

Handbook of Modules

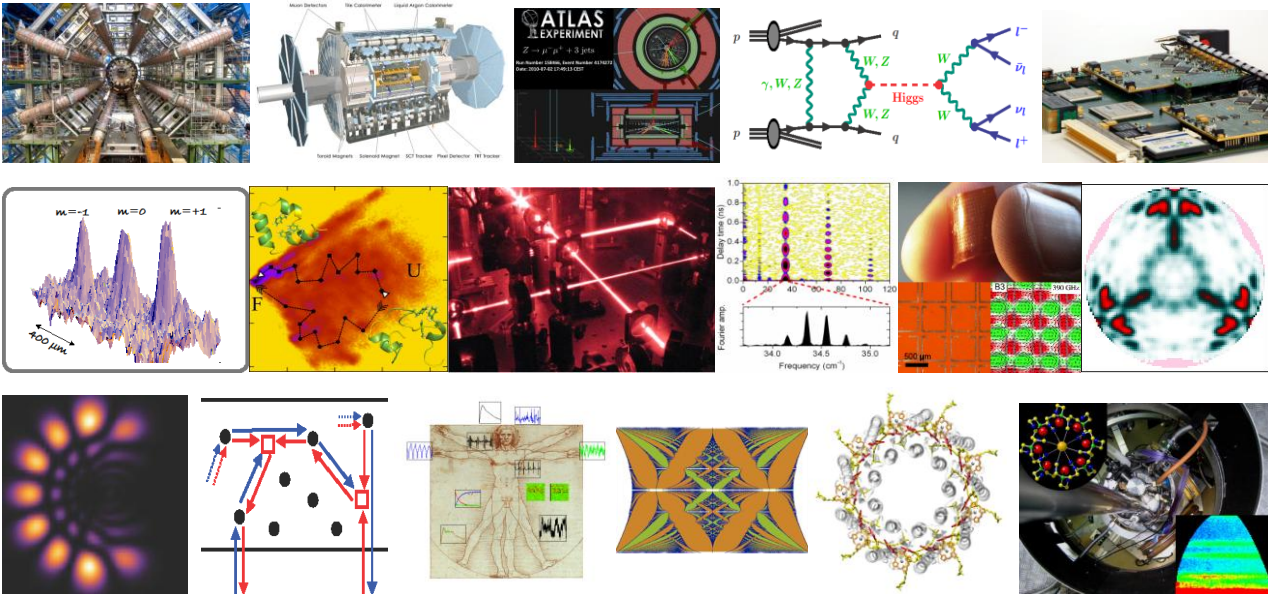
Master of Science (M.Sc.)

PHYSICS

Albert-Ludwigs-University of Freiburg / Germany



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Master of Science in Physics

Formalia

Final degree	Master of Science
Character of study	Postgraduate research-focused consecutive study
Application for admission	Yes (Link)
Begin of study	Winter term or summer term
Regular duration of study	4 terms
Language	generally English, partly German

Regulations (in German)

- General examination regulations ([Link](#), see pages 269-284)
- Specific examination regulations for the study program Master of Science in ([Link](#))
- Admission regulation ([Link](#))

Preliminaries

Why studying physics at the Masters degree ?

The M.Sc. Physics degree program completes at a more comprehensive level the study of physics after receiving the degree of a Bachelor of Science in Physics. The Master degree program imparts advanced scientific knowledge in physics with particular first specializations and a final one-year Master Thesis, which proves the ability of independent scientific work, building upon the basic principles of physics taught during the Bachelor program. For any kind of research career related to physics, receiving the degree as Master of Science in Physics, which is equivalent to the previous qualification as “Diplomphysiker”, is advisable. The Bachelor/Master structure of university degrees is still young in Germany, but first experiences show that the typical professional areas for university degree holders in physics – software or technical industry, consulting and financial management, etc. – appreciate higher qualification. Moreover, after receiving the Bachelor degree, passing the Masters program is also the next natural step towards a PhD study, which in turn is a prerequisite for leading positions in economy or industry, or for a later university career.

The Masters program at the University of Freiburg

At the Albert-Ludwigs-University Freiburg the Master program in physics builds on three core areas in physics: “Condensed/Soft Matter”, “Atomic, Molecular, and Optical Physics” and “Particles and Fields”. These areas cover both theoretical and experimental aspects of problems ranging from the fundamental constituents and interactions of matter to complex atomic and molecular systems with applications that vary from pure physics to biology, chemistry, medical science, and engineering. Apart from solid physics education, studying physics at Freiburg offers access to fundamental research as well.

The Masters degree program in Freiburg is held in English, with only very few exceptional lectures in German, and addresses German as well as international students with the degree of a Bachelor in Physics (or an equivalent degree in related sciences). The program runs over four semesters, i.e. two years, including a final one-year thesis, which can be accomplished either at the Physics Institute of the University directly or at associated research institutes – the Freiburg Materials Research Center (FMF), the Fraunhofer Institute for Solar Energy Systems (ISE), the Kiepenheuer Institute for Solar Physics (KIS), and the Freiburg Center for Data Analysis and Modeling (FDM).

Structure of Study

General plan

The first two semesters (first year)

- complete the basic education in quantum mechanics in the lecture “Advanced Quantum Mechanics”,
- extend the students’ knowledge to various specialized fields in the lectures within the two modules “Advanced Theory / Experiment” and “Elective Subjects”,
- intensify the presentation skills of the students in a seminar (module Term Paper),
- serve as an orientation phase before the required specialization in the final Master Thesis, and
- should comprise a well balanced selection of specialized courses between broadening the physics education and taking the first step towards deeper specialization in a specific field.

In the third and fourth semesters (second year)

- the Research Traineeship is the preparation phase for the Master Thesis and is usually accomplished within the research group in which the Master Thesis will be prepared, and
- the Master Thesis is the first step towards the ability of independent research and represents the last step to the Master degree.

Typical programmes of study

Example 1:

Semester	Courses
1	<ul style="list-style-type: none"> • Advanced Quantum Mechanics • 1 course from modules Advanced Theory / Experiment (10 ECTS) • 1 course from module Elective Subjects (10 ECTS)
2	<ul style="list-style-type: none"> • 1 course from modules Advanced Theory / Experiment (10 ECTS) • 1 course from module Elective Subjects (10 ECTS) • Term Paper (seminar)
3	Research Traineeship
4	Master Thesis

Example 2:

Semester	Courses
1	<ul style="list-style-type: none"> • Advanced Quantum Mechanics • 1 course from modules Advanced Theory / Experiment (10 ECTS) • Term Paper (seminar)
2	<ul style="list-style-type: none"> • 1 course from modules Advanced Theory / Experiment (10 ECTS) • 2 courses from module Elective Subjects (10 ECTS each)
3	Research Traineeship
4	Master Thesis

Comments:

- Within the modules Advanced Theory / Experiment 20 ECTS points have to be collected in total, where any distribution among theoretical and experimental lectures is allowed. Courses of type “3+3” (i.e. 3 weekly lecture hours + 3 weekly hours for exercises) or of type “4+2” usually correspond to 10 ECTS points.
- Within the module Elective Subjects 20 ECTS points have to be collected in total. Again, courses of types “3+3” or “4+2” correspond to 10 ECTS points. Courses of this module may also include lectures held by other faculties.
- Any order of courses in the first two semesters is possible.

Detailed survey of modules and courses

Module	Type of course (Lecture / Exercises)	ECTS points	Compulsory course / Elective course	Recommended term	Course Achievement (without grade) / Academic Record (with grade)
1. Advanced Quantum Mechanics	L + E	10	CC	1 or 2	AR: written and/or oral
2. Advanced Theory “Condensed/Soft Matter” or “Atomic, Molecular, and Optical Physics” or “Particles and Fields”	L + E	20	EC	1 or 2	AR: written and/or oral
and / or					
3. Advanced Experiment “Condensed/Soft Matter” or “Atomic, Molecular, and Optical Physics” or “Particles and Fields”					
4. Elective Subjects Advanced physics and/or mathematics and/or study field by own choice	not fixed	20	EC	1 or 2	CA
5. Term Paper	S	10	CC	1 or 2	AR: oral
6. Master Research					
Research Traineeship	PC	30	CC	3	CA
Master Thesis		28 2	CC	4	AR: Master Thesis (written) CA: Presentation (oral)

Abbreviations:

Type of course: L = Lecture, E = Exercises, S = Seminar, PC = Practical courses;

CC = Compulsory Course, EC = Elective Course;

CA = Course Achievement (without grade), AR = Academic Record (with grade).

In the context of the compulsory courses “Advanced Theory” and/or “Advanced Experiment”, at least two of the three fields “Condensed/Soft Matter” or “Atomic, Molecular, and Optical Physics” or “Particle and Fields” are to be selected, in which courses are to be completed (with 10 ECTS points each). The selected fields can originate either from one or from both compulsory modules.

In the context of the module “Elective Subjects”, at least 10 ECTS points (of 20 overall) have to be from the fields of “Advanced Physics” and/or “Mathematics”, i.e. a maximum of 10 ECTS points can be acquired upon studying courses by own choice; these courses can also be held by other faculties. On request the examination committee can admit other advanced courses. The courses that had already been taken in the Bachelor study are not allowed.

The admission requirement for the “Research Traineeship” is the achievement of the module “Term Paper” and of at least 20 ECTS points from the modules “Advanced Quantum Mechanics” and/or “Advanced Theory” and/or “Advanced Experiment”. The admission requirement for the “Master Thesis” is the achievement of the “Research Traineeship”.

Descriptions of modules

Module Advanced Quantum Mechanics

Course in module	Type of course	CC/EC	ECTS	CA/AR
Advanced lecture on quantum mechanics	L+E	CC	10	AR

Duration and volume: Duration of 1 term. Volume 4: contact hours per week for lecture and 2 contact hours per week for exercises.

Frequency of course: Yearly in winter term.

Lecturer: Lecturers of theoretical physics of the Institute of Physics.

Course content:

- symmetries in quantum mechanics,
- spin, addition of angular momenta, Wigner-Eckart theorem,
- time-dependent perturbation theory,
- scattering theory,
- many-particle systems,
- quantization of the electromagnetic field,
- relativistic quantum mechanics, Dirac equation.

Qualification objectives: Knowledge of advanced concepts and applications of quantum mechanics in the area of symmetries, perturbation theory, scattering theory, many-particle systems; basic concepts of field quantization and relativistic quantum mechanics.

Criteria of the written or oral examinations: They are given by the lecturer. Course achievements can be required for admission to academic record achievement (usually regular and successful participation in the exercises).

Registration for examination: Online, according to information by the Examination Office of Physics.

Literature, materials: Information on literature and text books is given during the course; depending the lecturer a script is available. Script and exercise sheets are usually available online, web pages to lecture and exercises are accessible via the homepage of the lecturer or the online lecture timetable:
<http://www.physik.uni-freiburg.de/Fakultaet/verz.html>

Previous knowledge: Contents of lectures Theoretical Physics I – V.

Module Advanced Theory

Courses in module	Type of course	CC/EC	ECTS	CA/AR
Advanced lectures on theoretical physics	L+E	EC	up to 20	AR

Courses

Field	Courses
Condensed/Soft Matter	Condensed Matter Physics
	Open Systems
Atomic, Molecular, and Optical Physics	Atomic and Molecular Physics
	Computational Physics
Particles and Fields	Relativistic Quantum Field Theory
	Gauge Theories – Strong Interactions, Electroweak Interactions and New Physics beyond the Standard Model
	General Relativity

Duration and volume: Duration of 1 term. Volume per course: either 3 contact hours per week for lecture with 3 contact hours per week for exercises or 4 contact hours per week for lecture with 2 contact hours per week for exercises, corresponding to 10 ECTS points in either case. In total 20 ECTS points are required from the two modules Advanced Theory / Experiment.

Frequency of course: Each course not less than once in the two-year cycle, in the summer term or in the winter term.

Lecturer: Lecturers of theoretical physics of the Institute of Physics.

Course content: See online lecture timetable for detailed descriptions.

Qualification objectives: Knowledge of advanced concepts and special subjects in the following areas of theoretical physics: condensed / soft matter, atomic, molecular and optical physics, or particle physics.

Criteria of the written or oral examinations: They are given by the lecturer. Course achievements can be required for admission to academic record achievement (usually regular and successful participation in the exercises).

Registration for examination: Online, according to information by the Examination Office of Physics.

Literature, materials: Information on literature and text books is given during the course; depending the lecturer a script is available. Script and exercise sheets are usually available online, web pages to lecture and exercises are accessible via the homepage of the lecturer or the online lecture timetable: <http://www.physik.uni-freiburg.de/Fakultaet/verz.html>

Previous knowledge: Contents of lectures Theoretical Physics I – V.

Module Advanced Experiment

Courses in module	Type of course	CC/EC	ECTS	CA/AR
Advanced lecture on experimental physics	L+E	EC	up to 20	AR

Courses

Field	Courses
Condensed/Soft Matter	Advanced Solid State Physics
	Polymer Physics
Atomic, Molecular, and Optical Physics	Advanced Optics and Lasers
	Advanced Atomic and Molecular Physics
Particles and Fields	Particle Physics II
	Detectors
	Hadron Collider Physics
	Astro-Particle Physics

Duration and volume: Duration of 1 term. Volume per course: either 3 contact hours per week for lecture with 3 contact hours per week for exercises or 4 contact hours per week for lecture with 2 contact hours per week for exercises, corresponding to 10 ECTS points in either case. In total 20 ECTS points are required from the two modules Advanced Theory / Experiment.

Frequency of course: Each course not less than once in the two-year cycle, in the summer term or in the winter term.

Lecturer: Lecturers of experimental physics of the Institute of Physics.

Course content: See online lecture timetable for detailed descriptions.

Qualification objectives: Knowledge of advanced concepts and special subjects in the following areas of experimental physics: condensed / soft matter, atomic, molecular and optical physics, or particle physics.

Criteria of the written or oral examinations: They are given by the lecturer. Course achievements can be required for admission to academic record achievement (usually regular and successful participation in the exercises).

Registration for examination: Online, according to information by the Examination Office of Physics.

Literature, materials: Information on literature and text books is given during the course; depending the lecturer a script is available. Script and exercise sheets are usually available online, web pages to lecture and exercises are accessible via the homepage of the lecturer or the online lecture timetable: <http://www.physik.uni-freiburg.de/Fakultaet/verz.html>

Previous knowledge: Contents of lectures Experimental Physics I – V.

Module Elective Subjects

Courses in module	Type of course	CC/EC	ECTS	CA/AR
Elective Subjects: • Advanced Physics and/or Mathematics and/or • Courses by own choice (can be held by another faculty)	not fixed	EC	20	CA

Duration and volume: Typically 2 courses with duration of 1 term each. Volume per course: about 3 or 4 contact hours per week for lecture and 2 or 3 contact hours per week for exercises, respectively.

Frequency of course: Courses of the modules Advanced Theory / Experiment are held regularly as stated above, a flexible survey of additional courses is offered without fixed frequency.

Courses in module Elective Subjects: In the context of module Elective Subjects, at least 10 ECTS points (of 20 in total) have to be taken from the fields of Advanced Physics and/or Mathematics (the courses that had already be taken in the first and second term of the Bachelor study are not allowed). On request the examination committee can admit also other advanced courses. Maximally 10 ECTS points can be acquired upon studying courses by own choice; these courses also be held by another faculty.

Course content and qualification objectives: Advanced knowledge of special subjects in physics or mathematics and/or related scientific areas.

Criteria for course achievement: They are given by the lecturer.

Registration for course achievement: Information by corresponding faculty.

Previous knowledge: Information by corresponding faculty.

Learning language: Information by corresponding faculty.

Module Term Paper

Course in Module	Kind of course	CC/EC	ECTS	CA/AR
Term Paper	S	CC	10	AR

Duration and volume: Duration of 1 term. Volume: about 2 contact hours per week for seminar.

Frequency of course: The research groups of the Institute of Physics offer a survey of seminars each term.

Lecturer: Lecturers of experimental and theoretical physics of the Institute of Physics.

Course content: The course “Term Paper“ is held in form of seminars by all three core areas of physics at the Institute of Physics. The seminar comprises approximately 10 lectures from a coherent field of physics or a neighbouring scientific area and consists of the elaboration of a lecture to a physics topic or an adjacent area with written documentation (handout) and an oral presentation. Beyond that, active participation in all lectures of the seminar is expected.

Qualification objectives: Handling scientific literature and search in scientific publications; learning of didactical preparation and presentation of a topic of current physical research; presentation and discussion in a group of researchers.

Academic record: Written documentation (handout) and oral presentation of a current research topic.

Registration for examination: Written form with the corresponding lecturers.

Literature, materials: Literature and references will be given at the beginning of the course.

Previous knowledge: According to corresponding lecturer.

Module Master Research

Course in module	Type of course	CC/EC	ECTS	CA/AR
Research Traineeship	PC	CC	30	CA
Master Thesis		CC	28 2	AR: Master Thesis CA: Presentation

Duration and volume: Research Traineeship and Master Thesis take each 1 term with a full time extent.

Frequency of course: Each term.

Lecturer: Lecturers of theoretical and experimental physics of the Institute of Physics.

Course content:

Research Traineeship: Scientific specialization, acquiring preliminary knowledge for the subject of Master Thesis. Learning scientific methods, planning of research-oriented projects and preparation for an independent research work. Planning of the master project and its presentation and discussion in a group of researchers.

Master Thesis: Independent research work – Master Thesis – under guidance in a selected area of experimental or theoretical physics (or areas adjacent to physics) in a research group of the Institute of Physics or of its associated institutes/research groups, including the written elaboration of the obtained scientific results. The Master Thesis will be defended in a specialized colloquium.

Qualification objectives:

Research Traineeship: Knowledge of specialized topics in physics, methodic skills, planning of a research project, advanced presentation skills, and ability for scientific discourse.

Master Thesis: Consolidation of knowledge in the selected specialized area. Acquisition of advanced skills to independent research work in the area of physics and/or adjacent areas. Presentation (written and scientific discourse) of a more extensive research project, including the further context.

Course achievement and academic record:

Research Traineeship: The oral presentation of the research traineeship will be assessed as course achievement.

Master Thesis: The written thesis will be valued as academic record, and its oral presentation with scientific discourse will be counted as course achievement.

Registration for the module: In written form, according the information by Examination Office Physics.

Research Groups and Scientific Scope

Particles and Fields	
	<p><u>Theory of Elementary Particles and Quantum Field Theory</u> Prof. Dr. S. Dittmaier</p> <p>Our group is working on the theory and phenomenology of the fundamental interactions of matter, in particular of the strong and electroweak forces, including models of "new physics" that intend to unify the descriptions of these interactions.</p> <p>Since matter is a system with many degrees of freedom and its fundamental objects obey quantum mechanical principles, (relativistic) quantum field theory represents its theoretical framework. The fundamental interactions are successfully described by geometrically motivated models – known as gauge theories – similar to the description of gravity by general relativity as the geometrical theory of space and time.</p> <p>In detail, the following issues comprise our main lines of research:</p> <ul style="list-style-type: none"> • Phenomenology of elementary particles at colliders such as the LHC and future e^+e^- colliders, • Gauge and Higgs bosons of electroweak interactions, • Search for "new physics", such as supersymmetry, • Quantum corrections of the strong and electroweak interactions, • Concepts and techniques of perturbative quantum field theory, • Monte Carlo simulation of particles reactions.
	<p><u>Experimental Particle Physics</u> Prof. Dr. G. Herten</p> <p>Our main research interest is the search for new effects and new particles beyond the Standard Model of Particle Physics. We think that the Large Hadron Collider (LHC) at CERN offers the best possibilities to discover new phenomena.</p> <p>With the ATLAS experiment at the LHC we focus at the moment on the analysis of events with missing transverse energy, indicating the production of new weakly interacting particles. They are predicted in supersymmetry and in theories with extra large spatial dimensions. At the same time they are perfect candidates for the dark matter observed in the universe. The next years at the LHC will be decisive, if there is new physics around the corner, we should see some signals very soon. These research projects offer a wide spectrum of topics for Bachelor, Master, and PhD theses.</p> <p>In parallel, we continue our research and development for new particle detectors. The main focus is on gaseous detectors for muon identification and momentum measurements. This research is aimed at upgrading part of the existing ATLAS muon detector for the high-luminosity phase. In this context many small scale laboratory experiments will be conducted in theses to improve the high rate capability of muon detectors.</p>
	<p><u>Experimental Particle Physics</u> Prof. Dr. K. Jakobs</p> <p>The main research activity of our group constitutes the investigation of proton-proton collisions in the ATLAS experiment at the Large Hadron Collider (LHC) at the European Centre for Particle Physics CERN in Geneva, Switzerland.</p>

	<p>At the LHC, where collisions take place at world-record centre-of-mass-energies, important fundamental questions of particle physics are investigated. Among these is the question of the origin of mass, which is linked to the possible existence of the Higgs particle, and the search for new types of matter, which could be responsible for the Dark Matter in the Universe.</p> <p>Our group is involved in the search for the Higgs particle in various final states ($H \rightarrow WW$ and $H \rightarrow \tau\tau$) and in the search for supersymmetric particles. These (so far undiscovered) particles are predicted in possible extensions of the Standard Model of particle physics. In the latter case, our focus lies on the investigation of final states with missing transverse energy and heavy quarks.</p> <p>In parallel, we are engaged in research and development (R&D) projects on semiconductor tracking detectors. The primary goal in this research line is to develop more radiation hard silicon tracking detectors for future high luminosity upgrades of the ATLAS experiment. This R&D work is partially carried out in the framework of the RD50 collaboration at CERN.</p> <p>In collaboration with a group at the Freiburg Centre for Material Research (FMF) we are investigating novel high-Z semiconductor detectors like CdTe or CdZnTe for applications in medical imaging, photon detection, and radiation protection projects.</p> <p>Both the ATLAS physics data analysis and the detector development projects are undertaken as part of large international collaborations.</p>
	<p><u>The Physics of Particles and Nuclei</u> Prof. Dr. K. Königsmann</p> <p>With the COMPASS experiment at CERN in Geneva we study the structure of the proton and the spectroscopy of hadrons. To this aim we investigate in particular:</p> <ul style="list-style-type: none"> • The composition of the protons in terms of quarks and gluons, • The contribution of the quarks and gluons angular momenta to the spin of the proton, • Determination of a three-dimensional picture in momentum and space of the proton, • Search for particles with exotic quantum numbers. <p>Such investigations require advanced detectors and fast read-out electronics. To this end we design and test novel particle detectors and the associated electronics:</p> <ul style="list-style-type: none"> • Fast detectors for photons and charged particles, • Ultra-fast time-to-digital converters, • Large bandwidth analog-to-digital converters with 1 GHz sampling rates, • Trigger systems implemented in FPGAs and GPUs, • Complete front-end read-out components.
	<p><u>Experimental Particle Physics</u> Prof. Dr. M. Schumacher</p> <p>Our group is active in the operation of the ATLAS detector at the Large Hadron Collider (LHC) located at CERN in Geneva, and in the analysis of the acquired proton-proton collision data.</p> <p>Unravelling the origin of electroweak symmetry breaking and of the masses of elementary particles is one of the most fascinating and pressing topics of contemporary particle physics. Usually the above question is explained via the Higgs-Brout-Englert-Kibble-Guralnik-Hagen mechanism, which predicts the existence of elementary spinless particles: the Higgs boson(s). In the Standard Model of particle physics the Higgs boson is the only missing ingredient and its mass the last undetermined parameter. Supersymmetry (SUSY) is the theoretically most favoured extension of the Standard Model. It potentially solves several open questions of the Standard</p>

	<p>Model, e.g. the origin of Dark Matter observed in the universe. SUSY predicts the existence of at least five Higgs bosons (three neutral and two charged Higgs bosons altogether).</p> <p>The LHC has the unique opportunity to test these predictions as it is the highest energy particle collider ever built. It will finally answer a question unsolved for 40 years: whether Higgs bosons as predicted by the SM or its SUSY extensions are realised in nature or not. Our group focuses on searches for these Higgs bosons in the Standard Model (SM) and its minimal supersymmetric extension (MSSM).</p> <p>In addition our group is responsible for operating a so-called local TIER2 computing center, using Grid computing technology, for data analysis at the LHC. This Grid cluster is part of the ATLAS computing model which is embedded in the Worldwide LHC Computing Grid (WLCG) and in the interdisciplinary Freiburg Black Forest Grid (BFG).</p> <p>In detail, the following topics comprise our main focus of research:</p> <ul style="list-style-type: none"> • The search for neutral Higgs bosons decaying into a pair of tau leptons in the SM and MSSM, • The search for charged Higgs bosons decaying into a tau lepton and its neutrino in extensions of the SM, in particular, the MSSM, • Optimisation of the identification of tau leptons, • Optimisation of mass reconstruction techniques for Higgs boson searches involving tau leptons, • Development of novel methods to study, control, reject, and estimate background processes for the aforementioned searches, • Optimisation of the data analysis chain when using the Grid infrastructure.
	<p><u>Elementary Particle Phenomenology</u> Prof. Dr. J.J. van der Bij</p> <p>The understanding of the fundamental building blocks of matter and their interactions is one of the most important goals of the study of nature. At the most fundamental level the description of nature has to be based on quantum mechanics, actually even quantum field theory. Experience has shown that the best theories for the fundamental interactions are based on geometrical principles. This includes gauge theories based on Lie groups but also Einstein's general theory of relativity.</p> <p>In our group we study such theories to gain a better understanding of their fundamental structure as well as their relation with experiment. Besides the phenomenology at high-energy colliders, we also consider applications in cosmology and astroparticle physics.</p> <p>There is a large area of common interest with the research group Dittmaier.</p>
<p>Atomic, Molecular, and Optical Physics</p>	
	<p><u>Molecular and Optical Physics</u> Prof. Dr. H. Helm</p> <p>The interaction of electromagnetic fields and matter is at the origin of all dynamic processes in nature. Prudent preparation of fields and matter permits the visualization of the quantum nature of the dynamics in the laboratory. For this purpose we use coherent radiation sources in the range from the near UV to the far infrared to</p> <ul style="list-style-type: none"> • image atomic and molecular dynamics in photodissociation and photoionization, • study the distortion of the electronic structure of atoms and molecules in strong laser fields,

	<ul style="list-style-type: none"> • control the refractive index of atoms in order to cool them to nano Kelvin temperatures, and • investigate the deformation of electromagnetic pulses caused by matter. <p>Recent highlights:</p> <ul style="list-style-type: none"> • The development of a near-field microscope, capable of imaging electric and magnetic field vectors with picosecond time resolution. This instrument is geared to study the propagation of electromagnetic fields on metamaterial and photonic-crystal interfaces. • The visualization of non-adiabaticity in molecular dynamics by multi-particle coincident imaging at the example of the neutral triatomic hydrogen molecule. • The control of quantum correlation and entanglement between electronic and vibrational degrees of freedom of a cold trapped atom. • The development of imaging tools to visualize the nodal planes of the wave function of an electron emerging in photodetachment and in photoionization.
	<p><u>Modelling and Simulation of Functional Nanosystems</u> Prof. Dr. M. Moseler</p> <p>Our modelling and simulation activities aim at a mechanism-oriented understanding of the functions of complex nanoscale systems, ranging from free, supported or ligand-protected clusters, nanoparticles, nanotubes, and graphene to nanoscale composites, coatings, and contacts. It is our goal to use and develop a whole spectrum of methods to explain and predict structures and processes in nanoscale materials including their experimental signatures. Our arsenal of methods include density functional theory for the efficient solution of the stationary and time-dependent many electron Schrödinger equation, quantum, classical, and coarse-grained molecular dynamics of the nuclei as well as effective continuum equations for nanoscale transport. This research provides valuable contributions to nanofluidics [1], thin film growth [2], cluster science [3,4,5], catalysis [3], and tribology [5].</p> <ol style="list-style-type: none"> 1. M.Moseler and U.Landman, Formation, Stability and Breakup of Nanojets, Science 289, 1165 (2000). 2. M. Moseler, P. Gumbsch, C. Casiraghi, A. Ferrari, J. Robertson, The ultrasmoothness of diamond-like carbon surfaces, Science 309, 1545 (2005). 3. B. Huber, P. Koskinen, H. Häkkinen, M. Moseler, Oxidation of magnesia-supported Pd-clusters leads to the ultimate limit of epitaxy with a catalytic function, Nature Materials 5, 44 (2006). 4. S. Duffe, L.Patryarcha, B.Sieben, C.Yin, B. von Issendorff, M.Moseler, and H.Hövel, Penetration of thin C₆₀ films by metal nanoparticles, Nature Nanotechnology 5, 335 (2010). 5. M. Walter, J. Akola, O. Lopez-Acevedo, P. D. Jadzinsky, G. Calero, C. J. Ackerson, R. L Whetten, H. Grönbeck and H. Häkkinen, A unified view of ligand-protected gold clusters as superatom complexes, PNAS 105, 9157 (2008)6. 6. L.Pastewka, S.Moser, P.Gumbsch, M.Moseler, Anisotropic mechanical amorphisation drives wear in diamond, Nature Materials 10, 34 (2011).
	<p><u>Molecule and Nanophysics</u> Prof. Dr. F. Stienkemeier</p> <p>The research interest of our group focuses on the properties of matter built on the characteristics, the structure and the dynamics of atoms, molecules, clusters and</p>

	<p>their interplay. In particular, nano-scaled and cold aggregates play a central role in the line of experimental studies. Isolation in helium nanodroplets at temperatures below 1 Kelvin allows us to probe quantum state selective in particular the electronic properties of molecular complexes. We apply a variety of laser spectroscopic tools ranging from high resolution measurements in the frequency domain to ultra-short time experiments involving time-resolution down to the attosecond range.</p> <p>Main questions concern the semiconducting properties of organic nanostructures, microscopic superfluidity, relaxation and decoherence processes of molecules coupled to an environment as well as chemical reactivity in the quantum regime.</p> <p>In detail, the following issues comprise our main lines of research:</p> <ul style="list-style-type: none"> • Excitation and energy transfer in organic nanostructures isolated in superfluid helium nanodroplets, • Synthesis and characterization of specific molecular complexes by means of helium droplet isolated electronic spectroscopy, • Exploration of the real-time dynamics of molecules and nanostructures applying femtosecond pump-probe spectroscopy, • Chemical reactivity at very low temperatures: Quantum effects in reactive atom-molecule collisions, • Molecular and cluster beam experiments with XUV free electron laser radiation.
	<p><u>Atomic and Molecular Quantum Dynamics</u> Prof. Dr. T. Schaetz</p> <p>The main research activity of our group addresses experimental quantum simulations based on trapped ions:</p> <p>Direct experimental access to some of the most intriguing and puzzling quantum phenomena is difficult. Their simulation on conventional computers is impossible, since quantum behaviour is not efficiently traceable by classical algorithms. However, one could gain deeper insight into complex quantum dynamics via experimentally simulating the quantum behaviour of interest in another quantum system, where the relevant parameters and interactions can be controlled and robust effects can be detected sufficiently well. One example is simulating quantum-spin systems with trapped ions. After successful proof-of-principle experiments, we now aim to explore the limitations and prospects of quantum simulations with ions.</p> <p>Our objectives are</p> <ul style="list-style-type: none"> • To change the paradigm that noise/decoherence has to be seen as a source of errors. We will explore engineering decoherence to establish it as a gadget to simulate itself. Noise is also present in nature and therefore no "error" and might even allow to enhance efficiencies like suspected in biological systems. • To investigate the options of new approaches to scaling quantum simulations to larger and two dimensional systems, <ul style="list-style-type: none"> ○ trapping ions in conceptually new arrays of radiofrequency surface traps, ○ trapping ions in optical lattices. <p>Even with the envisioned size of only tens of ions/spins, we could already perform useful QS, beyond the scope of classical computation.</p>
	<p><u>Biomolecular Dynamics</u> Prof. Dr. G. Stock</p>

	<p>State-of-the-art experiments on biomolecular dynamics generate an enormous amount of data, which require a careful theoretical description. However, neither straightforward quantum mechanics nor simple classical modeling is typically suited to describe the dynamics and spectroscopy of complex system. The theory is therefore challenged to develop new strategies. Approaches pursued in this group include the development of multidimensional reduced quantum models, of novel mixed quantum-classical concepts, and of linear and nonlinear approaches to analyze the data of molecular dynamics simulations. Hereby the ultimate goal is a truly microscopic understanding of the underlying physics and, of course, the pleasure to play with new theoretical ideas.</p> <p>Recent projects include</p> <ul style="list-style-type: none"> • ultrafast nonadiabatic photoreactions, • free energy landscapes of biomolecules, • biomolecular energy flow, • functional dynamics of RNA, • vibrational signatures of biomolecular dynamics, • maximum caliber.
	<p><u>Experimental clusterphysics</u> Apl. Prof. Dr. B. von Issendorff</p> <p>Clusters are small particles consisting of a few up to a few thousand atoms, which often exhibit very different properties than the corresponding bulk material. In our group we study the atomic and electronic structure of free size-selected metal and semiconductor clusters as well as dynamics in these systems.</p> <p>Examples of such studies are:</p> <ul style="list-style-type: none"> • Characterization of the electronic structure of simple metal clusters by angle-resolved photoelectron spectroscopy, • Study of ultrafast electron dynamics in metal and semiconductor clusters by femtosecond pump-probe spectroscopy, • Characterization of phase transitions in gas phase metal and molecular clusters by nanocalorimetry, • Search for low temperature quantum phenomena in pure and doped metal clusters by high-resolution photoelectron spectroscopy, • Determination of electron dynamics in metal clusters in strong laser fields, • Study of the electronic and geometric structure of free clusters by synchrotron spectroscopy.
<p>Physics of Complex Systems (Condensed/Soft Matter)</p>	
	<p><u>Theoretical Polymer Physics</u> Prof. Dr. A. Blumen</p> <p>While in the synthesis of polymers the chemical properties of the constituents (monomers) play a fundamental role, one often finds that the macroscopic and mesoscopic properties of polymers in solutions and melts depend mostly on their architecture, i.e. on the way in which the monomers are linked together. Our research is based both on theoretical-analytical models and on computer simulations. Usually, these approaches are combined and we focus on the following research topics:</p> <ul style="list-style-type: none"> • The dynamics of complex polymer networks, • The interaction of polymers with other materials, • Transport processes (both classical and quantal), • Fractal polymer systems as models for complex structures.

	<p><u>Quantum Optics and Statistics</u> Prof. Dr. A. Buchleitner</p> <p>Our central concern is the question of how complex dynamics arises in composite quantum systems, such as the helium atom or bosonic atoms in optical lattices. Our main lines of research in this direction are summarized in the following four topics:</p> <ul style="list-style-type: none"> • <i>Quantum Information</i>: Entanglement in composite quantum systems can be regarded as the most genuine trait of quantum physics. For our group, important questions concern the characterization of many-particle entanglement, the control of entanglement by suitable laser pulses, and its protection against decoherence. • <i>Cold Matter</i>: Cold atoms loaded into optical lattices open a new arena for the experimental investigation of quantum transport phenomena in spatially periodic potentials. External perturbations such as static and/or time periodic fields modify theoretically well understood dynamical phenomena such as quantum resonances or Wannier-Bloch oscillations in often surprising ways. • <i>Quantum Chaos</i>: Helium is a prototype of a strongly correlated and chaotic few-body system. Combining advanced parallel computation and semiclassical tools, we investigate the role and signatures of electronic correlations in single or double ionization processes, long-lived resonances in high-dimensional configuration space and electronic transport along the energy axis. • <i>Quantum Transport</i>: Quantum particles propagating in disordered media display interference effects that alter the properties of classical diffusive transport and might explain, e.g., the high efficiency of photosynthetic complexes. We especially study the role of nonlinearities in the scattering of photons by cold atoms and the propagation of bosons through random potentials.
	<p><u>Theoretical Condensed Matter Physics and Quantum Statistics</u> Prof. Dr. H. Grabert, apl. Prof. Dr. H.-P. Breuer, PD Dr. L. Mühlbacher</p> <p>Our team studies the dynamics and transport processes of complex many-body systems with particular emphasis on quantum mechanical effects of relevance for novel technological devices on the molecular and nanoscale. Keywords characterizing the area of current research include quantum dissipation and decoherence, quantum correlations and entanglement, quantum information and computation, electronic correlations, topological phases, and fermionic atoms in optical lattices. Our main lines of research can be subsumed under the following themes:</p> <ul style="list-style-type: none"> • <i>Dirac Fermions in two-dimensional nanostructures</i>: The low-energy physics of electrons in graphene, a single layer of carbon atoms on a honeycomb lattice, is described by a Dirac Hamiltonian with the speed of light replaced by the Fermi velocity. It is also possible to design lattices where the low-energy description corresponds to particles with an effective spin larger than 1/2. These systems can be created by means of fermionic cold atoms placed in optical lattices and they lead to novel physical phenomena such as super Klein tunneling. • <i>Carbon nanotubes</i>: Carbon nanotubes can be viewed as a stripe of graphene rolled to form a hollow cylinder. Their electronic properties, semiconducting or metallic, are uniquely determined by the width and angle of the cutout stripe. Nanotubes represent a prototype of one-dimensional conductors or quantum wires which display remarkable transport properties. • <i>Topological insulators</i>: The quantum Hall effect is a seminal phenomenon of modern solid state physics because it leads to a quantized conductance whose value is robust against external perturbations. Topological insulators display similar effects even in the absence of an external magnetic field. These materials have a high potential as dissipationless building blocks of

	<p>electronic devices with very low power consumption.</p> <ul style="list-style-type: none"> • <i>Quantum theory of dissipation and decoherence</i>: The theory of open, dissipative quantum systems plays an important role in many developments of modern quantum mechanics. It provides answers to numerous problems ranging from fundamental questions to predictions for technological applications. Our team studies general properties of open quantum systems and basic features of their dynamical behavior as well as applications to challenging questions of experimental relevance such as the entanglement dynamics of strongly driven trapped atoms in laser cooling and the control of quantum processes under dissipation. • <i>Quantum memory and dynamics of correlations</i>: The standard approach to the dynamics of dissipative quantum systems presupposes a memoryless time evolution. However, many realistic systems are influenced by strong system-environment correlations and involved quantum memory effects. The recent technological progress allows high-precision experiments which measure the degree of such effects using, e.g., photons moving in polarization-maintaining optical fibers or in birefringent materials. We develop theoretical tools and models to analyze these experiments which are important for applications in future quantum technologies. • <i>Quantum Monte Carlo simulations</i>: Since analytical tools are frequently limited to simplified models, quantitative studies of experimentally relevant systems often require advanced numerical methods. The Monte Carlo technique provides a powerful yet flexible approach to access the exact quantum dynamics. Based on a stochastic sampling of the underlying configurations, it can be used to calculate equilibrium and transport properties of molecular and nanostructures in the presence of dissipative environments. • <i>Energy transfer in light harvesting systems</i>: The highly effective mechanism of resonant energy transfer along networks of bacteriochlorophylls is a major incentive for improving the efficiency of dye and organic solar cells. Burning issues are the influence of the surrounding protein structure and the conditions for optimal energy transfer. Combining the quantum theory of open systems with quantum Monte Carlo simulation techniques, we aim at a detailed microscopic understanding of the underlying dynamical processes on the femtosecond timescale.
	<p><u>Experimental Polymer Physics</u> Prof. Dr. G. Reiter, apl. Prof. Dr. A. Kittel</p> <p>Experimental physics, especially in the field of "Soft Matter", provides an essential link between (Macromolecular) Chemistry, Biology, and Applied Sciences. This is particularly true in the understanding and controlling of complex molecular systems and materials, which to some extent are inspired by processes found in nature.</p> <p>In this context, the tasks of physics are mainly to identify the fundamental processes and to set parameters that describe them, to develop appropriate models based on predictions or requirements regarding their implementation in appropriate applications. Polymer physics, therefore, represents a essential pillar in terms of fundamental and conceptual issues in an interdisciplinary approach of innovative materials research. Research in our group concentrates on questions dealing with properties of surfaces and interfaces, growth and structure formation processes, functional materials based on complex, nano-structured systems. Emphasis is on the study of molecular interactions, which control organization and structure formation.</p> <p>The group follows a "bottom-up" approach: Molecular interactions and their control on a sub-nanometer scale determine the hierarchical organization of complex and functional (macro-)molecules over many length scales up to macroscopic lengths. These structures are made visible, the underlying ordering processes are identified and structure formation is varied and controlled by appropriate manipulation (external factors). Emphasis is intentionally placed on surface phenomena, because the</p>

	<p>corresponding (quasi-)two-dimensional systems allow for a set of experimental approaches and on the other hand, these phenomena play a central role in materials research.</p> <p>Research projects:</p> <ul style="list-style-type: none"> • Controlling properties of polymers in thin films, • Frictional and adhesive properties of polymer surfaces and films of controlled structure and function, • Functional properties of polymeric nanocrystals and their ordered structures at surfaces, • Permanent adhesion systems of plants as a model for bionic composite materials, • Self-assembled nanoribbons and nanotubes.
	<p><u>Dynamical Processes in Live-Sciences</u> Prof. Dr. J. Timmer</p> <p>Dynamic processes are ubiquitous in the life sciences. They can be found from the regulation in cells up to oscillations in tremor. Malfunction of these dynamical processes can be a cause or a sign of diseases. In interdisciplinary projects, we develop and apply mathematical methods to analyse and model these processes based on measured data.</p>
	<p><u>Neural Networks</u> Apl. Prof. Dr. T. Filk (substitute for Prof. Timmer)</p> <p>In this group we investigate the learning behaviour of neural networks with the help of computer simulations of special models as well as by theoretical techniques based on graph theory (in particular algebraic and spectral graph theory), biological systems theory, statistical mechanics, and dynamical systems.</p> <p>The basic assumption is that under certain conditions some of the phenomena related to neural networks are generic in a similar sense as the "universality classes" in statistical mechanics. Therefore, we investigate small but highly recurrent networks with simple dynamics. The long-term aim is to get a better understanding of various learning processes (not only) in biological systems.</p> <p>Research projects are related both to actual computer simulations (e.g., developing and testing programs for the simulation of neural networks, testing training and learning strategies for neural networks and investigating the dependence of learning success on various neural network parameters) and to more theoretical investigations (e.g., developing classification schemes for graphs, extending random graph theory to models with various types of nodes and/or connections, stability analysis, the application of algebraic graph theory to dynamical systems).</p>
	<p><u>Nanophysics: Molecular Nanomagnets</u> Prof. Dr. O. Waldmann</p> <p>Our main research focus is the magnetism in molecules of hundreds of atoms, which are hence in the nanometer regime. Magnetism is a scientific challenge, and its importance for technology is widely appreciated. Magnetic objects on the nanoscale would offer many benefits science- and applications-wise. Molecules appear as logical targets, but they are usually non-magnetic due to the nature of the chemical bond. Nevertheless, in the last decade researchers developed synthetic schemes, which nowadays provide us with the best defined magnetic nanoparticles. This novel field of molecular nanomagnets provides a unique and fascinating view on the magnetism in tiny, mesoscopic quantum objects, allowing to study fundamental ques-</p>

	<p>tions of quantum mechanics on the nanoscale, the crossover from quantum to classical mechanics, and applications in molecular data storage or quantum information technology. We study these aspects using a variety of experimental techniques, both in-house and at external large-scale facilities, such as high-field micro-Hall magnetometry or inelastic neutron scattering, as well as numerical/theoretical techniques for the analysis. Combined they provide us deep insights into the physics of molecular nanomagnets.</p>
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