduce basic concepts in quantum information, models of quantum computation, cover the above quantum algorithms, and show how quantum communication can be used to design unconditionally secure protocols for key exchange, something that is impossible with classical communication.

Main learning outcomes

The aim of this course is to understand the basic concepts of quantum information, quantum algorithms and applications to quantum cryptography.

At the end of the course, the student should be able to:

- Define quantum states (pure and mixed) and calculate the effects of quantum computational operations applied to these states.
- Define quantum circuits and compute the effects of a quantum circuit on a given quantum state.

- Reproduce the statements and analyses of basic quantum algorithms and protocols.
- Apply the basic techniques introduced in the course to analyze the correctness of a given quantum algorithm/protocol.
- Analyze the time-complexity of a given quantum algorithm and prove upper and lower bounds on the query complexity of black-box quantum algorithms.
- Design quantum algorithms for variations of the computational problems seen in the course.
- Explain definition and proof of security for quantum key exchange protocols.

5.16. Photonic Devices (elective)

Content summary

The course will first introduce the fundamentals of light-matter interaction in semiconductors, focusing on effects like optical gain and absorption, light emission and optical waveguiding. The main electro-optic components, such as LEDs, laser diodes, modulators and detectors will be discussed. Finally it will be shown how these components can be combined into a photonic integrated circuit, also known as an optical chip. The main integration platforms, for example silicon nanophotonics and indium phosphide photonics, and their fabrication technology will be discussed. Applications of photonic devices and circuits in communications, microwave technology, and biomedical sensing and imaging will be reviewed.

Main learning outcomes

The objective of the course is to acquaint the student with the main photonic devices, their integration onto a photonic integrated circuit and the applications of this technology. This will be achieved by first introducing some fundamentals of light-matter interaction. Then an overview of the most important photonic devices will be presented. It will be discussed how these photonic devices can be considered as building blocks that can be combined into a circuit and which material systems can be used for that. Emphasis will be put on the required trade-offs and the main differences between material systems.

After this course the student should be familiar with the main photonic devices and the main platforms for photonic integration that are available. The student should be able to make a design study, with a qualitative understanding of the required trade-offs and a quantitative knowledge of the typical component and/or circuit operation parameters.

The participants must at the end of the course be able to:

- explain the physics behind the selected photonic devices;
- model a selected device and/or circuit in a design study;
- explain how a photonic integrated circuit can be made and in which materials;
- know which building blocks are available in each platform and know typical operating parameters;
- discuss the trade-offs that have to be made when choosing a platform and designing a circuit.