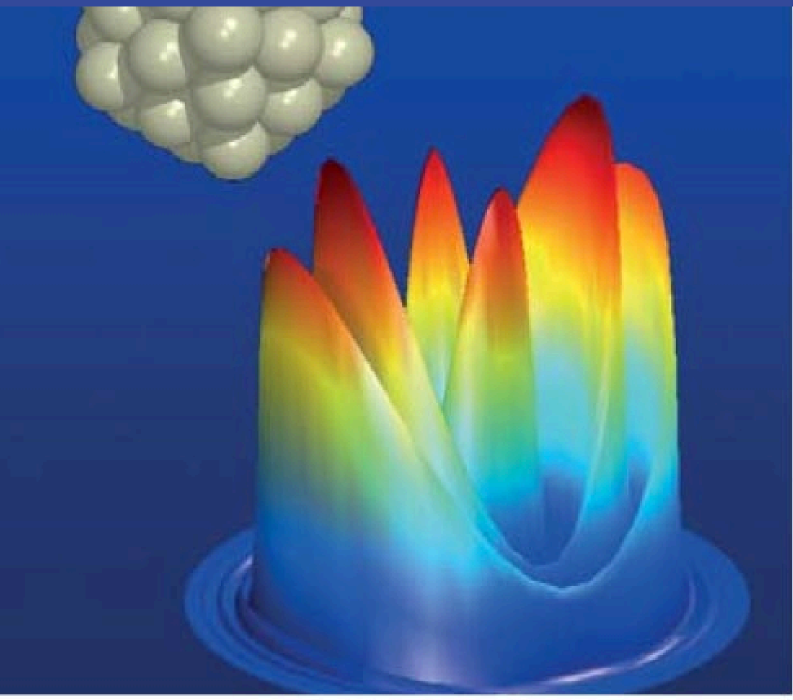
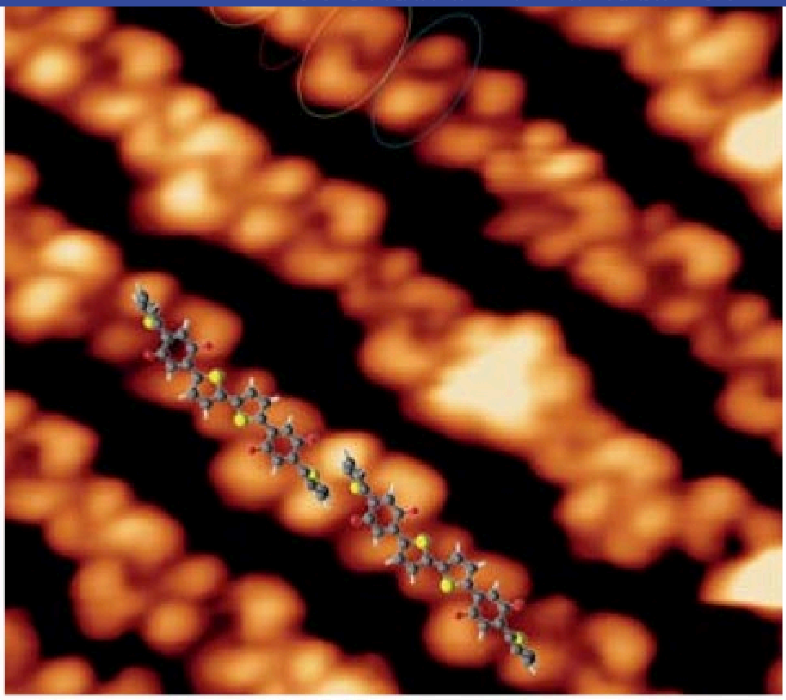
universität freiburg

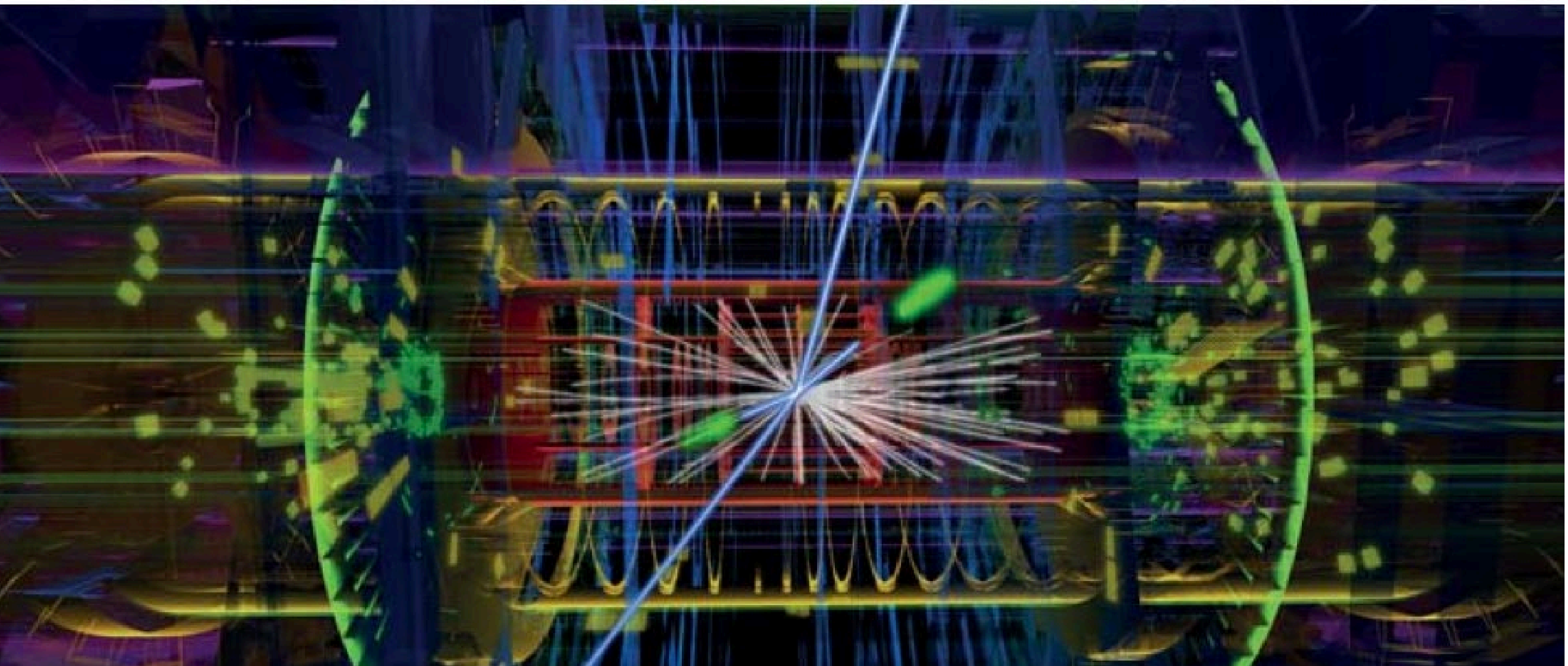
Handbook of Modules

Master-of-Science (M.Sc.) Physics

Physikalisches Institut
Fakultät für Mathematik und Physik
Albert-Ludwigs-Universität Freiburg







Fach / *Subject*	Physik / *Physics*
Abschluss / *Degree*	Master of Science (M.Sc.)
Prüfungsordnung / *Examination regulations*	PO 2015, PO 2020
Art des Studiengangs / *Type of degree*	konsekutiv / *consecutive*
Studienform / *Study form*	Vollzeitstudium / *full time study*
Studiendauer / *Duration of study*	4 Semester (Regelstudienzeit) / *4 semester (regular duration of study)*
Unterrichtssprache / *Language of instruction*	englisch / *English*
Studienbeginn / *Start of studies*	Winter- oder Sommersemester / *winter or summer semester*
Hochschule / *University*	Albert-Ludwigs-Universität Freiburg
Fakultät / *Faculty*	Fakultät für Mathematik und Physik / *Faculty for Mathematics and Physics*
Institut / *Institute*	Physikalisches Institut / *Institute of Physics*
Internetseite / *Website*	www.physik.uni-freiburg.de
Profil des Studiengangs / *Profile of the study program*	*The English-taught M.Sc. Physics aims to continue and broaden studies begun at the bachelor level.* *In the first year of their studies, participants consolidate their knowledge in advanced theoretical and experimental physics covering state-of-the-art topics in the institute's core research areas Atomic, Molecular and Optical Sciences, Condensed Matter and Applied Physics, and Particles, Fields and Cosmos. Advanced Quantum Mechanics and the Master Laboratory are mandatory modules. Advanced physics courses can be selected from a range of state-of-the-art topics in the main research areas of the department. During their final one-year Master thesis, students specialize in a particular field by participating in a cutting-edge research project at the Institute of Physics or one of the associated research centers.* *The Master's program offers the possibility for an optional specialization in a particular area of physics, such as Particle Physics, or Atomic, Molecular and Optical Physics, if the students choose their courses accordingly*
Ausbildungsziele / Qualifikationsziele des Studiengangs *Qualification goals of the study program*	Fachliche Qualifikationsziele / Professional *qualification goals*: ▪ *Consolidation of advanced knowledge in physics* ▪ *In-depth knowledge acquired in at least one specialist area of physics as defined by the master thesis topic and/or an optional specialization* ▪ *Ability to apply modern methods, techniques and concepts in physics as well as to implement them efficiently* ▪ *Ability to develop and pursue a self-contained scientific project with adequate methods and to conduct independent research in a specialized field of physics* ▪ *Experience with working processes in joint research projects at research institutions or at large-scale research facilities* ▪ *Capability to communicate scientific results in written reports and in presentations to an academic audience*

	Überfachliche Qualifikationsziele / *General qualification goals*: ■ *Ability to pursue independent, responsible and creative scientific work* ■ *Ability to organize, carry out and manage complex projects* ■ *Preparation to take on management responsibility and to supervise, lead and guide others* ■ *Ability to operate in a professional environment* ■ *Acquisition of abstraction skills, system-analytical thinking, teamwork and communication skills* ■ *International and intercultural experience* ■ *Social responsibility*
Zulassungs-voraussetzungen *Admission requirements*	Qualifizierter Bachelor-Abschluss in Physik oder einem gleichwertigen Studiengang. Außerdem / *Qualifying bachelor's degree in physics or an equivalent degree course. In addition* ■ mindestens 32 ECTS-Punkte in Theoretischer Physik, ■ mindestens 32 ECTS-Punkte in Experimenteller Physik, ■ mindestens 24 ECTS-Punkte in Mathematik, ■ mindestens 18 ECTS-Punkte aus physikalischen Praktika, ■ Bachelor-Arbeit in Physik (10 ECTS-Punkte), ■ Niveau B2 in Englisch.

Preliminary notes:

The handbook of modules does not substitute the course catalogue, which is updated every semester to provide variable information about the courses (e.g. time and location).

List of Abbreviations

M.Sc.	Master of Science
Credit hrs	A credit hour corresponds to a course of a duration of 45 minutes per week (in German: Semesterwochenstunden, SWS)
SL	Assessed coursework („Studienleistung“), ungraded, does not contribute to final grade
PL	Exam („Prüfungsleistung“), graded, contributes to final grade
L	Lecture
E	Exercise/Tutorials
S	Seminar
Lab	Laboratory
SoSe	Summer semester (summer term)
WiSe	Winter semester (winter term)
ECTS	Credit Points based on the European Credit Transfer System (ECTS-Points)

Table of Contents

1. Master-of-Science (M.Sc.) in Physics

1.1. Programme Structure

The Institute of Physics offers a research-oriented curriculum leading to a Master-of-Science degree in Physics. The program comprises a total of 120 ECTS credit points, which are collected in various compulsory and elective modules as defined by the study regulations.

Module	Type	Contact hours	ECTS	Compulsory/ Elective	Recommended semester	Assessment
Advanced Quantum Mechanics	L+E	4+3	10	C	1 or 2	SL: exercises PL: written exam
Advanced Physics 1	L+E	4+2	9	E	1 or 2	SL: exercises PL: written or oral exam
Advanced Physics 2	L+E	4+2	9	E	1 or 2	SL: exercises PL: written or oral exam
Advanced Physics 3	L+E	4+2	9	E	1 or 2	SL: exercises SL: written or oral exam
Elective Subjects	L+E	variable	9	E	1 or 2	SL: exercises and written or oral exam
Term Paper	S	2	6	E	1 or 2	PL: presentation and written report
Master Laboratory	Lab	10	8	C	1 or 2	PL: oral exam, practical achievement, written report, presentation
Research Traineeship	-	-	30	C	3	SL: internship
Master Thesis	-	-	28 2	C	4	PL: thesis SL: presentation

Abbreviations in table:
Type = type of course; L = lecture; E = exercises; S = seminar; Lab = laboratory;
C = compulsory module; E = elective module;
SL = assessed coursework (´Studienleistung´); PL = exam (‘Prüfungsleistung’)

1.2. Forms of Assessment (Prüfungsleistung PL, Studienleistung SL)

A module is successfully passed, when all corresponding assessments have been successfully accomplished. Modules consist of the following forms of assessments:

Prüfungsleistungen (PL) are written or oral module exams, which test all components of a module. PLs are marked (graded) and contribute to the final mark of the degree as listed in 1.5.

Studienleistungen (SL) are individual achievements, which are accomplished in combination with a corresponding course or lecture. Passing a SL may require solving regular assignments, the regular and successful participation in exercise classes and/or passing a final written or oral exam. SLs are not marked (non-graded) and therefore do not contribute to the final mark.

Successful participation in exercise classes requires at least 50-60% of the points awarded for working on the exercise sheets and 1-2 times presenting solutions in the weekly tutorial. **Regular participation** in the exercises is defined in the examination regulations and requires that no more than 15% of the exercise hours are missed.

1.3. Workload / ECTS-Point System

The *European Credit Transfer and Accumulation System (ECTS)* is a standard for comparing the study attainment and performance of students of higher education across the European Union and other collaborating European countries. It provides more compatibility and mobility between the programmes at different institutions and different countries.

The ECTS credit points (CP), which can be acquired, determine the time requirements for a module with one CP corresponding to a workload of about 30 hours. This workload includes participation in courses, preparation and post-processing of the courses, exercises and exams. The ECTS-System enables the accumulation of credits and marks throughout the entire studies and facilitates documenting the study progress.

1.4. Contents of Modules

Advanced Quantum Mechanics (10 ECTS credit points)

All students have to accomplish the compulsory module Advanced Quantum Mechanics. The module mark is the mark of the final exam (PL).

Advanced Physics 1 (9 ECTS credit points)

Within the module Advanced Physics 1 students may select a lecture on Advanced Experimental or Advanced Theoretical Physics. Eligible lectures are listed in section 4 and in the course catalogue for the current semester. The module mark is the mark of the final exam (PL).

Advanced Physics 2 (9 ECTS credit points)

Within the module Advanced Physics 2 students may select a lecture on Advanced Experimental or Advanced Theoretical Physics. Eligible lectures are listed in section 4 and in the course catalogue for the current semester. The module mark is the mark of the final exam (PL).

Advanced Physics 3 (9 ECTS credit points)

Within the module Advanced Physics 1 students may select a lecture on Advanced Experimental or Advanced Theoretical Physics. Eligible lectures are listed in section 4 and in the course catalogue for the current semester. If both lectures in Advanced Physics 1 and 2 are from the same field (Experimental/Theoretical Physics) a lecture from the other field has to be selected. The module is an unmarked course achievement (SL).

Elective Subjects (9 ECTS credit points)

All 9 ECTS credits of this module can be acquired by selecting different courses by own choice. The selected courses have to be at the Master's level, i.e. from the M.Sc. programme in Applied Physics and/or other Master programmes. The examination committee may permit other courses on request. Note that for courses at other faculties different application modalities and requirements may apply. Students are responsible to prove successful participation, so that the examination office of physics can transfer the credits.

Term Paper (6 ECTS credit points)

Within the elective module Term Paper students select a seminar on a specific topic, with several seminars offered each term.

Master Laboratory (8 ECTS credit points)

In the Master Laboratory students accomplish different lab experiments with the total workload of 8 ECTS credit points. Successful completion of the Master Laboratory is prerequisite for beginning the Research Traineeship.

Research Traineeship (30 ECTS credit points)

Before working on their Master Thesis students engage in a Research Traineeship, which is accomplished in a six-month period. The aim of this module is to acquire preliminary knowledge in a certain research topic in preparation for the Master Thesis. For their traineeship and thesis students select a supervisor at the

Institute of Physics or the associated research institutes. Admission to the Master Research module requires successful accomplishment of the module *Master Laboratory* and three of the four marked courses in the modules *Advanced Quantum Mechanics, Advanced Physics 1, 2,* and *Term Paper*.

Master Thesis (30 ECTS credit points)

In the final six-months master thesis students perform independent research on a specialized topic in applied physics and prepare a written thesis. Typically, the Master Thesis is accomplished at the same research group as the traineeship. In a period of 2 weeks before to 4 weeks after submitting the Master Thesis, the students present the results of their thesis work in a public presentation.

1.5. Final mark / grade

The individual module marks contribute to the final grade with the following weights:

Module	weight
Advanced Quantum Mechanics	11 %
Advanced Physics 1	11 %
Advanced Physics 2	11 %
Term Paper	7 %
Master Laboratory	10 %
Master Thesis	50 %

2. Organisation of studies

2.1. Study plan

In the first year, the master students consolidate their knowledge in compulsory and elective courses. For the first and second semester, an equally balanced workload is recommended with a total of about 30 ECTS credit points each.

The following study plan is recommended for students starting their studies in the winter semester and and may differ depending on the lectures offered and the student's particular choice.

<table>
<tr><th>FS</th><th colspan="5">Module</th><th>∑ ECTS</th></tr>
<tr><td rowspan="1">1</td><td>Advanced Quantum Mechanics
10 ECTS</td><td>Advanced Physics 1
9 ECTS</td><td></td><td>Term Paper
6 ECTS</td><td>Master Laboratory
8 ECTS</td><td>33</td></tr>
<tr><td rowspan="2">2</td><td rowspan="2"></td><td>Advanced Physics 2
9 ECTS</td><td rowspan="2">Elective Subjects
Advanced Physics and/or other discipline by own choice
9 ECTS</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2">27</td></tr>
<tr><td>Advanced Physics 3
9 ECTS</td></tr>
<tr><td>3</td><td colspan="5">Research Traineeship
30 ECTS</td><td>30</td></tr>
<tr><td>4</td><td colspan="5">Master Thesis (Thesis and Presentation)
30 ECTS</td><td>30</td></tr>
</table>

Note that, *Advanced Quantum Mechanics* is only offered in the winter term, so depending on the start of the Master studies (start in winter or summer semester) the course can be taken either in the first or second semester. The *Master Laboratory* is offered as a block course during the semester break following the winter term. Depending on the start of studies, students participate either in their first or second semester.

2.2. Optional Specialization

Within their Master studies, students can select their courses in order to obtain a certain specialization. Note that obtaining a specialization is optional and not required. Currently the following specializations are offered:

2.2.1. Specialization in “Atomic, Molecular and Optical Physics”

Within their Master studies, students can specialize in ***Atomic, Molecular and Optical Physics*** by choosing their courses in the modules Advanced Physics 1-3 accordingly. Students who choose this specialization also need to complete their research phase (Research Traineeship and Master Thesis) in this field. If all requirements are met the specialization will be certified on the final transcript of records.

The following study plan lists the choice of courses required for the specialization:

<table>
<tr><th>FS</th><th colspan="5">Module</th></tr>
<tr><td>1</td><td>Advanced Quantum Mechanics
10 ECTS</td><td>Advanced Physics 1*
Advanced Atomic and Molecular Physics (Exp WiSe)
9 ECTS</td><td></td><td>Term Paper
6 ECTS</td><td>Master Laboratory
8 ECTS</td></tr>
<tr><td rowspan="2">2</td><td rowspan="2"></td><td>Advanced Physics 2
9 ECTS</td><td rowspan="2">Elective Subjects
Advanced Physics and/or other discipline by own choice
9 ECTS</td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>Advanced Physics 3
9 ECTS</td></tr>
<tr><td>3</td><td colspan="5">Research Traineeship in Atomic, Molecular and Optical Physics*
30 ECTS</td></tr>
<tr><td>4</td><td colspan="5">Master Thesis in Atomic, Molecular and Optical Physics* (Thesis and Presentation)
30 ECTS</td></tr>
</table>

* These components are mandatory

The course Advanced Atomic and Molecular Physics (Exp, WiSe) is mandatory in Advanced Physics 1. The following courses can be selected in the modules Advanced Physics 2 and 3:

Experimental Physics

- Advanced Optics and Lasers (Exp, SoSe)
- Quantum Hardware (Exp, SoSe)

Theoretical Physics

- Classical Complex Systems (Theo, WiSe)
- Quantum Optics (Theo, WiSe)
- Complex Quantum Systems (Theo, SoSe)
- Theoretical Condensed Matter Physics (Theo, SoSe)
- Quantum Information Theory (Theo, SoSe)

Note, that at least one lectures selected in Advanced Physics 2 and 3 must be from Theoretical Physics.

2.2.2. Specialization in "Condensed Matter Physics"

Within their Master studies, students can specialize in ***Condensed Matter Physics*** by choosing their courses in the modules Advanced Physics 1-3 accordingly. Students who choose this specialization also need to complete their research phase (Research Traineeship and Master Thesis) in this field. If all requirements are met the specialization will be certified on the final transcript of records.

The following study plan lists the choice of courses required for the specialization:

FS	Module				
1	**Advanced Quantum Mechanics** 10 ECTS	**Advanced Physics 1** 9 ECTS **Advanced Physics 2** 9 ECTS **Advanced Physics 3** 9 ECTS (not all three lectures from only Exp or Theo)		**Term Paper** 6 ECTS	**Master Laboratory** 8 ECTS
2			**Elective Subjects** Advanced Physics and/or other discipline by own choice 9 ECTS		
3	**Research Traineeship in Condensed Matter Physics*** 30 ECTS				
4	**Master Thesis in Condensed Matter Physics*** (Thesis and Presentation) 30 ECTS				

* These components are mandatory

The following courses can be selected in the modules Advanced Physics 1-3:

Experimental Physics

- Condensed Matter Physics I: Solid State Physics (Exp, WiSe)
- Condensed Matter Physics II: Interfaces and Nanostructures (Exp, SoSe)

Theoretical Physics

- Theoretical Condensed Matter Physics (Theo, SoSe)
- Classical Complex Systems (Theo, WiSe)
- Computational Physics: Materials Science (Theo, SoSe)

Note, that not all three lectures can be selected from only one of the above lists (Experimental or Theoretical Physics).

2.2.3. Specialization in “Particle Physics”

Within their Master studies, students can specialize in ***Particle Physics*** by choosing their courses in the modules Advanced Physics 1-3 accordingly. Students who choose this specialization also need to complete their research phase (Research Traineeship and Master Thesis) in this field. If all requirements are met the specialization will be certified on the final transcript of records.

The following study plan lists the choice of courses required for the specialization:

<table>
<tr><th>FS</th><th colspan="5">Module</th></tr>
<tr><td>1</td><td>Advanced Quantum Mechanics
10 ECTS</td><td rowspan="2">Advanced Physics 1
9 ECTS
Advanced Physics 2
9 ECTS
Advanced Physics 3
9 ECTS
(not all three lectures from only Exp or Theo)</td><td></td><td>Term Paper
6 ECTS</td><td>Master Laboratory
8 ECTS</td></tr>
<tr><td>2</td><td></td><td>Elective Subjects
Advanced Physics and/or other discipline by own choice
9 ECTS</td><td></td><td></td></tr>
<tr><td>3</td><td colspan="5">Research Traineeship in Particle Physics*
30 ECTS</td></tr>
<tr><td>4</td><td colspan="5">Master Thesis in Particle Physics* (Thesis and Presentation)
30 ECTS</td></tr>
</table>

* These components are mandatory

The following courses can be selected in the modules Advanced Physics 1-3:

Experimental Physics

- Advanced Particle Physics (Exp, WiSe)
- Particle Detectors (Exp, WiSe)
- Hadron Collider Physics (Exp, SoSe)
- Astroparticle Physics (Exp, SoSe)

Theoretical Physics

- Quantum Field Theory (Theo, SoSe)
- Gauge Theories of Fundamental Interactions (Theo, WiSe)
- General Relativity (Theo, irregular)

Note, that not all three lectures can be selected from only one of the above lists (Experimental or Theoretical Physics).

2.3. Enrolment for lectures and courses

For participation in lectures, a registration is recommended, which is possible via the electronic campus management system HISinOne https://campus.uni-freiburg.de/. In order to take part in the final exam a separate registration is required (see below).

For participation in the master laboratory students have to register via the central learning platform ILIAS https://ilias.uni-freiburg.de. Details see on: https://www.physik.uni-freiburg.de/studium/labore

2.4. Registration for exams (SL or PL)

In order to finish a module all exercises and exams contained in the module (Studienleistungen SL and Prüfungsleistungen PL) have to be passed. For participating in the exams, a registration via the electronic campus management system HISinOne https://campus.uni-freiburg.de/ is necessary.

The common registration period typically starts with the beginning of the semester end ends one week before the first exam. Within this period registration to and deregistration from an exam is possible. Details on the registration period for each semester and other modalities can be found on the webpage of the examination office www.physik.uni-freiburg.de/studium/pruefungen.

2.5. Resitting exams

Failed examinations may be repeated twice in the modules *Advanced Quantum Mechanics* and *Advanced Physics 1* and *2*, and once in the modules *Term Paper, Master Laboratory*, and *Master Thesis*. It is not possible to resit passed examinations to improve the marks.

3. List of Modules and Description

3.1. Advanced Quantum Mechanics (10 ECTS)

Module 07LE33M-AQM	**Advanced Quantum Mechanics** **10 ECTS**
Responsibility	Dean of Studies, Lecturers for Theoretical Physics
Courses	

	Type	**Credit hrs**	**ECTS**	**Assessment**	**Term**
Advanced Quantum Mechanics	L	4	10	PL: written exam	WiSe
Advanced Quantum Mechanics	E	3		SL: exercises	WiSe
Total:		**4+3**	**10**		

Required academic assessment	The final module exam (PL) is a written exam (duration: 60-180 minutes). The course achievement (SL) is the regular and successful participation in the exercises.
Grading	The grade of the final exam is the final grade of the module.
Qualification objectives	• Students know the foundations of scattering theory and are able to apply these to problems involving simple potentials. • Students know the representations of the rotational group and their relevance for quantum theory. They have basic knowledge in group theory and representation theory in general. They know the meaning of product representations and irreducible representations. They are able to apply Clebsch-Gordon coefficients to simple problems involving angular momentum and spin in atomic spectra. • Students know the connection between spin and statistics. They are able to symmetrize respectively anti-symmetrize multi-particle states. They can describe the Hartree and Hartree-Fock methods and apply them to simple multi-particle systems. • Students know the fundamentals of time-dependent perturbation theory and can apply them to specific time-dependent problems. • Students know Dirac's equation and can solve it for the free case.
Course content	• Scattering theory: scattering amplitude and cross-section, partial wave expansion, Lippmann-Schwinger equation and Born series. • Fundamentals of the representation theory of groups, in particular of the rotation group SO(3). Tensor product representations and irreducible representations. Wigner-Eckart theorem. Applications to angular momentum and spin couplings in atomic, molecular and condensed matter physics. • Time-dependent perturbation theory: Dyson-expansion, Fermi's Golden Rule, examples of application to important time-dependent quantum processes. • Many-particle systems: identical particles, spin-statistic theorem, variational principles, Hartree and Hartree-Fock approximations.

<table>
<tr><td></td><td colspan="5">Interaction between radiation and matter. Quantization of the electromagnetic field. Interaction Hamiltonian, emission and absorption.
Relativistic quantum mechanics and quantum field theory; Dirac equation, quantization of Klein-Gordon and Dirac's equation.</td></tr>
<tr><td rowspan="4">Workload (hours)</td><td>Course</td><td>Type</td><td>Contact hrs</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Advanced Quantum Mechanics</td><td>L</td><td>60 h</td><td>120 h</td><td>180 h</td></tr>
<tr><td>Advanced Quantum Mechanics</td><td>E</td><td>45 h</td><td>75 h</td><td>120 h</td></tr>
<tr><td>Total:</td><td></td><td>105 h</td><td>195 h</td><td>300 h</td></tr>
<tr><td>Usability</td><td colspan="5">M.Sc. Physics, M.Sc. Applied Physics</td></tr>
<tr><td>Previous knowledge</td><td colspan="5">Contents of lectures Theoretical Physics I-IV (B.Sc. Physics)</td></tr>
<tr><td>Language</td><td colspan="5">English</td></tr>
</table>

3.2. Advanced Physics 1 (9 ECTS)

<table>
<tr><th>Module
07LE33K-ADV_PHYS1</th><th colspan="6">Advanced Physics 1 — 9 ECTS</th></tr>
<tr><td>Responsibility</td><td colspan="6">Dean of Studies, Lecturers of the Institute of Physics</td></tr>
<tr><td rowspan="4">Courses</td><td></td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assess-ment</td><td>Term</td></tr>
<tr><td>Advanced Physics</td><td>L</td><td>4</td><td>9</td><td>PL: written or oral exam</td><td>WiSe + SoSe</td></tr>
<tr><td>Advanced Physics</td><td>E</td><td>2</td><td></td><td>SL: exercises</td><td>WiSe + SoSe</td></tr>
<tr><td>Total:</td><td></td><td>4+2</td><td>9</td><td></td><td></td></tr>
<tr><td>Required academic assessment</td><td colspan="6">The final module exam (PL) is a written exam (duration: 60-180 minutes) or oral exam (duration: 30 minutes). The course achievement (SL) is the regular and successful participation in the exercises.</td></tr>
<tr><td>Grading</td><td colspan="6">The grade of the final exam is the final grade of the module.</td></tr>
<tr><td>Qualification objectives</td><td colspan="6">• Students obtain advanced knowledge in a particular field of modern physics.
• Students are familiar with current problems and research topics in particular fields of modern research in physics.
• Students know advanced tools and methods in particular fields.
• Specific qualification objectives for each lecture are listed in individual course descriptions section 4.</td></tr>
<tr><td>Course content</td><td colspan="6">A suitable lecture has to be selected by own choice from the list of Advanced Experimental or Advanced Theoretical Physics lectures given below.

List of eligible Advanced Lectures offered regularly:
(Exp = Experimental Lectures; Theo = Theory Lectures)

Lecture Course: — Term
Advanced Atomic and Molecular Physics — Exp — WiSe
Advanced Optics and Lasers — Exp — SoSe
Condensed Matter I: Solid State Physics — Exp — WiSe
Condensed Matter II: Interfaces and Nanostructures — Exp — SoSe
Advanced Particle Physics — Exp — WiSe
Hadron Collider Physics — Exp — SoSe
Particle Detectors — Exp — WiSe
Astroparticle Physics — Exp — SoSe
Theoretical Condensed Matter Physics — Theo — SoSe
Classical Complex Systems — Theo — WiSe
Computational Physics: Materials Science — Theo — SoSe
Quantum Field Theory — Theo — SoSe
Gauge Theories of Fundamental Interactions — Theo — WiSe</td></tr>
</table>

	In addition, various lectures on specialized physics topics are offered on an irregular basis and are indicated in the course catalogue as Advanced Physics lectures. **List of eligible Advanced Lectures offered irregularly:** Theoretical Quantum Optics — Theo Complex Quantum Systems — Theo General Relativity — Theo				
Workload (hours)	**Course**	**Type**	**Contact hrs**	**Self-studies**	**Total**
	Advanced Physics	L	60 h	120 h	180 h
	Advanced Physics	E	30 h	60 h	90 h
	Total:		**90 h**	**180 h**	**270 h**
Usability	M.Sc. Physics				
Previous knowledge	Basic experimental or theoretical physics lecture in the respective field				
Language	English				

3.3. Advanced Physics 2 (9 ECTS)

<table>
<tr><td>Module
07LE33K-ADV_PHYS2</td><td colspan="6">Advanced Physics 2 9 ECTS</td></tr>
<tr><td>Responsibility</td><td colspan="6">Dean of Studies, Lecturers of the Institute of Physics</td></tr>
<tr><td rowspan="4">Courses</td><td></td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assess-ment</td><td>Term</td></tr>
<tr><td>Advanced Physics</td><td>L</td><td>4</td><td>9</td><td>PL: written or oral exam</td><td>WiSe + SoSe</td></tr>
<tr><td>Advanced Physics</td><td>E</td><td>2</td><td></td><td>SL: exercises</td><td>WiSe + SoSe</td></tr>
<tr><td>Total:</td><td></td><td>4+2</td><td>9</td><td></td><td></td></tr>
<tr><td>Required academic assessment</td><td colspan="6">The final module exam (PL) is a written exam (duration: 60-180 minutes) or oral exam (duration: 30 minutes). The course achievement (SL) is the regular and successful participation in the exercises.</td></tr>
<tr><td>Grading</td><td colspan="6">The grade of the final exam is the final grade of the module.</td></tr>
<tr><td>Qualification objectives</td><td colspan="6">• Students obtain advanced knowledge in a particular field of modern physics.
• Students are familiar with current problems and research topics in particular fields of modern research in physics.
• Students know advanced tools and methods in particular fields.
• Specific qualification objectives for each lecture are listed in individual course descriptions section 4.</td></tr>
<tr><td>Course content</td><td colspan="6">A suitable lecture has to be selected from the catalogue of Advanced Experimental or Advanced Theoretical Physics lectures given in the (online) course catalogue of the Physics Institute. A range of advanced courses is offered on a regular or irregular basis. The specific content of each lecture is detailed in individual course descriptions section 4 or in the online course descriptions.</td></tr>
<tr><td rowspan="4">Workload (hours)</td><td>Course</td><td>Type</td><td colspan="2">Contact hrs</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Advanced Physics</td><td>L</td><td colspan="2">60 h</td><td>120 h</td><td>180 h</td></tr>
<tr><td>Advanced Physics</td><td>E</td><td colspan="2">30 h</td><td>60 h</td><td>90 h</td></tr>
<tr><td>Total:</td><td></td><td colspan="2">90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Usability</td><td colspan="6">M.Sc. Physics</td></tr>
<tr><td>Previous knowledge</td><td colspan="6">Basic experimental or theoretical physics lecture in the respective field</td></tr>
<tr><td>Language</td><td colspan="6">English</td></tr>
</table>

3.4. Advanced Physics 3 (9 ECTS)

Module 07LE33K-ADV_PHYS3	**Advanced Physics 3**					**9 ECTS**
Responsibility	Dean of Studies, Lecturers of the Institute of Physics					
Courses		**Type**	**Credit hrs**	**ECTS**	**Assess-ment**	**Term**
	Advanced Physics	L	4	9	SL: written or oral exam	WiSe + SoSe
	Advanced Physics	E	2		SL: exercises	WiSe + SoSe
	Total:		**4+2**	**9**		
Required academic assessment	The course achievements (SL) are a written exam (duration: 60-180 minutes) or oral exam (duration: 30 minutes) and the regular and successful participation in the exercises.					
Grading	unmarked					
Qualification objectives	• Students obtain advanced knowledge in a particular field of modern physics. • Students are familiar with current problems and research topics in particular fields of modern research in physics. • Students know advanced tools and methods in particular fields. • Specific qualification objectives are listed in individual course descriptions.					
Course content	A suitable lecture has to be selected from the catalogue of Advanced Experimental or Advanced Theoretical Physics lectures given in the (online) course catalogue of the Physics Institute. A range of advanced courses is offered on a regular or irregular basis. The specific content of each lecture is detailed in individual course descriptions section 4 or in the online course descriptions. If both lectures Advanced Physics 1 and 2 have been selected from one field (Advanced Experimental Physics or Advanced Theory) Advanced Physics 3 has to be chosen from the other field.					
Workload (hours)	**Course**	**Type**	**Contact hrs**		**Self-studies**	**Total**
	Advanced Physics	L	60 h		120 h	180 h
	Advanced Physics	E	30 h		60 h	90 h
	Total:		**90 h**		**180 h**	**270 h**
Usability	M.Sc. Physics					
Previous knowledge	Basic experimental or theoretical physics lecture in the respective field					
Language	English					

3.5. Elective Subjects (9 ECTS)

Module 07LE33K-ELSUB	**Elective Subjects**					**9 ECTS**
Responsibility	Dean of Studies, or Faculty/Department responsible for selected course					
Courses		**Type**	**Credit hrs**	**ECTS**	**Assessment**	**Term**
	Advanced Physics or Mathematics lectures or courses from other M.Sc./M.A. programs by own choice	L+E	According to selected courses	9	SL: written or oral exam	WiSe + SoSe
	Total:			**9**		
Required academic assessment	The course achievements (SL) are written (duration: 60-180 minutes) or oral exams (duration: 30 minutes) and the regular and successful participation in the exercises.					
Grading	unmarked					
Qualification objectives	The qualification objects are subject to the selected course.					
Course content	Students select different courses in order collect at least 10 ECTS credit points in total. The selection may contain lectures of the M.Sc. Physics program, or of the M.Sc./M.A. programs of other disciplines. The examination committee may admit courses of other external programs upon application. The course content is subject to the selected course. Also lectures of the B.Sc. programme in Mathematics can be chosen with the exception of Analysis I and II, and Linear Algebra I and II. The examination committee may admit courses of other external programmes upon application.					
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**		
	Elective courses	subject to selected courses		270 h		
	Total:			**270 h**		
Usability	M.Sc. Physics					
Previous knowledge	Subject to selected courses					
Language	Subject to selected courses					

3.6. Term Paper (6 ECTS)

Module 07LE33M-TP	**Term Paper**					**6 ECTS**
Responsibility	Dean of Studies, Lecturers of the Institute of Physics					
Courses		**Type**	**Credit hrs**	**ECTS**	**Assess-ment**	**Term**
	Term paper seminar	S	2	6	PL: oral presentation and written report	WiSe + SoSe
	Total:		**2**	**6**		
Required academic assessment	The final module exam (PL) is an oral presentation to a specialized physics topic or an adjacent area (duration 30-45 minutes) and a written report. Active participation in all presentations of the seminar is expected.					
Grading	The final grade is the arithmetic mean of the grades for the oral presentation and the written report.					
Qualification objectives	• Students are able to handle scientific literature and to search in scientific publica-tions • Students are able to prepare and present a topic of current physical research in front of a broad audience • Participants have the skills to lead a discussion in a group of students • Students can give a scientific lecture and are able to incorporate didactical ele-ments					
Course content	The research groups of the Institute of Physics offer various seminars each term. Allo-cation and registration to a particular seminar will be in a common event generally held in the first week of the semester. The *Term Paper* seminar comprises approximately 10 presentations from a coherent field of physics or a neighbouring scientific area.					
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**		
	Term paper seminar	21 h	159 h	180 h		
	Total:	**21 h**	**159 h**	**240 h**		
Usability	M.Sc. Physics, M.Sc. Applied Physics					
Previous knowledge	Basic knowledge in respective topic as acquired in self-studies or lecture					
Language	English					

3.7. Master Laboratory (8 ECTS)

<table>
<tr><th>Module
07LE33M-MLAB</th><th colspan="6">Master Laboratory 8 ECTS</th></tr>
<tr><td>Responsibility</td><td colspan="6">Head of the master laboratory</td></tr>
<tr><td rowspan="3">Courses</td><td>Course</td><td>Type</td><td></td><td>ECTS</td><td>Assessment</td><td>Term</td></tr>
<tr><td>Master Laboratory</td><td>Lab</td><td>block course</td><td>8</td><td>PL: experimental work, written report, oral presentation</td><td>WiSe</td></tr>
<tr><td>Total:</td><td></td><td></td><td>8</td><td></td><td></td></tr>
<tr><td>Organisation</td><td colspan="6">The Master Laboratory is offered as a block course during the semester break. Students have to register for the course online 10 weeks before the start of the course (https://www.physik.uni-freiburg.de/studium/labore).
Students perform 3 experiments and prepare written lab reports. The students perform each experiment in teams of two. Two experiments have to be completed within one week each. One experiment is performed within an allocated time of two weeks. For this extended experiment the students prepare an oral presentation given in a common seminar at the end of the Master Laboratory.</td></tr>
<tr><td>Required academic assessment</td><td colspan="6">For each experiment the students have to prepare the scientific background, which is tested in an initial written and/or oral exam, perform the experiment and collect their data, and prepare a written lab report. For one extended experiment the students additionally prepare and give an oral presentation (duration 30-45 minutes).</td></tr>
<tr><td>Grading</td><td colspan="6">The grade for each of the 3 lab experiments is determined according to the following:
- 20% initital exam (written/oral)
- 20% practical performance
- 60% lab report (written)
An additional grade is given for the final oral seminar presentation.
All four grades contribute equally to the final module grade (arithmetic mean).</td></tr>
<tr><td>Repetition</td><td colspan="6">Individual experiments have to be repeated at specially offered dates immediately after the regular end of the laboratory course. In case the entire Laboratory course has to be repeated, this is only possible by participating in next semester’s course.</td></tr>
<tr><td>Qualification objectives</td><td colspan="6">• Students are able to perform complex advanced experiments over several days
• Students are able to apply advanced statistical data analysis methods
• Students are able to prepare a written lab report
• Students are able to critically evaluate and assess their experimental results</td></tr>
<tr><td>Course content</td><td colspan="6">Performance of three Advanced Physics Experiments from Particle & Nuclear Physics, Atomic & Molecular Physics, Solid State Physics and Optics.
The current catalogue of laboratory experiments is available online on https://www.physik.uni-freiburg.de/studium/labore/fp/fp2/#section-3</td></tr>
</table>

Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Master Laboratory	150 h (20 days*7.5 h)	90 h	240 h
	Total:	**150 h**	**90 h**	**240 h**
Usability	M.Sc. Physics			
Previous knowledge	- Experimental skills as acquired e.g. in the Physics Laboratory B (B.Sc.) - Statistical methods of data analysis			
Language	English			

3.8. Research Traineeship (30 ECTS)

Module 07LE33M-RTRAIN	**Research Traineeship**			**30 ECTS**
Responsibility / Supervision	Dean of Studies, Group leaders at the Institute of Physics and associated Institutes			
Course details	**Type**		**ECTS**	**Assessment**
	Research (under supervision)	6 months	30	SL
Organisation	Prior to their master's thesis students engage in a Research Traineeship which is accomplished in a six-month period. The aim of this module is to acquire basic knowledge in a certain research topic and field in preparation for the subsequent Master Thesis. For the traineeship, students select a supervisor at the Institute of Physics or at one of the associated and participating research institutes. The research traineeship can be started at any time and has a duration of exactly 6 months. The students have to register for the research traineeship at the examination office.			
Grading	ungraded			
Qualification objectives	• Students have specialized basic knowledge in a certain research topic. • Students know and are able to apply specific experimental and/or theoretical tools and methods in a specialised field of research. • Students are prepared for performing a self-dependent research project (preparation for Master Thesis)			
Course content	• Students acquire basic knowledge in a certain field of research in preparation for their Master Thesis. • Participants obtain training in applying experimental and/or theoretical tools in a specialized field of research. • Students participate in a current research project under the supervision of lecturers and researchers (post-docs and doctoral researchers).			
Workload (hours)	900 h distributed over a six-month period			
Usability	M.Sc. Physics, M.Sc Applied Physics			
Precondition	Admission to the Research Traineeship requires successful accomplishment of the module *Master Laboratory* and of three of the four marked courses (AR) of the modules *Advanced Quantum Mechanics*, *Advanced Physics 1*, *Advanced Physics 2*, and *Term Paper*.			
Language	English			

3.9. Master Thesis (30 ECTS)

Module 07LE33M-MSC	**Master Thesis**			**30 ECTS**
Responsibility / Supervision	Group leaders at the Institute of Physics and associated Institutes			
Module details	**Type**		**ECTS**	**Assessment**
	Master Thesis	6 months	28	PL: final thesis
	Master Colloquium	45 min	2	SL: oral presentation
	Total:		**30**	
Organisation	For their master thesis students select a supervisor at the Institute of Physics or at one of the associated and participating research institutes. Typically, the master thesis is pursued within the same work group as the traineeship. The Master Thesis starts at the latest 2 weeks after successful completion of the Research Traineeship. Registration has to be arranged with the examination office.			
Grading	The final thesis is graded by two examiners. One examiner is the supervisor of the thesis. Both grades contribute equally to the final grade (arithmetic mean).			
Qualification objectives	• Students acquired specialized knowledge of a certain research topic and field. • Students have strong expertise in applying specific experimental and/or theoretical tools and methods in their field of research. • Students are able to perform independent research and can critically evaluate and assess their scientific results. • Students can search and read scientific literature and apply and relate reported results to their research.			
Module content	• Acquiring in-depth knowledge in the field of the master thesis work. • Working on a particular problem in a specialized field of research. • Development of the required experimental and/or theoretical tools and methods. • Preparation of a written report on the performed research work. • Preparation and performance of an oral presentation in the form of a public colloquium, discussing the topic of the master thesis, its physical context, and the underlying physical concepts.			
Workload (hours)	900 h distributed over a six-month period. This workload includes research, preparation of the written thesis and preparation of the final presentation.			
Usability	M.Sc. Physics, M.Sc Applied Physics			
Precondition	Admission to the Master Thesis requires successful accomplishment of the module *Research Traineeship*.			
Language	English or German			

4. Advanced Physics Lectures

4.1. Advanced Atomic and Molecular Physics (9 ECTS)

Lecture 07LE33M-ADV_EXP_AMO	**Advanced Atomic and Molecular Physics** Adv. Experiment			
Lecturer/s	Lecturers from Experimental Atomic, Molecular and Optical Physics			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L+E)	4+2	9	SL or PL
Term	In general, the course will be offered each winter term.			
Qualification objectives	Students have a deeper understanding of both the properties of matter based on the nature and interactions of atoms and molecules, and of current and future technologies based on controlled quantum processes, such as those employed in atomic clocks, atom interferometers, quantum optics and quantum computing, nanoscale engineering, photochemistry and energy conversion.			
Course content	• Light-matter interaction: scattering, absorption and emission of light, dressed states, coherence, strong fields • Scattering of atomic and molecular systems • Properties of diatomic molecules: vibrations and rotations • Properties of polyatomic molecules: electronic states, molecular symmetries, chemical bonds • Modern AMO applications in science and technology			
Previous knowledge	Experimental Physics I-IV (B.Sc. Physik)			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	90 h	180 h	270 h
Usability	M.Sc. Physics modules: Advanced Physics 1 or 2 (PL), Advanced Physics 3 (SL) or Elective Subjects (SL), M.Sc. Applied Physics modules: Advanced Experimental Physics (PL), Applied Physics (PL or SL) or Elective Subjects (SL)			
Language	English			

4.2. Advanced Optics and Lasers (9 ECTS)

<table>
<tr><td>Lecture
07LE33M-ADV_EXP_OL</td><td colspan="4">Advanced Optics and Lasers Adv. Experiment</td></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Experimental Atomic, Molecular and Optical Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">In general, the course will be offered each winter term.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• Students are familiar with the physical concepts of lasers and know the fundamentals of the interaction between laser light and matter.
• Students are able to describe in detail the inherent behaviour and functionality of the many different types of modern lasers.
• Students have a deep understanding of the properties of coherent laser light and are able to understand and analyse nonlinear optical effects, e.g. those induced by lasers in transparent materials.</td></tr>
<tr><td>Course content</td><td colspan="4">• Light-matter interaction: Absorption/emission, line broadening
• Coherence and interference: temporal, spatial coherence, interferometers
• The laser principle: 2, 3, 4-level lasers, rate equation models, output power of a laser;
• Optical resonators: transmission spectra, stability
• Laser modes: Paraxial approximation, Gaussian beams, longitudinal and transverse modes, mode selection
• Short laser pulses: Dynamic solutions of rate equation, Q-switching, mode locking, intense short pulses, generation of ultra-short laser pulses
• Nonlinear optics: Second, third order polarizability, frequency conversion, optical parametric amplification, high-harmonics generation</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Experimental Physics I-IV (B.Sc. Physik)</td></tr>
<tr><td rowspan="2">Workload (hours)</td><td>Course</td><td>Contact hrs</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. Physics modules: Advanced Physics 1 or 2 (PL), Advanced Physics 3 (SL) or Elective Subjects (SL),
M.Sc. Applied Physics modules: Advanced Experimental Physics (PL), Applied Physics (PL or SL) or Elective Subjects (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

4.3. Condensed Matter I: Solid State Physics (9 ECTS)

<table>
<tr><th>Lecture
07LE33M-ADV_EXP_CM1</th><th colspan="4">Condensed Matter I:
Solid State Physics   Adv. Experiment</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Experimental Condensed Matter and Applied Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">In general, the course will be offered each winter term.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• Students know the reciprocal space description of crystals and related quasiparticles like phonons
• Students know the quantum mechanical description of electrons in periodic potentials (Bloch- and Wannier-functions)
• Students have a good overview of experimental state of the art techniques for the study of the properties of solid-state materials
• Students know how to obtain and are able to interpret experimental data like measurements of electronic band structures or phonon dispersion curves
• Students know about newer developments in the experimental characterization of many-body quantum effects like magnetism or superconductivity</td></tr>
<tr><td>Course content</td><td colspan="4">• Atomic structure of matter
• lattice dynamics, phonons
• electronic structure of materials
• optical properties
• magnetism/superconductivity</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Experimental Physics I-IV (B.Sc. Physik)</td></tr>
<tr><td rowspan="2">Workload (hours)</td><td>Course</td><td>Contact hrs</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. Physics modules: Advanced Physics 1 or 2 (PL), Advanced Physics 3 (SL) or Elective Subjects (SL),
M.Sc. Applied Physics modules: Advanced Experimental Physics (PL), Applied Physics (PL or SL) or Elective Subjects (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

4.4. Condensed Matter II: Interfaces and Nanostructures (9 ECTS)

<table>
<tr><th>Lecture
07LE33M-ADV_EXP_CM2</th><th colspan="4">Condensed Matter II: Interfaces and Nanostructures — Adv. Experiment</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Experimental Condensed Matter and Applied Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">In general, the course will be offered each summer term.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• Students are able to describe interaction forces at interfaces in terms of their range and their consequences on thermodynamic and kinetic properties.
• Students understand processes at surfaces like adsorption/desorption, surface reconstruction, surface transport, or wettability.
• Students are able to describe processes as well as structural transitions at liquid, solid-liquid, and solid interfaces with respect to their hydrodynamic and electronic properties.
• Students know processes for preparing well defined and patterned surfaces.
• Students identify the relevant processes for the formation of nanostructures and structuring of surfaces at the nm-scale.</td></tr>
<tr><td>Course content</td><td colspan="4">• Surfaces and interface
• structure formation on surfaces
• self-assembly, morphology and transitions
• optical and electronic properties</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Experimental Physics I-IV (B.Sc. Physik)</td></tr>
<tr><td rowspan="2">Workload (hours)</td><td>Course</td><td>Contact hrs</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. Physics modules: Advanced Physics 1 or 2 (PL), Advanced Physics 3 (SL) or Elective Subjects (SL),
M.Sc. Applied Physics modules: Advanced Experimental Physics (PL), Applied Physics (PL or SL) or Elective Subjects (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

4.5. Advanced Particle Physics (9 ECTS)

<table>
<tr><td>Lecture
07LE33M-ADV_EXP_PP</td><td colspan="4">Advanced Particle Physics Adv. Experiment</td></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Experimental Particle Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">In general, the course will be offered each winter term.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• Students know the guiding principle of internal symmetries and how discrete and local gauge theories are constructed. They are able to analyse the symmetries of a Lagrangian and understand the implications for the phenomenology.
• Students learn to discriminate different particles/processes via the characteristic signature in different detector components.
• Students know the interplay of model building and experimental findings. They are able to critically compare theoretical predictions with experimental findings.
• Students can perform simple cross section evaluations using Feynman calculus.
• Students know the structure and phenomenology of the Standard Model of Particle Physics and its limitations.</td></tr>
<tr><td>Course content</td><td colspan="4">• Quantum Electrodynamics as prototype of a local gauge theory: Feynman rules, calculation of matrix elements, higher order corrections, principle of renormalisation, running coupling strength, basic experimental tests at low (g-2, Lamb shift) and high energies (PETRA, LEP colliders)
• Quantum Chromodynamics: phenomenological differences between abelian and non-abelian gauge theories, confinement, asymptotic freedom, stability of hadrons, jets, and basic experimental tests at PETRA, LEP, Tevatron and LHC.
• Parton density functions of the proton and its determination in deep inelastic scattering, Bjorken scaling and its violation.
• Electroweak theory and formulation of the Standard Model of particle physics: charged and neutral weak currents, from Fermi theory to the Glashow-Salam-Weinberg theory, massive weak gauge bosons, parity violation, CP violation, basic experimental tests at various colliders.
• Observation and phenomenology of neutrinos oscillations.
• Electroweak symmetry breaking: Higgs mechanism, Higgs boson physics (experimental aspects)
• Limitations of the Standard Model (neutrinos masses, dark matter,…) and possible extensions (SUSY, extra dimensions,…)</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Experimental Physics V (Nuclear and Particle Physics) and Theoretical Physics III (Quantum Mechanics) (B.Sc. Physics)</td></tr>
<tr><td rowspan="2">Workload (hours)</td><td>Course</td><td>Contact hrs</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
</table>

Usability	M.Sc. Physics modules: Advanced Physics 1+2 (PL), Advanced Physics 3 (SL) or Elective Subjects (SL), M.Sc. Applied Physics modules: “Advanced Experimental Physics” (PL), “Applied Physics” (PL or SL) or “Elective Subjects” (SL)
Language	English

4.6. Particle Detectors (9 ECTS)

<table>
<tr><td>Lecture
07LE33M-ADV_EXP_PDET</td><td colspan="4">Particle Detectors Adv. Experiment</td></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Experimental Particle Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">In general, the course will be offered each winter term</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• Students are able to understand the physics of particle detection
• Students are able to understand the interaction of particles with matter
• Students are able to understand the different types of particle detectors
• Students are able to design a particle detector for specific experiments</td></tr>
<tr><td>Course content</td><td colspan="4">• Interaction of particles with matter
• General properties of particle detectors
• Tracking detectors
• Time measurement
• Energy measurement
• Particle identification
• Electronics, trigger and data acquisition
• Detector systems in Particle and Astroparticle Physics
• Applications of particle detectors in medicine</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Experimental Physics V (Nuclear and Particle physics) (B.Sc. Physics)
Experimental Physics IV (Atoms, Molecules, Solid State Physics) (BSc. Physics)</td></tr>
<tr><td rowspan="2">Workload (hours)</td><td>Course</td><td>Contact hrs</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. Physics modules: Advanced Physics 1 or 2 (PL), Advanced Physics 3 (SL) or Elective Subjects (SL),
M.Sc. Applied Physics modules: Advanced Experimental Physics (PL), Applied Physics (PL or SL) or Elective Subjects (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

4.7. Hadron Collider Physics (9 ECTS)

<table>
<tr><th>Lecture
07LE33M-ADV_EXP_HCP</th><th colspan="4">Hadron Collider Physics Adv. Experiment</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Experimental Particle Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">In general, the course will be offered each summer term</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• Students acquire the basic experimental concepts of experiments at hadron colliders (detector and trigger concept, soft and hard collisions, underlying event, pile-up)
• Students know the concept of cross-section calculations at hadron colliders from first principles (Feynman diagrams) and from numerical calculations using Monte Carlo generators
• Students know the concepts of tests of the Standard Model at hadron colliders, including precision measurements in some areas
• Students acquire deeper insight and familiarize with modern multivariate techniques for the separation of signal and background processes in the search for new physics / deviations from the Standard Model
• Students know the up-to-date status on experimental tests of the
• Standard Model and on Searches for New Physics</td></tr>
<tr><td>Course content</td><td colspan="4">• Introduction to accelerators, with focus on the Large Hadron Collider
• Detector and trigger concepts of hadron collider experiments
• Phenomenology of pp collisions
• Structure functions, calculation of cross sections, Monte Carlo generators for pp collisions
• Particle signatures in LHC experiments
• pp collisions with low transverse momentum (underlying event, minimum bias)
• Test of QCD at hadron colliders (jet production, top-quark production, W/Z + jet production)
• Measurements of important parameters of the Standard Model (m_t, m_W, gauge couplings, ..)
• Physics of heavy quarks (b-physics, the top quark and its properties)
• Higgs boson physics (experimental detection, measurements of Higgs boson properties, additional Higgs bosons,..)
• Search for supersymmetric particles
• Search for other extensions of the Standard Model</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Experimental Physics V (Nuclear and particle physics) (B.Sc. Physik)
Advanced Particle Physics (desirable, MSc Physics)</td></tr>
<tr><td rowspan="2">Workload (hours)</td><td>Course</td><td>Contact hrs</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
</table>

Usability	M.Sc. Physics modules: “Advanced Physics 1+2” (PL), Advanced Physics 3 (SL) or Elective Subjects (SL)
Language	English

4.8. Polymer Physics (9 ECTS)

<table>
<tr><th>Module no.
07LE33M-POL</th><th colspan="4">Polymer Physics Adv. Experiment</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Prof. Dr. Günter Reiter</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">The lecture is offered in the winter term</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• Students get to know fundamental concepts in polymer physics.
• They are familiar with experimental techniques for the characterization of polymers.</td></tr>
<tr><td>Course content</td><td colspan="4">We can't imagine life and technology today without polymers, if you think of materials like PET bottles and PVC, nylon, teflon or rubber. Also in nature biopolymers are ubiquitous, e.g. DNA, proteins or cellulose. This lecture will give an introduction to the experimental and theoretical concepts used to understand and characterise polymer systems. . Both applied and material aspects will be discussed - like polymer flow, elastomers and crystalline polymers - as well as present topics of fundamental research, e.g. glass transition, dynamics in confined geometries and self-assembly. The lecture will deal with basic theoretical concepts and descriptive experiments. It will start with simple single chain phenomena and gradually develop more complex structures and dynamics of polymer solutions, melts and blends.</td></tr>
<tr><td>Literature</td><td colspan="4">• G. Strobl, The Physics of Polymers
• Colby & Rubinstein, Polymer Physics</td></tr>
<tr><td>Preliminaries / Previous knowledge</td><td colspan="4">Experimental Physics I-IV (B.Sc. Physik), Thermodynamics</td></tr>
<tr><td>Final Exam</td><td colspan="4">Written (120 min) or oral (30 min) exam</td></tr>
<tr><td rowspan="2">Workload (hours)</td><td>Course</td><td>Contact hrs</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. Physics modules: Advanced Physics 1 or 2 (PL), Advanced Physics 3 (SL) or Elective Subjects (SL),
M.Sc. Applied Physics modules: Advanced Experimental Physics (PL), Applied Physics (PL or SL) or Elective Subjects (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

4.9. Astroparticle Physics (9 ECTS)

Lecture 07LE33M- ADV_EXP_APART	**Astroparticle Physics** Adv. Experiment			
Lecturer/s	Lecturers from Experimental Particle Physics			
Course details	**Type**	**Credit hrs**	**E CTS**	**Assessment**
	Lecture and exercises (L+E)	4+2	9	SL or PL
Term	In general, the course will be offered each summer term			
Qualification objectives	• Students are familiar with the standard models of particle physics and cosmology • Students acquire an understanding of the physics of the early universe • Students know the characteristics of the energy density in the universe • Students are familiar with up-to-date research on dark matter and dark energy • Students acquire insight on nuclear fusion and the evolution of stars • Students have knowledge of the nature of cosmic rays			
Course content	• The standard model of particle physics • Conservation Rules and symmetries • The expanding universe • Matter, Radiation • Dark matter • Dark energy • Development of structure in the early universe • Particle physics in the stars • Nature and sources of high energy cosmic particles • Gamma ray and neutrino astronomy • Gravitational Waves			
Previous knowledge	Experimental Physics V (Nuclear and Particle Physics) (B.Sc. Physics) Theoretical Physics III (Quantum Mechanic s) (B:Sc Physics)			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	90 h	180 h	270 h
Usability	M.Sc. Physics modules: Advanced Physics 1 or 2 (PL), Advanced Physics 3 (SL) or Elective Subjects (SL), M.Sc. Applied Physics modules: Advanced Experimental Physics (PL), Applied Physics (PL or SL) or Elective Subjects (SL)			
Language	English			

4.10. Quantum Hardware (9 ECTS)

<table>
<tr><td>Module no.
07LE33M-ADV_EXP_QHW</td><td colspan="4">Quantum Hardware Adv. Experiment</td></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Experimental Atomic, Molecular and Optical Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Examination</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>PL: written or oral exam</td></tr>
<tr><td>Term</td><td colspan="4">In general, the course will be offered each summer term</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• Students are familiar with the main concept behind the experimental setups based on quantum interactions. They are familiar with the concept of scalability of quantum systems and decoherence.
• Students have a deep understanding of the peculiarities of and differences between the quantum platforms
• Students are familiar with different kinds of technologies used for the implementation of quantum simulations.</td></tr>
<tr><td>Course content</td><td colspan="4">• Introduction (qubit concept; entanglement)
• Quantum platforms: photons, cold atoms, ions, spins, SQUID
• Quantum sensing
• Potential applications: quantum computing; quantum simulations; cryptography</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Experimental Physics I-IV (B.Sc. Physik)</td></tr>
<tr><td rowspan="2">Workload (hours)</td><td>Course</td><td>Contact hrs</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. Physics modules: Advanced Physics 1 or 2 (PL), Advanced Physics 3 (SL) or Elective Subjects (SL),
M.Sc. Applied Physics modules: Advanced Experimental Physics (PL), Applied Physics (PL or SL) or Elective Subjects (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

4.11. Classical Complex Systems (9 ECTS)

<table>
<tr><td>Lecture
07LE33M-ADV_THEO_CS</td><td colspan="4">Classical Complex Systems Adv. Theory</td></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Theoretical Atomic, Molecular and Optical Sciences
or from Theoretical Condensed Matter and Applied Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">In general the course will be offered each winter term.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">
• Students are familiar with stochastic and deterministic concepts to model complex systems.
• Students are capable of recognizing and rigorously describing phenomena commonly encountered in complex systems.
• Students are able to use probabilistic notions to model systems subject to uncertainty about their microscopic states and laws.
• Students are able to run and interpret Monte Carlo computer simulations as well as to quantify the confidence in results produced by randomized algorithms.
• Students are able to use basic statistical tools to infer probabilistic statements from empirical observations.</td></tr>
<tr><td>Course content</td><td colspan="4">The first two thirds of the lecture cover basic theory, while the final third is concerned with concrete applications. Topics treated in the latter part depend more strongly on the lecturer.

Stochastic Processes:
• Random walks, Markov model
• Stochastic differential equations and master equations (Langevin- and Fokker-Planck Equation)
• Numerical treatment and Monte Carlo techniques

Non-Linear Dynamics / Chaos Theory:
• Dynamical systems (discrete, differential equations, Hamiltonian)
• Lyapunov exponents
• Attractors and bifurcations

Applications:

Molecular dynamics simulations
• Molecular driving forces and force field models
• Simulation techniques and sampling
• Energy landscapes and analysis of dynamics

Time series analysis and inverse problems
• Estimation and test theory
• Spectral analysis
• State space model</td></tr>
</table>

Previous knowledge	Theoretical Physics I-V (B.Sc. Physik)			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	90 h	180 h	270 h
Usability	M.Sc. Physics modules: “Advanced Physics 1+2” (PL), “Advanced Physics 3” (SL) or “Elective Subjects” (SL), M.Sc. Applied Physics modules: “Advanced Experimental Physics” (PL), “Applied Physics” (PL or SL) or “Elective Subjects” (SL)			
Language	English			

4.12. Theoretical Condensed Matter Physics (9 ECTS)

Module no. 07LE33M-ADV_THEO_CONDMAT	**Theoretical Condensed Matter Physics** Adv. Theory			
Lecturer/s	Lecturers from Theoretical Condensed Matter and Applied Physics			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L+E)	4+2	9	PL: written or oral exam
Term	In general, the course will be offered each summer term.			
Qualification objectives	• Students are familiar with the relevant theoretical concepts in Condensed Matter Physics. • Students are able to calculate physical properties of various condensed matter systems based on quantum mechanics, and appreciate the physical ideas behind these approximation schemes, as well as their limitations.			
Course content	• Crystal structures, crystal vibrations, quantization of harmonically coupled lattices, phonons. • Electrons in periodic potentials, Bloch waves, band structure. Application to conductors, insulators and semi-conductors. • Electron phonon coupling. BCS theory of superconductivity. • Spin degrees of freedom. Classical and quantum spin chains.			
Previous knowledge	Experimental Physics I-IV, Theoretical Physics I-IV (B.Sc. Physik)			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	90 h	180 h	270 h
Usability	M.Sc. Physics modules: Advanced Physics 1 or 2 (PL), Advanced Physics 3 (SL) or Elective Subjects (SL), M.Sc. Applied Physics modules: Advanced Experimental Physics (PL), Applied Physics (PL or SL) or Elective Subjects (SL)			
Language	English			

4.13. Complex Quantum Systems (9 ECTS)

<table>
<tr><td>Lecture
07LE33M-ADV_THEO_OS</td><td colspan="4">Complex Quantum Systems Adv. Theory</td></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Theoretical Atomic, Molecular and Optical Sciences
or from Theoretical Condensed Matter and Applied Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">Lecture is offered on an irregular basis.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• The students know the advanced physical concepts and mathematical techniques in the field of complex and open quantum systems;
• They have the ability to apply these concepts and techniques to the theoretical modelling and analysis of specific complex systems and to derive emergent phenomena in open systems (e.g. macroscopic classicality) from microscopic laws of quantum mechanics (e.g. decoherence).
• For structural track: The students know how to reason about counter-intuitive aspects of quantum theory using mathematically rigorous notions.</td></tr>
<tr><td>Course content</td><td colspan="4">• Quantum states: Pure and mixed states, density matrices, quantum state space
• Composite quantum systems: Tensor product, entangled states, partial trace and reduced density matrix, quantum entropy
• Open quantum systems: Closed and open systems, dynamical maps, quantum operations, complete positivity and Kraus representation
• Dynamical semigroups and quantum master equations: Semigroups and generators, quantum Markovian master equations, Lindblad theorem
• General properties of the master equation: Dynamics of populations and coherences, Pauli master equation, relaxation to equilibrium
• Decoherence: Destruction of quantum coherence through interaction with an environment, decoherence versus relaxation

Applied Track:
• Microscopic theory: System-reservoir models, Born-Markov approximation, microscopic derivation of the master equation.
• Applications: Quantum theory of the laser, superradiance, quantum transport, quantum Boltzmann equation

Structural Track:
• Uncertainty relations: Joint measurability, uncertainty relations for continuous and discrete observables, information-disturbance trade-off
• Contextuality: Non-Locality, Bell's Theorem, Marginals</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Theoretical Physics IV (Quantum Mechanics, B.Sc. Physik) and
Advanced Quantum Mechanics (M.Sc. Physics)</td></tr>
</table>

Workload (hours)	Course	Contact hrs	Self-studies	Total
	Lecture and exercises (L+E)	90 h	180 h	270 h
Usability	M.Sc. Physics modules: Advanced Physics 1 or 2 (PL), Advanced Physics 3 (SL) or Elective Subjects (SL), M.Sc. Applied Physics modules: Advanced Experimental Physics (PL), Applied Physics (PL or SL) or Elective Subjects (SL)			
Language	English			

4.14. Quantum Field Theory (9 ECTS)

Lecture 07LE33M-ADV_THEO_QFT	**Quantum Field Theory**			Adv. Theory
Lecturer/s	Lecturers from Theoretical Particle Physics			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L+E)	4+2	9	SL or PL
Term	In general the course will be offered each summer term.			
Qualification objectives	• Students get familiar with the basics of representation theory for the Lorentz and Poincare groups. • They are able to write down the Lagrangian function for the standard field theories (scalar, Dirac and gauge theories). • They are familiar with concepts of canonical relativistic field quantization. • They can derive the Feynman rules for perturbative expansions from a given Lagrangian and are able to construct Feynman diagrams. • They can apply the standard methods for evaluating Feynman diagrams in Born approximation. • They are familiar with quantum electrodynamics and its phenomenology.			
Course content	• Classical field theory, Lagrangian formalism • Relativistic wave equations: Klein-Gordon, Dirac, Maxwell, Proca equations • Basics of Lie Groups, Lorentz group and its representations, Poincare group and its representations • Canonical quantisation of free fields (scalar, Dirac, vector fields), causal propagator • Interacting fields, gauge theories • Scattering theory, S-matrix • Perturbation theory, Wick's theorem, and Feynman diagrams • Quantum electrodynamics and phenomenological applications (Compton scattering, pair creation and annihilation, Bhabha scattering in Born approximation) • Optional: Functional Integrals, generating functionals, Grassman variables for fermionic fields • Optional: Introduction to higher perturbative orders			
Previous knowledge	Electrodynamics, quantum mechanics, special relativity Theoretical Physics II, III (BSc Physics)			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	90 h	180 h	270 h
Usability	M.Sc. Physics modules: Advanced Physics 1+2 (PL), Advanced Physics 3 (SL) or Elective Subjects (SL)			
Language	English			

4.15. Gauge Theory of Fundamental Interactions (9 ECTS)

Lecture 07LE33M-ADV_THEO_GTFI	**Gauge Theories of Fundamental Interactions** Adv. Theory			
Lecturer/s	Lecturers from Theoretical Particle Physics			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L+E)	4+2	9	SL or PL
Term	In general the course will be offered each winter term.			
Qualification objectives	• Students are able to construct Lagrangians for abelian and non-abelian gauge theories • They are familiar with the concepts of field quantization via functional integrals, the concept of Green functions and of their gauge symmetries. • They can evaluate gauge theories perturbatively at the one-loop level, including renormalization. • They know the gauge theories of strong (QCD) and/or electroweak interactions (Glashow-Salam-Weinberg model) and the corresponding basic phenomenology. • They are prepared to work on experimental or theoretical research at particle colliders such as the CERN Large Hadron Collider (LHC).			

Course content	• Quantization of field theories via functional integrals
	• Perturbation theory and Feynman diagrams
	• Gauge theories and their quantization
	• BRS symmetry and Slavnov-Taylor identities
	• Theories of strong (QCD) and/or electroweak interactions, with optional emphasis
	• Quantum corrections, regularization, and renormalization
	• Renormalization group equations
	• Jet production in e+e- annihilation
	• Drell-Yan process
	• Optional chapters depending on the emphasis:
	  ○ Strong interaction:
	  parton model for hadronic particle reactions; parton distribution function and DGLAP evolution; deep inelastic electron-nucleon scattering
	  ○ Electroweak interaction:
	  production and decay of electroweak gauge bosons and Higgs bosons			

Previous knowledge	Electrodynamics, quantum mechanics, relativistic quantum field theory Theoretical Physics II, III (BSc Physics)			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	90 h	180 h	270 h
Usability	M.Sc. Physics: Advanced Physics 1+2 (PL), Advanced Physics 3 or El. Subjects (SL)			
Language	English			

4.16. General Relativity (9 ECTS)

Lecture 07LE33M-ADV_THEO_GR	**General Relativity**			Adv. Theory
Lecturer/s	Lecturers from Theoretical Particle Physics			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L+E)	4+2	9	SL or PL
Term	The lecture is offered on an irregular basis.			
Qualification objectives	• Students know the fundamentals of special and general relativity, Lorentz transformations, and the Poincare group. They can explain the fundamental phenomena related to relativity (perihelion precession of Mercury, relativistic red/blue shift, influence of gravity on clocks, accelerated systems, gravitational waves). • They know the mathematical foundations of (pseudo-)Riemannian geometry and know to interpret and obtain the metric, Christoffel symbols and Riemannian curvature components for simple geometric structures. • They can derive the geodesic equation from the action principle and know its relation to parallel transport. They can find geodesics in simple geometries. • They know how to calculate the energy-momentum tensor from a given field theory, for free particles and for collective systems (radiation dominated or matter dominated homogeneous universes). • They know how to read and construct space-time diagrams (Finkelstein, Kruskal, Carter-Penrose) for classical geometries (Minkowski space, Rindler space, Schwarzschild and Kerr geometries).			
Course content	• Equivalence principles: Minkowski space, Poincare group, space-time diagrams, world lines, proper time and distance, application to simple phenomena (elevator thought experiments, relativistic Doppler effect, accelerated systems), Lorentz transformations and general coordinate transformations. • Differential geometry: manifolds and tangent spaces, forms, metric tensor, integration, Stokes' theorem, outer derivative, Lie derivative, covariant derivative and Christoffel symbols, parallel transport, geodesics, curvature (Riemann tensor, Weyl tensor, Ricci tensor and scalar), torsion, Killing vectors, Riemann coordinates. • Einstein-Hilbert action and variational principle. • Dynamics of the gravitational field: Einstein equations, cosmological constant, energy-momentum tensor of matter systems (perfect fluids, point particles, Klein-Gordon and Maxwell theory). • Effects based on post-Newtonian approximations: red/blue shift effects, precession of the perihela, effect of gravitation on clocks, deflection of light. • Gravitational waves: perturbative expansion of field equations, gauge invariance, origin and detection of gravitational waves. • Classical space-times: Minkowski, Rindler, Schwarzschild, Kerr, Reissner-Nordstrøm, Kerr-Newman geometries; Robertson-Walker metrics, Friedmann universes and deSitter space. Discussion of causal structure, geodesic completeness, key coordinate systems and Carter-Penrose diagrams. • Optional: Modern topics in cosmology: CMB, the Inflation Model.			

Previous knowledge	Electrodynamics, special relativity, Lagrangian mechanics Theoretical Physics I and II (BSc Physics)			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	90 h	180 h	270 h
Usability	M.Sc. Physics modules: Advanced Physics 1 or 2 (PL), Advanced Physics 3 (SL) or Elective Subjects (SL), M.Sc. Applied Physics modules: Advanced Experimental Physics (PL), Applied Physics (PL or SL) or Elective Subjects (SL)			
Language	English			

4.17. Theoretical Quantum Optics (9 ECTS)

Lecture 07LE33M-ADV_THEO_QO	**Theoretical Quantum Optics** Adv. Theory			
Lecturer/s	Lecturers from Theoretical Atomic, Molecular and Optical Physics			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L+E)	4+2	9	SL or PL
Term	Lecture is offered on an irregular basis.			
Qualification objectives	• Students are able to characterize the quantum state of the electromagnetic field • Students are able to interpret the dynamics of the quantized field in terms of canonically conjugate variables • Students are able to distinguish classical from quantum features of the quantized field, and to perform the classical limit • Students are able to infer the quantum state of the light field from multi-point correlation functions • Students are able to describe the quantum state of strongly coupled light-matter systems • Students are able to give a semiclassical description of light-matter systems • Students are familiar with a selection of paradigmatic experimental settings to probe generic quantum properties of the light field			
Course content	• Quantization of the radiation field • Coherent states • Phase space representation of quantum states • Counting statistics • Dressed states • Floquet theory • Special topics, e.g. micromaser theory, elements of entanglement theory, laser theory, master equations, coherent control • Light-matter interaction			
Previous knowledge	Introductory courses of experimental and theoretical physics (mechanics, electrodynamics, quantum mechanics)			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	90 h	180 h	270 h
Usability	M.Sc. Physics modules: Advanced Physics 1 or 2 (PL), Advanced Physics 3 (SL) or Elective Subjects (SL), M.Sc. Applied Physics modules: Advanced Experimental Physics (PL), Applied Physics (PL or SL) or Elective Subjects (SL)			
Language	English			

4.18. Quantum Information Theory (9 ECTS)

Module no. 07LE33M-ADV_THEO_QIT	**Quantum Information Theory**			Adv. Theory
Lecturer/s	Lecturers from Theoretical Atomic, Molecular and Optical Physics			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L+E)	4+2	9	PL: written or oral exam
Term	In general the course will be offered each summer term.			
Qualification objectives	• Students are familiar with the main concepts of quantum information theory. • Students are familiar with the main differences between classical and quantum computing.			
Course content	Certain information processing tasks can be performed more efficiently with quantum mechanical systems than with classical ones. Famous examples are Shor's quantum algorithm for factoring large integer numbers and quantum cryptography enabling secure communication between two parties. In this lecture, we will introduce fundamental concepts of quantum information theory (e.g. entangled states and quantum correlations) and discuss possible applications such as quantum teleportation or quantum computing. 1. Foundations of quantum information theory (Quantum state space, qubits, composite systems, tensor product, correlations and entanglement, quantum entropies) 2. Quantum cryptography (Quantum key distribution, BB84 protocol) 3. Quantum computation (Quantum gates, quantum circuit model, universal quantum gates, quantum algorithms: Shor, Grover) 4. Physical realizations (Trapped ions, cavities, NMR, squids, spintronics) 5. Quantum error correction (Quantum noise, quantum operations, quantum error correction, fault-tolerant quantum computation)			
Previous knowledge	Theoretical Physics I-IV (B.Sc. Physik)			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	90 h	180 h	270 h

Usability	M.Sc. Physics modules: Advanced Physics 1 or 2 (PL), Advanced Physics 3 (SL) or Elective Subjects (SL), M.Sc. Applied Physics modules: Advanced Experimental Physics (PL), Applied Physics (PL or SL) or Elective Subjects (SL)
Language	English

4.19. Computational Physics: Materials Science (9 ECTS)

<table>
<tr><td>Lecture
07LE33V-ADV_THEO_COMPPHYS</td><td colspan="4">Computational Physics: Materials Science Adv. Theory</td></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Computational Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">The lecture is offered on an irregular basis.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• Students have understood the basic Hamiltonian of CMS
• Students are familiar with the various approximations that lead to different methods in CMS: Born-Oppenheimer approximation, classical approximation for the nuclei, local density approximation, tight-binding, semi-empirical interatomic potentials, coarse grained models, hydrodynamic limit
• Students have a basic knowledge of density functional theory.
• Students can set up simple molecular dynamics calculations.
• Students are familiar with the different types of Born-Oppenheimer surfaces for the different types of interatomic binding.
• Students are familiar with extended molecular dynamics methods.</td></tr>
<tr><td>Course content</td><td colspan="4">This lecture provides an introduction into basic concepts of atomistic computational materials science. The computational tools for different time and length scales will be introduced and it will be discussed how these tools can be combined in order to solve physical problems extending over too many scales for one single method alone. We will start with a brief introduction to density functional theory and more approximate methods such as tight binding. Quantum derived forces can be extracted from these methods and the short term dynamics of small nanosystems can be studied. For the simulation of larger systems and longer time scales, classical interatomic potentials are required. The students will become familiar with some examples for the different types of interatomic potentials: e.g. Lennard-Jones, Born-Mayer, Embedded-Atom, Bond-Order-potentials as well as bead-spring potentials for polymers. A brief introduction into the basic methodology of micro-canonical and thermostated molecular dynamics simulations will be given.
The lecture is accompanied by a hands-on programming course. Classical molecular dynamics simulations will be used to study metallic and covalently bonded materials.</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Basic knowledge in classical and quantum mechanics</td></tr>
<tr><td rowspan="2">Workload (hours)</td><td>Course</td><td>Contact hrs</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. Physics modules: “Advanced Physics 1+2” (PL), “Advanced Physics 3” (SL) or “Elective Subjects” (SL),</td></tr>
</table>

	M.Sc. Applied Physics modules: “Advanced Theoretical Physics” (PL), “Applied Physics” (PL or SL), “Elective Subjects” (SL)
Language	English

5. Elective Subjects

5.1. Machine Learning in Particle Physics (7 ECTS)

Lecture 07LE33M-MLinPP	**Machine Learning in Particle Physics**			
Lecturer/s	Lecturers from Experimental Particle Physics			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L+E)	3+2	7	SL
Term	The lecture is offered on an irregular basis.			
Qualification objectives	• Students learn the tasks and basic principles of machine learning (ML). • Student learn different methods of supervised and unsupervised ML. • Students know how methods are trained, avoiding overfitting, and are optimised. • Students can perform simple ML tasks using Jupyter notebooks			
Course content	• Overview of machine learning tasks: regression, classification, simulation, anomaly detection. • Overview of basic principles: loss function and minimization, bias-variance-decomposition, overtraining and regularisation, hyperparameters, cross-validation, • Overview of ML algorithms: linear methods, ensemble methods / trees, neural networks (deep fully connected, convolutional, recurrent, generative adversarial, • Linear methods: linear regression, logistic regression, linear discriminant analysis, RIDGE and LASSO • Ensemble methods: bagging, boosting, Boosted Trees, Random Forests. • Fully connected networks: error-back-propagation, training, dropout, L2 regularisation, optimisation of network architecture and choice of features. • Convolutional and recurrent networks. • Networks for simulations tasks: Generative adversarial networks (GANs) • Networks for anomaly detection: autoencoders, bi-directional GANS.			
Previous knowledge	Basic knowledge in linear algebra, analysis and statistical data analysis			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	75 h	135 h	210 h
Usability	M.Sc. Physics modules: “Elective Subjects” (SL)			
Language	English			

5.2. Dark Matter (5 ECTS)

<table>
<tr><th>Lecture
07LE33V-DARK</th><th colspan="4">Dark Matter</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Experimental or Theoretical Particle Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>2+1</td><td>5</td><td>SL</td></tr>
<tr><td>Term</td><td colspan="4">The lecture is offered on an irregular basis.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• The students understand the evidence for dark matter.
• They know which role it plays in the Lambda-CDM model and can perform simple calculations for dark matter freeze-out.
• They learn about different techniques to detect dark matter experimentally.
• They are familiar with alternatives to particle dark matter and understand their phenomenology</td></tr>
<tr><td>Course content</td><td colspan="4">• Astrophysical evidence for Dark Matter.
• Introduction to early universe thermodynamics
• Dark Matter production in the early Universe
• Dark matter nucleon scattering and direct detection. Low-background techniques.
• Indirect detection of dark matter annihilations and decay
• Introduction to collider physics and accelerator searches for dark matter
• Alternatives to particle dark matter
• Hidden sector, very light DM</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Quantum Mechanics, basics of particle physics (e.g. Experimenal Physics V), Special Relativity, Thermodynamics</td></tr>
<tr><td rowspan="2">Workload (hours)</td><td>Course</td><td>Contact hrs</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>45 h</td><td>105 h</td><td>150 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. Physics modules: “Elective Subjects” (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

5.3. Cosmology (5 ECTS)

Lecture 07LE33V-COSM	**Cosmology**			
Lecturer/s	Lecturers from Theoretical Particle Physics			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L+E)	2+1	5	SL
Term	The lecture is offered on an irregular basis.			
Qualification objectives	• The students understand the mathematical tools to describe the Universe on large scales. • They are familiar with the origin of remnants from the early Universe, in particular photon decoupling and BBN. • They can derive the perturbed Einstein equations and understand the evolution of perturbations in an expanding background. • They are familiar with the basics of structure formation and the CMB.			
Course content	• The expansion of the Universe and the Hubble law. • FRW metric and derivation of the Friedmann equations • Equilibrium thermodynamics in a FRW background • Departures from equilibrium and the Boltzmann equation • Neutrino and photon decoupling • Big Bang Nucleosynthesis • Cosmological Perturbation Theory • Structure formation and CMB anisotropies • Inflation (optional)			
Previous knowledge	Special Relativity, Thermodynamics, basic knowledge of General Relativity helpful but not required			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	45 h	105 h	150 h
Usability	M.Sc. Physics modules: “Elective Subjects” (SL)			
Language	English			

5.4. Group Theory for Physicists (9 ECTS)

<table>
<tr><th>Lecture
07LE33V-GT</th><th colspan="4">Group Theory for Physicists</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Theoretical Particle Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL</td></tr>
<tr><td>Term</td><td colspan="4">The lecture is offered on an irregular basis.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• The students get some deeper understanding of symmetries in quantum mechanics in the language of group theory.
• They understand the most important notions of mathematical groups and their representations.
• They deepen their basic knowledge in the structure of the Lie groups SO(3) and SU(2), in their representations, and their appearance in physical applications and extend this knowledge to the group SU(3).
• The students become familiar with the general structure of Lie groups and Lie algebras and their representations.
• They know the classification of (semi)simple Lie groups and algebras and can make contact to the gauge groups in the quantum field theories of fundamental interactions.</td></tr>
<tr><td>Course content</td><td colspan="4">• Basic concepts and group theory in quantum mechanics (symmetry transformations in quantum mechanics, group-theoretical definitions, classes, invariant subgroups, group representations, characters, (ir)reducibility, Schur's lemmas)
• Finite groups (unitarity theorem, orthogonality relations, classic finite groups, applications in physics)
• SO(3) and SU(2) (basic properties, relation between SO(3) and SU(2), irreducible representations, product representations and Clebsch-Gordan decomposition, irreducible tensors, Wigner-Eckart theorem)
• SU(3) (basic properties, irreducible representations, product representations, applications in the quark model of hadrons)
• Lie groups (basic properties, Lie's theorems, Lie algebra, matrix representations and exponentiation)
• Semisimple Lie groups and algebras (basic concepts, Cartan subalgebra, Cartan-Weyl and Chevalley bases, root systems, classification of complex (semi)simple Lie algebras, Dynkin diagrams, finite-dimensional representations, a glimpse on applications in theories of fundamental interactions in particle theory)</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Quantum mechanics, linear algebra, analysis</td></tr>
<tr><td rowspan="2">Workload (hours)</td><td>Course</td><td>Contact hrs</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. Physics modules: “Elective Subjects” (SL)</td></tr>
</table>

Language	English

5.5. Physics of Microscopy and Image Formation (7 ECTS)

<table>
<tr><th>Module no.
07LE33M-MOIF</th><th colspan="4">Physics of Microscopy and Image Formation</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Prof. Dr. Alexander Rohrbach</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>Type</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>3+2</td><td>Lecture and exer-cises (L+E)</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">The lecture is offered in the winter term</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">The student should learn how to guide light through optical systems, how optical information can be described very advantageously by three-dimensional transfer functions in Fourier space, how phase information can be transformed to amplitude information to generate image contrast. Furthermore, one should learn that wave diffraction is does not reduce the information and how to circumvent the optical resolution limit. The student should learn to distinguish between coherent and incoherent imaging, learn about modern techniques using self-reconstructing laser beams, two photon excitation, fluorophores depletion through stimulated emission (STED) or multi-wave mixing by coherent anti-Stokes Raman scattering (CPLS).
The tutorials help the student to get a more in depth and thorough under-standing of the lecture. Here, a special focus is put on the transfer of knowledge obtained in the lecture. To achieve this, the students should pre-pare weekly exercise and present them during the tutorial. Only difficult exercises are presented by the tutors.</td></tr>
<tr><td>Course content</td><td colspan="4">The scientific breakthroughs and technological developments in optical microscopy and imaging have experienced a real revolution over the last 10-15 years. Hence, the 2014 Nobel-Prize for super-resolution microscopy could be seen as a logical consequence. This lecture gives an overview about physical principles and techniques used in modern photonic imaging.

Topics:
1. Microscopy: History, Presence and Future
2. Wave- and Fourier-Optics
3. Three-dimensional optical imaging and information transfer
4. Contrast enhancement by Fourier-filtering
5. Fluorescence – Basics and techniques
6. Point scanning and confocal microscopy
7. Microscopy with self-reconstructing beams
8. Optical tomography
9. Nearfield and Evanescent Field Microscopy
10. Super-resolution using structured illumination
11. Multi-Photon-Microscopy
12. Super resolution imaging by switching single molecules

The lecture has an ongoing emphasis on applications, but nevertheless presents a mixture of fundamental physics, compact mathematical descriptions and many examples and illustrations. The lecture aims to encompass the current state of a scientific</td></tr>
</table>

	field, which will influence the fields of nanotechnology and biology/medicine quite significantly.			
Literature	Optical Microscopy: • Jerome Mertz: Introduction to Optical Microscopy, Roberts & Co Publ. 2009 • U. Kubitschek, Fluorescence Microscopy, Wiley-Blackwell 2013 • Min Gu, Advanced optical imaging theory, Springer - Berlin, 1999 • James B. Pawley: Handbook of Biological Confocal Microscopy, Springer - Berlin, 2006 • Herbert Gross: Handbook of optical systems, Vol 2: Physical image formation, Wiley VCH 2005 General Optics: • Hecht, E. (2002). Optics, Addison Wesley. • Saleh, B. E. A. and M. C. Teich (1991). Fundamentals of Photonics, Wiley & Sons,Inc. • Herbert Gross: Handbook of optical systems, Vol 1-5			
Preliminaries / Previous knowledge				
Final Exam	Written or oral exam (120 min)			
Workload (hours)	**Course**	**Workload (hours)**	**Course**	**Workload (hours)**
	Lecture and exercises (L+E)	75 h	Lecture and exercises (L+E)	210 h
Usability	M.Sc. Physics: Elective Subjects (SL), M.Sc. Applied Physics: Applied Physics (PL or SL) or Elective Subjects (SL)			
Language	English			

5.6. Biophysik - Grundlagen und Konzepte (7 ECTS)

Module no. 07LE33M-BIOPHYS	**Biophysik - Grundlagen und Konzepte**			
Lecturer/s	Prof. Dr. Alexander Rohrbach			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L+E)	3+2	7	SL or PL
Term	The lecture is offered in the winter term			
Qualification objectives	Die Vorlesung stellt einen Streifzug durch die moderne Zellbiophysik dar, adressiert Fragen der aktuellen Forschung und stellt moderne Untersuchungsmethoden vor. Dies beinhaltet klassische, aber auch neueste physikalische Modelle und Theorien, welche in Kombination mit experimentellen Messmethoden einen erheblichen Fortschritt in der Biophysik, ermöglicht haben. Die Studierenden sollen lernen, wie Methoden aus der klassischen Mechanik mit denen der statistischen Physik verknüpft werden, um das Verhalten biologischer Strukturen in Zeit und Raum zu verstehen. Dies beinhaltet die Reduktion und Abstraktion komplexer biologischer Probleme, damit diese mathematisch und durch Computersimulationen beschrieben und so durch den Vergleich mit Messungen und Analysemethoden besser verstanden werden können. Die Vorlesung (3 ECTS) richtet sich an Physiker:innen und Ingenieur:innen im Master-studium. Der Vorlesungsstoff wird mit wöchentlichen Übungen (zusätzlich 3-4 ECTS) veranschaulicht und gefestigt.			
Course content	Die Vorlesung stellt Grundlagen und moderne Konzepte der Biophysik und der Physik der weichen Materie dar. Vielfältiges Anschauungsmaterial wird mit mathematischen Konzepten der statistischen Mechanik vorgestellt - im Ortsraum wie im Frequenzraum. Inhalte: 1. Aufbau der Zelle oder Das Rezept für biophysikalische Forschung 2. Diffusion und Fluktuationen 3. Mess- und Manipulationstechniken 4. Biologisch relevante Kräfte 5. Biophysik der Proteine 6. Polymerphysik einzelner Filamente 7. Visko-Elastizität und Mikro-Rheologie 8. Die Dynamik des Zytoskeletts 9. Molekulare Motoren 10. Membran-Biophysik 11. Anhang			
Literature	• Rob Phillips: Physical Biology of the Cell • Joe Howard: Mechanics of Motor Proteins and the Cytoskeleton • Gary Boal: Mechanics of the Cell • Erich Sackmann & Rudolf Merkel: Lehrbuch der Biophysik			

Preliminaries / Previous knowledge				
Final Exam	Written or oral exam (120 min)			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	75 h	135 h	210 h
Usability	M.Sc. Physics: Elective Subjects (SL), M.Sc. Applied Physics: Applied Physics (PL or SL) or Elective Subjects (SL)			
Language	German			

5.7. Nano-Photonics - Optical Manipulation and Particle Dynamics (7 ECTS)

Module no. 07LE33M-NANOOPT	**Nano-Photonics - Optical Manipulation and Particle Dynamics**			
Lecturer/s	Prof. Dr. Alexander Rohrbach			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L+E)	3+2	7	SL or PL
Term	The lecture is offered in the summer term			
Qualification objectives	In this lecture students will learn • the transfer from the Maxwell equations and the electromagnetic force density to optical forces and optical tweezers, which allow to control molecular processes relevant to cellular biology and medicine. • the basics of light scattering, how photons transfer momentum to microscopic objects and how scattered photons transfer information about the state of the objects. In contrast to incoherent photons, coherent light encodes significantly more information about small objects, which, driven by thermal forces, continuously change their position and orientation relative to their environment. All this can be directly measured through µs-nm particle tracking. • how smallest probes can interact on a molecular scale with their environment, which can be analyzed by correlations of changes in the probe's states. In this way, the interactions of probes with living cells give new insights into cellular diseases, such as bacterial and viral infections, but also exposure of particulate matter to lung cells.			
Course content	• Introduction • Light – Carrier of Information and Actor • Microscopy und Light Focussing • Light Scattering • Manipulation by Optical Forces • Particle Tracking beyond the Uncertainty Regime • Thermal Motion and Calibration • Photonic Force Microscopy • Applications in Biophysics and Medicine • Time-Multiplexing and holographic optical traps • Applications in Micro- and Nano-Technology • Appendix			
Literature	General optics: • Hecht, E. (2002). Optics, Addison Wesley. • Saleh, B. E. A. and M. C. Teich (1991). Fundamentals of Photonics, Wiley & Sons Nano optics • L. Novotny & B. Hecht, E. (2002). Principles of Optics, Cambridge. Statistical physics and thermodynamics • Standard text books			

	Chemical and biological forces and interactions • Leckband, D. & J. Israelachvili (2001). "Intermolecular forces in biology." Quart. Rev. Biophys 34: 105–267			
Final Exam	Written or oral exam (120 min)			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	75 h	135 h	210 h
Usability	M.Sc. Physics: Elective Subjects (SL), M.Sc. Applied Physics: Applied Physics (PL or SL) or Elective Subjects (SL)			
Language	English			

5.8. Wave Optics (7 ECTS)

Module no. 11LE50MO-5221S	**Wave Optics**			
Lecturer/s	Prof. Dr. Alexander Rohrbach			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L+E)	3+2	7	SL or PL
Term	The lecture is offered in the summer term			
Qualification objectives	The goal of this lecture is to teach the students how light interacts with small structures and how optical systems guide light. The students will start at Maxwell's equations and move on to the description of light as photon or wave, depending on the given problem. Furthermore, the close connection between spatial and temporal coherence, interference and holography is demonstrated. The last chapter teaches concepts of linear and non-linear light scattering, as well as the most important plasmonic effects. In total, the students learn how to shape light in three dimensions and how optical problems that arise in research and development are solved.			
Course content	1. Introduction Some motivation, literature and a bit of history 2. From Electromagnetic Theory to Optics What is light? Which illustrative pictures do the Maxwell equations provide? If matter, dielectric and metallic, consists of coupled, damped springs (harmonic oscillators), how does matter depend on the frequency of light? What do the wave equation and the Helmholtz equation express and how can one handle waves in position space and frequency space. 3. Fourier-Optics How does a wave transform position information into directional information? Why can this be well described by Fourier transformations in 1D, 2D and 3D? What has this to do with linear optical system theory including spatial frequency filters and the sampling theorem? 4. Wave-optical Light Propagation and Diffraction Different methods are introduced of how to describe the propagation of ways in position space and frequency space. We do the direct transfer from propagation to diffraction of light and momentum space. We treat evanescent waves, thin diffracted objects, the propagation of light in inhomogeneous media and the diffraction at gratings. This allows to discuss important active elements such as acousto-optic and spatial light modulators. We end with adaptive optics and phase conjugation. 5. Interference, Coherence and Holography We learn how a composition of k-vectors defines the phases of interfering waves and the resulting stripe patterns. The relative phases of each partial wave in space and time change the interference significantly and define the coherence of light - these concepts will be discussed in detail. We learn how to write and read phase information in holography.			

	6. Light Scattering and Plasmonics The interaction of light with matter is based on particle scattering: we discuss the theoretical concepts of light scattering on the background of Fourier theory. We expend these approaches to photon diffusion, nonlinear optics, fluorescence and Raman scattering or scattering at semiconductor quantum dots - which are all hot topics in modern Photonics. A big emphasis is put on the description of surface plasmons and particle plasmons, where light can be extremely confined.			
Literature	Accompanying to the lecture printed lecture notes with defined gaps (white boxes) are distributed.			
Final Exam	Written or oral exam (120 min)			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	75 h	135 h	210 h
Usability	M.Sc. Physics: Elective Subjects (SL), M.Sc. Applied Physics: Applied Physics (PL or SL) or Elective Subjects (SL)			
Language	English			

5.9. Laser-based Spectroscopy and Analytical Methods (5 ECTS)

Module no. 07LE33M-LSPEC	**Laser-based Spectroscopy and Analytical Methods**			
Lecturer/s	PD Dr. Frank Kühnemann (Fraunhofer IPM)			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L+E)	2+1	5	SL or PL
Term	The lecture is offered in the summer term			
Qualification objectives	At the end of the course, the students • Will have knowledge about laser-based spectroscopic methods, particularly with respect to analytical applications. • Will understand the physical principles of tuneable laser operation. • Will be enabled to evaluate the fundamental and practical limitations of detection techniques. • Will have insight into development processes necessary to transfer a scientific method into a practical tool for industrial environments. • Will be trained in the preparation and presentation of scientific talks.			
Course content	Lasers did become a powerful tool for measurement applications in areas like industry, medicine, or environment. The current course focuses on the use of tuneable lasers to interrogate the spectral “fingerprints” of gases, liquids and solids for analytical purposes. Typical examples are air quality monitoring or process control in industry. The **lecture** block in the first half of the course will give a comprehensive introduction into the following topics • Infrared molecular spectra • Tuneable lasers • Spectroscopic techniques (absorption, photoacoustic spectroscopy, cavity-based methods) • Background signals, noise and detection limits The **seminar** talks in the second block will focus on the application of different spectroscopic methods for analytical tasks. At the start of the course, students will choose from a list of provided topics to prepare a talk and a short written summary. The preparation will be supported by topical literature and discussion sessions with the course staff. Duration of the talks will be approximately 30 minutes, followed by a discussion of content and presentation style.			
Literature	• lecture script • recommended literature will be announced in the lecture			
Preliminaries / Previous knowledge	Advanced Optics and Lasers			
Final Exam	Oral (graded seminar talk) and written (talk summary)			

Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	45 h	105 h	150 h
Usability	M.Sc. Physics: “Elective Subjects” (SL), M.Sc. Applied Physics: “Applied Physics” (PL or SL) or “Elective Subjects” (SL)			
Language	English			

5.10. Photovoltaic Energy Conversion (5 ECTS)

Module no. 07LE33M-PHOTOVOLT	**Photovoltaic Energy Conversion**			
Lecturer/s	Dr. Uli Würfel (Fraunhofer ISE), Prof. Dr. Andreas Bett (Fraunhofer ISE)			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L+E)	2+1	5	SL or PL
Term	The lecture is offered in the winter term			
Qualification objectives	• Students have a profound understanding of the working principles of solar cells and are thus able to apply these principles to different kinds of solar cell configurations • Students are familiar with state-of-the-art solar cells, the processes limiting their conversion efficiency, how these factors can be identified and if they could (in principle) be overcome			
Course content	• Fundamentals of semiconductors, intrinsic and extrinsic, Fermi-Dirac statistics, bands • Generation, recombination and transport of charge carriers • Lifetime, diffusion length, pn-junction, ideal solar cell • Real solar cell structures, carrier selectivity & semi-permeable membranes • Characterisation methods • Overview about different PV technologies: Si-based, thin film, Organic, Perovskite, Concentrator-PV			
Literature	• lecture script • P. Würfel, Physics of Solar Cells, 2nd edition 2009, Wiley VCH			
Preliminaries / Previous knowledge	Basic knowledge of semiconductor physics is helpful but not mandatory			
Final Exam	Written exam (120 min) or oral exam (30 min)			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	45 h	105 h	150 h
Usability	M.Sc. Physics: Elective Subjects (SL), M.Sc. Applied Physics: Applied Physics (PL or SL) or Elective Subjects (SL)			
Language	English			

5.11. Multi-Junction Solar Cell Technology and Concentrator Photovoltaic (3 ECTS)

Module no. 11LE68MO-4103	**Multi-Junction Solar Cell Technology and Concentrator Photovoltaic**			
Lecturer/s	Prof. Dr. Andreas Bett (Fraunhofer ISE)			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L)	2	3	SL
Term	The lecture is offered in the summer term			
Qualification objectives	• Students have a profound understanding of the concept of of multi-junction solar cells and the underlying physical principles. • Students are familiar with concentrator photovoltaics and characterization & manufacturing of CPV systems			
Course content	• multi-junction solar cell approach to increase the sunlight conversion efficiency, different solar cell architectures • introduction III-V materials, adjustment of band-gap, growth techniques • methods for characterisation of III-V materials and multi-junction solar cells • PV concentrator technology: low and high concentration • components of CPV systems: optics, cells, manufacturing • CPV system analysis including an economical evaluation			
Literature	• "Solar Cells and Their Applications", L. Fraas, L.Partain, Wiley, 2010; • "Advanced Concepts in Photovoltaics", AJ Nozik, G. Conibeer, MC Beard, Royal Society of Chemistry, 2014; • "Next Generation Photovoltaics", AB Cristobal Lopez, A. Marti Vega, A. Luque Lopez, Springer Series in Optical Sciences 165, 2012, • "Concentrator Phtovoltaics", A Luque, V. Andreev, Springer Verlag, Series in Optical Sciences, 2011			
Preliminaries / Previous knowledge	-			
Final Exam	-			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L)	30 h	60 h	90 h
Usability	M.Sc. Physics: Elective Subjects (SL), M.Sc. Applied Physics: Applied Physics (PL or SL) or Elective Subjects (SL)			
Language	English			

5.12. Dynamic Systems in Biology (7 ECTS)

<table>
<tr><td>Module no.
07LE33M-DYNBIO</td><td colspan="4">Dynamic Systems in Biology</td></tr>
<tr><td>Lecturer/s</td><td colspan="4">Prof. Dr. Jens Timmer</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>3+2</td><td>7</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">The lecture is offered on an irregular basis</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• Students are familiar with classical and modern dynamic systems in biology.
• Students are able to mathematically formulate dynamic systems in biology as differential equations and implement these on the computer.</td></tr>
<tr><td>Course content</td><td colspan="4">• Numerical integration of differential equations
• Mathematical biology
• Population models
• Hodgkin-Huxley model
• Turing model
• Enzyme kinetics
• Systems biology
• Metabolism
• Signal transduction
• Gene regulation</td></tr>
<tr><td>Literature</td><td colspan="4">• J.D. Murray. Mathematical Biology, Springer</td></tr>
<tr><td>Preliminaries / Previous knowledge</td><td colspan="4">Basics of Analysis and Linear Algebra</td></tr>
<tr><td>Final Exam</td><td colspan="4">Written (120 min) or oral (30 min) exam</td></tr>
<tr><td rowspan="2">Workload (hours)</td><td>Course</td><td>Contact hrs</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>75 h</td><td>135 h</td><td>210 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. Physics: Elective Subjects (SL),
M.Sc. Applied Physics: Applied Physics (PL or SL) or Elective Subjects (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

5.13. Molecular Dynamics & Spectroscopy (7 ECTS)

<table>
<tr><th>Module no.
07LE33M- MOLDYN</th><th colspan="4">Molecular Dynamics & Spectroscopy</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Prof. Dr. Gerhard Stock</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>3+2</td><td>7</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">The lecture is offered on an irregular basis</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• Students have a profound knowledge of theoretical principles underlying the dynamics of molecular systems.
• Students are familiar with time-resolved spectroscopic techniques that are able to probe dynamics in molecular systems.</td></tr>
<tr><td>Course content</td><td colspan="4">• Time-Dependent Quantum Dynamics
• Density Matrix Theory
• Quantum-Classical Formulation
• Linear Spectroscopy
• Nonlinear Techniques
• Multidimensional Spectroscopy</td></tr>
<tr><td>Literature</td><td colspan="4">• P. Hamm, M. Zanni, Concepts and Methods of 2D Infrared Spectroscopy, Cambridge University Press, 2011
• V. May, O. Kühn, Charge and Energy Transfer Dynamics in Molecular Systems, Wiley-VCH, 2004
• S. Mukamel, Principles of Nonlinear Optical Spectroscopy, Oxford University Press, 1995</td></tr>
<tr><td>Preliminaries / Previous knowledge</td><td colspan="4"></td></tr>
<tr><td>Final Exam</td><td colspan="4">Written (120 min) or oral (30 min) exam</td></tr>
<tr><td rowspan="2">Workload (hours)</td><td>Course</td><td>Contact hrs</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>75 h</td><td>135 h</td><td>210 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. Physics: Elective Subjects (SL),
M.Sc. Applied Physics: Applied Physics (PL or SL) or Elective Subjects (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

5.14. Physics of Nano-Biosystems (5 ECTS)

<table>
<tr><th>Module no.
07LE33M-NANOBIO</th><th colspan="4">Physics of Nano-Biosystems</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Prof. Dr. Thorsten Hugel (Faculty of Chemistry), Dr. Thomas Pfohl</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L)</td><td>2+1</td><td>5</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">The lecture is offered regularly in the summer term.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• Students have a profound knowledge of the physical principles that govern biological systems in particular molecular machines.
• Students are familiar with the experimental methods to study biological systems in particular molecular machines.
• In the tutorials the students gain an in-depth understanding of of the lecture and discuss most recent literature.</td></tr>
<tr><td>Course content</td><td colspan="4">• Fundamental forces in Nano-Biosystems (elastic, viscous, thermal, chemical, entropic, polymerization)
• Concepts of equilibrium and non-equilibrium systems and measurements
• Jarzynski equation
• Linear and rotational molecular motors
• Molecular details of muscle function
• Optical and magnetic tweezers, AFM
• Single molecule force spectroscopy
• Single molecule fluorescence
• Concepts of nanotribology and biolubrication</td></tr>
<tr><td>Literature</td><td colspan="4">• Jonathon Howard: “Mechanics of Motor Proteins and the Cytoskeleton“ (2005)
• Phil Nelson: "Biological Physics: Energy, Information, Life" (2003)
• Rob Philips, Jane Kondev, Julie Theriot, Hernan Garcia: "Physical Biology of the Cell" (2012)
• Recent journal publications</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Basic knowledge of statistics and optics is helpful but not mandatory.</td></tr>
<tr><td>Final Exam</td><td colspan="4">Written (120 min) or oral exam (30 min)</td></tr>
<tr><td rowspan="2">Workload (hours)</td><td>Course</td><td>Contact hrs</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L)</td><td>30 h</td><td>120 h</td><td>150 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. Physics: Elective Subjects (SL),
M.Sc. Applied Physics: Applied Physics (PL or SL) or Elective Subjects (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

5.15. Physics of Medical Imaging Methods (5 ECTS)

<table>
<tr><td>Module no.
07LE33M-PHYSMED</td><td colspan="4">Physics of Medical Imaging Methods</td></tr>
<tr><td>Lecturer/s</td><td colspan="4">Prof. Dr. Michael Bock (Universitätsklinikum)</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L)</td><td>2+1</td><td>5</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">The lecture is offered regularly in the winter term.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">Students are able to distinguish and describe the physical basis of currently applied medical imaging methods
Students will become familiar with recent developments in medical imaging technology and their clinical application</td></tr>
<tr><td>Course content</td><td colspan="4">Medical imaging is becoming increasingly important in the detection of disease, in the management of the patients, and in the monitoring of a therapy. In this lecture, the physical basics of different medical imaging technologies will be presented and different clinical application scenarios will be discussed. The following topics will be addressed:
overview over the physics of medical imaging
Magnetic Resonance Imaging (MRI)
magnetisation, Bloch equations, relaxation times T1 and T2
spin gymnastics and image contrast
magnets, gradients and radio-frequency coils
quantitative MRI
functional MRI, flow, diffusion, perfusion measurements
Nuclear Medicine
principles of radio-tracer detection
scintigraphy
single photon emission computed tomography (SPECT)
positron emission tomography (PET)
ultrasound (US)
sound generation and propagation in tissue
US imaging
Doppler US
therapeutic applications of US (Lithotrypsy)
X-ray Imaging
properties and generation of X-rays
fluoroscopy
computed tomography
image reconstruction from projections
role of medical imaging in
the detection of disease
in patient management
therapy monitoring</td></tr>
<tr><td>Literature</td><td colspan="4">Oppelt A: Imaging Systems for Medical Diagnostics</td></tr>
</table>

	• Dössel O: Bildgebende Verfahren in der Medizin: Von der Technik zur medizinischen Anwendung			
Preliminaries / Previous knowledge				
Final Exam	Written (120 min) or oral exam (30 min)			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L)	45 h	105 h	150 h
Usability	M.Sc. Physics: Elective Subjects (SL), M.Sc. Applied Physics: Applied Physics (PL or SL) or Elective Subjects (SL)			
Language	English			

5.16. Biophysics of Cardiac Function and Signals (5 ECTS)

<table>
<tr><th>Module no.
07LE33M-CARDI</th><th colspan="4">Biophysics of cardiac function and signals</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Dr. Viviane Timmermann, Prof. Dr. Peter Kohl (Faculty of Medicine, Institute for Experimental Cardiovascular Medicine)</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L)</td><td>2+1</td><td>5</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">The lecture is offered regularly in the winter term.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">The basic concept of this lecture is to examine a biological system, analyse it and define mathematical equations in order to describe the system. In this lecture, the heart is used as this system. The students learn the electrical and mechanical function of the heart and its modelling. Additionally, the bioelectrical signals that are generated in the human body are described and how these signals can be measured, interpreted and processed. The content is explained both on the biological level and based on mathematical modelling.</td></tr>
<tr><td>Course content</td><td colspan="4">• Cell membrane and ion channels
• Cellular electrophysiology
• Conduction of action potentials
• Cardiac contraction and electromechanical interactions
• Optogenetics in cardiac cells
• Numerical field calculation in the human body
• Measurement of bioelectrical signals
• Electrocardiography
• Imaging of bioelectrical sources
• Biosignal processing</td></tr>
<tr><td>Literature</td><td colspan="4">• lecture slides</td></tr>
<tr><td>Preliminaries / Previous knowledge</td><td colspan="4">Basic interest in biology and computational modelling. Knowledge in Matlab or Python are beneficial</td></tr>
<tr><td>Final Exam</td><td colspan="4">Written (120 min) or oral exam (30 min)</td></tr>
<tr><td rowspan="2">Workload (hours)</td><td>Course</td><td>Contact hrs</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L)</td><td>45 h</td><td>105 h</td><td>150 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. Physics: Elective Subjects (SL),
M.Sc. Applied Physics: Applied Physics (PL or SL) or Elective Subjects (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

5.17. Computational Neuroscience: Models of Neurons and Networks (7 ECTS)

<table>
<tr><th>Module no.
07LE33M-Neuro</th><th colspan="4">Computational Neuroscience:
Models of Neurons and Networks</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Prof. Dr. Stefan Rotter (Faculty of Biology, Bernstein Center Freiburg)</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>2+2</td><td>7</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">The lecture is offered regularly in the summer term.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">The students have the competence to
• link mathematical models with biological phenomena arising in systems neuroscience both using theory and computer simulations;
• understand the fundamental trade-off between biological detail and mathematical abstraction, and evaluate its consequences;
• explain the steps necessary to develop and validate models of a biological neuron or a biological neuronal network;
• appreciate and explain the gain in understanding biological mechanisms that arise from the study of mathematical models of neuronal systems;
• critically discuss the limits of mathematical modelling and numerical methods in computational neuroscience.</td></tr>
<tr><td>Course content</td><td colspan="4">This lecture series covers important standard topics in computational neuroscience, focusing on dynamic networks of spiking neurons
• Mathematical concepts and methods
• Hodgkin-Huxley theory of the action potential
• Stochastic theory of ionic channels
• The integrate-and-fire neuron model
• Stochastic point processes
• Stochastic theory of synaptic integration
• Stochastic theory of spike generation: The perfect integrator
• Stochastic theory of spike generation: The leaky integrator
• Conductance based neurons and networks
• Correlated neuronal populations
• Pulse packets and synfire chains
• Random graphs and networks
• Dynamics of spiking networks
• Population dynamics of recurrent networks.</td></tr>
<tr><td>Literature</td><td colspan="4">• lecture slides
• a bibliography and web-links to complementary reading for each course day will be provided along with the slides of the lecture.</td></tr>
<tr><td>Preliminaries / Previous knowledge</td><td colspan="4">Familiarity with elementary calculus and linear algebra is assumed. Background in basic neurobiology is helpful, but not required.</td></tr>
</table>

Final Exam	Written exam (120 min), oral exam (60 min) or term paper (10 pages), in combination with course below.			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L)	105 h	105 h	210 h
Usability	M.Sc. Physics: Elective Subjects (SL), M.Sc. Applied Physics: Applied Physics (PL or SL) or Elective Subjects (SL)			
Language	English			

5.18. Computational Neuroscience: Simulation of Biological Neuronal Networks (5 ECTS)

Module no. 07LE33M-Neuro	**Computational Neuroscience:** **Simulation of Biological Neuronal Networks**			
Lecturer/s	Prof. Dr. Stefan Rotter (Faculty of Biology, Bernstein Center Freiburg)			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L+E)	1+2	5	SL or PL
Term	The lecture is offered regularly in the summer term.			
Qualification objectives	• link mathematical models with biological phenomena arising in systems neuroscience, both using theory and computer simulations; • implement and simulate simple neuronal network models using modern tools and methods of scientific programming (based on Python and NEST); • implement simple programs for data analysis and apply them to simulated data; • appreciate and explain the gain in understanding biological mechanisms that arise from the study of mathematical models of neuronal systems and their simulation • critically discuss the limits of mathematical modelling and numerical methods in computational neuroscience.			
Course content	This course covers the fundamentals of simulating networks of single-compartment spiking neuron models. We start from the concept of a point neuron and then introduce more complex topics such as phenomenological models of synaptic plasticity, connectivity patterns and network dynamics.			
Literature	• lecture slides • see also http://www.nest-initiative.org/ for some general information and an online tutorial on the BNN simulator NEST			
Preliminaries / Previous knowledge	Basic knowledge in scientific computing with Python is absolutely required. Self-study is possible, see http://www.python.org/ for some general information and an online tutorial on the programming language Python. Further documentation on the scientific libraries used in the course is also found online (see http://scipy.org/).			
Final Exam	Written exam (120 min), oral exam (60 min) or term paper (10 pages), in combination with course above.			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L)	60 h	90 h	150 h
Usability	M.Sc. Physics: Elective Subjects (SL), M.Sc. Applied Physics: Applied Physics (PL or SL) or Elective Subjects (SL)			
Language	English			

5.19. Physical Processes of Self-Assembly and Pattern Formation (7 ECTS)

<table>
<tr><th>Module no.
07LE33M-SELFAS</th><th colspan="4">Physical Processes of Self-Assembly and Pattern Formation</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Prof. Dr. Günter Reiter</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>3+2</td><td>7</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">The lecture is offered on an irregular basis.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">Students will learn how structural organization, i.e., the increase in internal order of a system, can lead to regular patterns on scales ranging from molecular to the macroscopic sizes. They will understand the physics of how molecules or objects put themselves together without guidance or management from an outside source.</td></tr>
<tr><td>Course content</td><td colspan="4">Goal:
Questions about how organization and order in various systems arises have been raised since ancient times. Self-assembling processes are common throughout nature and technology. The ability of molecules and objects to self-assemble into supra-molecular arrangements is an important issue in nanotechnology. The limited number of forms and shapes we identify in the objects around us represent only a small sub-set of those theoretically possible. So why don't we see more variety? To be able answering such a question we have to learn more about the physical processes responsible for self-organization and self-assembly.

Preliminary program:
“Physical laws for making compromises”
Self-assembly is governed by (intermolecular) interactions between pre-existing parts or disordered components of a system. The final (desired) structure is 'encoded' in the shape and properties of the basic building blocks.
In this course, we will discuss general rules about growth and evolution of structures and patterns as well as methods that predict changes in organization due to changes made to the underlying components and/or the environment.</td></tr>
<tr><td>Literature</td><td colspan="4">• Yoon S. LEE, Self-Assembly and Nanotechnology: A Force Balance Approach, Wiley 2008
• Robert KELSALL, Ian W. HAMLEY, Mark GEOGHEGAN, Nanoscale Science and Technology, Wiley, 2005
• Richard A.L. JONES, Soft Machines: Nanotechnology and Life, Oxford University Press, USA 2008
• Philip BALL, Shapes, Flow, Branches. Nature's Patterns: A Tapestry in Three Parts, Oxford University Press, USA
• J.N. ISRAELACHVILI, Intermolecular and Surface Forces, Third Edition, Elsevier, 2011
• Continuative and supplementary references will be given during the lecture.</td></tr>
<tr><td>Preliminaries / Previous knowledge</td><td colspan="4">Experimentalphysik IV (Condensed Matter)</td></tr>
</table>

Final Exam	Written (120 min) or oral (30 min) exam			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	75 h	135 h	210 h
Usability	M.Sc. Physics: Elective Subjects (SL), M.Sc. Applied Physics: Applied Physics (PL or SL) or Elective Subjects (SL)			
Language	English			

5.20. Fundamentals of Semiconductors & Optoelectronics (5 ECTS)

<table>
<tr><th>Module no.
07LE33M- HL</th><th colspan="4">Fundamentals of Semiconductors & Optoelectronics</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">apl. Prof. Dr. Joachim Wagner, Prof. Andreas Bett (Fraunhofer ISE)</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>2+1</td><td>5</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">The lecture is offered in the winter term</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• Students become familiar with fundamental concepts of semiconductor physics as well as techniques for the fabrication of bulk semiconductor materials and epitaxial semiconductor layers; furthermore, they gain knowledge in experimental techniques for the characterization of semiconductors as well as for determining band structure parameters.
• Students become also familiar with the working principle and different variants of key optoelectronic devices.</td></tr>
<tr><td>Course content</td><td colspan="4">• Inorganic crystalline semiconductor materials (such as Si and GaAs)
• Fabrication of bulk semiconductor crystals and epitaxial layers
• Electronic band structure, tight-binding vs. nearly free electron approach
• Effective mass of electrons and holes, n- and p-type doping
• Density of states, statistics of electrons and holes
• Electrical transport by electrons and holes, electric fields and currents
• Quantization effects in semiconductors, quantum films and superlattices
• p-n-junction, photodiode, light emitting diode (LED), diode laser</td></tr>
<tr><td>Literature</td><td colspan="4">• H. Ibach, H. Lüth, „Festkörperphysik" (Springer, 2009)
• K. Seeger, „Semiconductor Physics“ (Springer, 2004)
• P. Yu, M. Cardona, „Fundamentals of Semiconductors“ (Springer, 2010)</td></tr>
<tr><td>Preliminaries / Previous knowledge</td><td colspan="4">Solid-state physics and theoretical physics at the level of a BSc in Physics</td></tr>
<tr><td>Final Exam</td><td colspan="4">Oral exam (30 min)</td></tr>
<tr><td rowspan="2">Workload (hours)</td><td>Course</td><td>Contact hrs</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>45 h</td><td>105 h</td><td>150 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. Physics: Elective Subjects (SL),
M.Sc. Applied Physics: Applied Physics (PL or SL) or Elective Subjects (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English or German</td></tr>
</table>

5.21. Semiconductor Devices (5 ECTS)

Module no. 07LE33M- HLBAU	**Semiconductor Devices**			
Lecturer/s	apl. Prof. Dr. Harald Schneider (Helmholtz-Zentrum Dresden-Rossendorf HZDR)			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L+E)	2+1	5	SL or PL
Term	The lecture is offered in the summer semester as a block course during the Pentecost break (May/June)			
Qualification objectives	• Students are familiar with fundamental concepts of semiconductor physics. • They know the principle of basic and advanced semiconductor devices.			
Course content	• Transport phenomena • Metal-semiconductor-contact, Schottky-Diode • p-n junction: diode rectifier, photodiode, LED, laserdiode, solar cell • Bipolar transistors, HBT • Field effect-transistors: JFET, MESFET, HEMT, MOSFET, FGFET • Quantum structure-elements: RTD, QWIP, QCL, ICL			
Literature	• S.M. Sze and K.K. Ng, Physics of Semiconductor Devices, Wiley, 2006 • S.M. Sze, Semiconductor Devices, Wiley, 2001			
Preliminaries / Previous knowledge	Experimentalphysik IV (Solid state physics), lecture „Fundamentals of Semiconductors & Optoelectronics" (apl. Prof. J. Wagner)			
Final Exam	Oral exam (30 min)			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	45 h	105 h	150 h
Usability	M.Sc. Physics: Elective Subjects (SL), M.Sc. Applied Physics: Applied Physics (PL or SL) or Elective Subjects (SL)			
Language	English or German			

5.22. Theory and Modeling of Materials (5 ECTS)

<table>
<tr><th>Module no.
07LE33M- MODMAT</th><th colspan="4">Theory and Modeling of Materials</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">apl. Prof. Dr. Christian Elsässer (Fraunhofer IWM)</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>2+1</td><td>5</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">Courses of the lecture series are offered regularly in alternating order.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• Students become able to develop and apply theoretical models to investigate practical problems of the physics of materials
• Students become familiar with theoretical condensed-matter physics and computational modeling and simulation of materials</td></tr>
<tr><td>Course content</td><td colspan="4">The series of one- or two-semester elective-subject lectures introduces theoretical models and computational methods of solid-state physics for the description of many-electron systems, by means of which cohesion and structure, physical, chemical, or mechanical properties of perfect crystals and real materials can be understood qualitatively and calculated quantitatively on a microscopic fundament.
The lecture series comprises courses on, e.g., these topics:
• Electronic-structure theory of condensed matter I + II
• Superconductivity I (phenomenology) + II (microscopic theory)
• Theoretical models for magnetic properties of materials
• Theory of atomistic and electronic structures at interfaces in crystals
• etc.
The content of each course will be announced for each semester.</td></tr>
<tr><td>Literature</td><td colspan="4">recommended literature will be announced in each lecture</td></tr>
<tr><td>Preliminaries / Previous knowledge</td><td colspan="4">Theoretical physics and solid-state physics on the level of a BSc in Physics</td></tr>
<tr><td>Final Exam</td><td colspan="4">Oral exam (30 min)</td></tr>
<tr><td rowspan="2">Workload (hours)</td><td>Course</td><td>Contact hrs</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>45 h</td><td>105 h</td><td>150 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. Physics: Elective Subjects (SL),
M.Sc. Applied Physics: Applied Physics (PL or SL) or Elective Subjects (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

5.23. Quantum Transport (7 ECTS)

<table>
<tr><td>Module no.
07LE33M- QTRANS</td><td colspan="4">Quantum Transport</td></tr>
<tr><td>Lecturer/s</td><td colspan="4">PD Dr. Michael Walter, PD Dr. Thomas Wellens</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>3+2</td><td>7</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">The lecture is offered on an irregular basis.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• Students become familiar with advanced theoretical tools relevant for quantum transport theory (Green functions, scattering theory, diagrammatic methods for performing disorder average, Landau-Büttiker formalism)
• Students understand how quantum effects modify the transport behaviour in various physical systems</td></tr>
<tr><td>Course content</td><td colspan="4">How to describe transport of a particle from one point in space to another one is a fundamental problem in theoretical physics, which is at the same time highly relevant for many technological applications, for example in electronics (transport of electrons) or solar cells (separation of positive and negative charge carriers generated by light). On microscopic scales, quantum properties -- such as the wave nature of a quantum particle, or the quantization of energy levels -- become relevant and make quantum transport different from classical transport based on Newton's equations. In this lecture, we will approach the topic of quantum transport from different perspectives, with focus on (i) transport of quantum particles (or waves) in disordered structures which are described in a statistical way, and (ii) the explicit description of transport in an electronic device at the atomic scale, with the single molecule transistor as prominent example, which is likely to be the basis of future electronics.</td></tr>
<tr><td>Literature</td><td colspan="4">• E. Akkermans and G. Montambaux, Mesoscopic Physics of electrons and photons (Cambridge University Press, Cambridge, 2007)
• P. Sheng, Introduction to Wave Scattering, Localization, and Mesoscopic Phenomena (Academic Press, New York, 1995)
• S. Datta, Quantum Transport: Atom to Transistor (Cambridge, 2005).</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Basic quantum mechanics</td></tr>
<tr><td>Final Exam</td><td colspan="4">Written (120 min) or oral (30 min) exam</td></tr>
<tr><td rowspan="2">Workload (hours)</td><td>Course</td><td>Contact hrs</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>75 h</td><td>135 h</td><td>210 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. Physics: Elective Subjects (SL),
M.Sc. Applied Physics: Applied Physics (PL or SL) or Elective Subjects (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

5.24. Low Temperature Physics (9 ECTS)

<table>
<tr><th>Module no.
07LE33M- LTPHYS</th><th colspan="4">Low Temperature Physics</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Prof. Dr. Frank Stienkemeier</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Term</td><td colspan="4">The lecture is offered on an irregular basis.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• The lecture Low Temperature Physics provides an introduction to the physical principles as well as the experimental techniques for working at low temperatures and reaching extreme low temperature conditions.
• Students will be familiar with material properties at low temperatures.
• Students will know how low temperatures are generated, how cryostats are designed, and what materials are used.
• Students will learn modern scientific work at low as well as ultra-low temperatures</td></tr>
<tr><td>Course content</td><td colspan="4">• Temperature-dependent material properties (Phase diagrams and physical states, thermal expansion, friction, viscosity, thermal conductivity, electrical conductivity)
• Superfluidity
• Matrix and helium droplet isolation techniques
• Superconductivity
• Generation of low temperatures (refrigerators, Joule-Thompson effect, cryocoolers)
• Measurements at low temperature conditions (temperature, pressure, levels of liquids, magnetic measurements, acoustic measurements, etc.)
• Cryostats (thermal insulation, materials, containers and transfer lines, etc.)
• Cold dilute samples (cold molecular beams, trapped molecules and trapped ions)
• Ultra-cold temperatures</td></tr>
<tr><td>Literature</td><td colspan="4">• Enss, Hunklinger, Tieftemperaturphysik, Springer (2000)
• Frank Pobell, Matter and Methods at Low Temperatures, Springer (1996)
• J.G. Weisend II, Handbook of Cryogenic Engineering, Taylor & Francis (1998)</td></tr>
<tr><td>Preliminaries / Previous knowledge</td><td colspan="4">Experimental Physics I-IV
Quantum Mechanics</td></tr>
<tr><td>Final Exam</td><td colspan="4">Written (120 min) or oral (30 min) exam</td></tr>
<tr><td rowspan="2">Workload (hours)</td><td>Course</td><td>Contact hrs</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
</table>

Usability	M.Sc. Physics: Advanced Physics 2 (PL), Advanced Physics 3 (SL), Elective Subjects (SL), M.Sc. Applied Physics: Advanced Experimental Physics (PL), Applied Physics (PL or SL) or Elective Subjects (SL)
Language	English

5.25. Statistics and Numerics (7 ECTS)

Module no. 07LE33M-STATNUM	**Statistics and Numerics**			
Lecturer/s	Prof. Dr. Jens Timmer			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L+E)	3+2	7	SL or PL
Term	The lecture is offered on an irregular basis			
Qualification objectives	• Students are familiar with the basic concepts of statistical reasoning. • Students are able to mathematically formulate statistical and numerical problems. • Students can implement computer programs to solve statistical and numerical problems.			
Course content	• Random variables • Parameter estimation • Test theory • Solution of systems of linear equations • Optimization • Non-linear modeling • Kernel estimator • Integration of ordinary, partial and stochastic differential equations • Spectral analysis • Markov Chain Monte Carlo procedures			
Literature	Press et al. Numerical Recipes, Cambridge University Press			
Preliminaries / Previous knowledge	Basics of Analysis and Linear Algebra			
Final Exam	Written (120 min) or oral (30 min) exam			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	75 h	135 h	210 h
Usability	M.Sc. Physics: Elective Subjects (SL), M.Sc. Applied Physics: Applied Physics (PL or SL) or Elective Subjects (SL)			
Language	English or German			

5.26. Computational Physics: Density Functional Theory (7 ECTS)

Module no. 07LE33M-DFT	**Computational Physics: Density Functional Theory**			
Lecturer/s	Prof. Dr. Michael Moseler			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L+E)	3+2	7	SL or PL
Term	The lecture is offered on an irregular basis			
Qualification objectives	• Students are familiar with electronic structure calculations. • Students are familiar with the basic Hamiltonian of the electronic structure problem and electronic many-body wave function. • Students know the Hartree-Fock equations and post Hartree-Fock methods – such as Møller-Plesset and Configurational Interaction. • Students are familiar with the Hohenberg-Kohn-theorem, the Kohn-Sham-equations, the concept of an exchange-correlation potential and the various local approximations to it. • Student arefamiliar with time-dependent DFT and know the Runge-Gross-theorem and the time-dependent Kohn-Sham-equations.			
Course content	Density functional theory (DFT) has become one of the most important tools for the numerical solution of the electronic many-body Schrödinger equation. It is currently used by many material scientists to study the properties complex systems containing up to several thousand atoms and electrons. This lecture introduces the theoretical foundations of DFT within the Hohenberg-Kohn-Sham frame work. It also touches numerical questions in an accompanying hands-on course. Numerical exercises will cover the electronic structure of atoms and nanoparticles.			
Literature	Lecture script: Electronic structure of matter			
Preliminaries / Previous knowledge	Basic knowledge in many-body quantum mechanics			
Final Exam	Written or oral exam (60 min)			
Workload (hours)	**Course**	**Contact hrs**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	75 h	135 h	210 h
Usability	M.Sc. Physics: Elective Subjects (SL), M.Sc. Applied Physics: Applied Physics (PL or SL) or Elective Subjects (SL)			
Language	English			