# Handbook for Master Study Program Advanced Quantum Physics

at the Department of Physics at TU Kaiserslautern

2021


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1 Master Study Program Advanced Quantum Physics

1.1 Qualification goals

The Advanced Quantum Physics study program aims to impart the theoretical and practical fundamentals of modern quantum physics and the technologies associated with it at a highly scientific level in the international atmosphere. Together with an insight in the current research and a look into other disciplines of the TU Kaiserslautern, students are enabled to complete professional tasks in the field of research and practical application as well as in fields of activity close to the sciences. Responsible and critical engagement with acquired knowledge is an integral part of the training. The study program is completed with the “Master of Science” degree, abbreviated “M. Sc.”. It is a basic research-oriented program.

Physics is a basic science that explores the universal laws of nature and describes them quantitatively. On the one hand, physical laws have contributed significantly to the formation of our scientific worldview, and on the other hand, they form the foundation for the technical and technological advancement of our society. Quantum physics has triggered a technological revolution in the last century, for e.g. in the form of the semiconductor industry. The concepts, ways of thinking, and solution strategies of modern quantum physics developed thereby offer the graduates ideal conditions to identify, draw abstracts from, formulate and find integrated solutions for problems in various contexts. Furthermore, it enables them to analyze, question and assess products, processes and methods by means of a structured and research-trained approach even in a non-academic environment.

The semiconductor industry or optical technologies are prominent, ubiquitous examples for the significance of such quantum physical applications, which are now an indispensable part of applications in medicine, research, industry, communication and entertainment. Direct applications from quantum physics in research and development lead to enhancement of knowledge, such as in precision experiments, which develop new applications for the future. Experience shows that the activity spectrum of physics graduates expands continuously in this rapidly evolving environment. New questions are investigated and innovative problem solutions are required according to the various fields of activity. The Advanced Quantum Physics study program prepares for this complex field of activity through advanced knowledge in theoretical and experimental physics as well as through abstract, method-oriented training. This includes experimental and theoretical methods and work techniques, numerical procedures and their implementation in computer systems as well as techniques of electronic knowledge processing. The increasing interdisciplinary and international nature of scientific research also calls for the acquisition of basic knowledge of phenomena and terms as well as methodologies in related areas. This includes the acquisition of skills in the interlinking of the concepts learned with other basic knowledge, and their applications.

The basic research- and method-oriented training should enable the graduates to tackle tasks, the handling of which requires technical and methodical competence and flexibility along with scientific independence. Additional core competencies going beyond the disciplinary borders are indispensable to ensure success in professional life. These core competencies comprise, for e.g. training in teamwork skills beyond disciplinary or language borders or gaining experience in the presentation of results, as well as the development of leadership skills. Internships, seminars and the master's thesis serve this purpose. In professional life, physicists must be open to the organizational and social aspects of their occupation and must be able to categorize their own results in a critical manner. Even these qualifications are a central component of the training objective in the Advanced Quantum Physics master program. It offers the opportunity to deepen previously learned basics with individually chosen focal points and developing competencies further. The master program offers a deeper insight in organizational processes of research projects, which qualifies the graduates even for subsequent work in the field of research.

The entry into the master program is possible for the winter and the summer semester. The study schedule and the individual teaching-studying modules are described in detail below: The professional examination regulations of the Advanced Quantum Physics master program can be found on the website: https://www.physik.uni-kl.de/studium, also an English, however, legally non-binding version.
# 1.2 Curriculum

<table>
<thead>
<tr>
<th>Semester</th>
<th>Quantum Technologies</th>
<th>Many-Body Quantum Systems</th>
<th>Science Electives</th>
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<tbody>
<tr>
<td>1</td>
<td>Courses in Quantum Technologies V: 4 SWS</td>
<td>Courses in Many-Body Quantum Systems V: 6 SWS</td>
<td>Science Electives non-physics courses from any sciences curriculum</td>
<td>General Electives courses from any university department</td>
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<tr>
<td></td>
<td>8 CP</td>
<td>12 CP</td>
<td>4 CP</td>
<td>3 CP</td>
<td></td>
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<tr>
<td>2</td>
<td>Courses in Quantum Technologies V: 4 SWS</td>
<td>Courses in Many-Body Quantum Systems V: 4 SWS</td>
<td>Science Electives non-physics courses from any sciences curriculum</td>
<td>General Electives courses from any university department</td>
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</tr>
<tr>
<td></td>
<td>8 CP</td>
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<td></td>
<td>Module Exam QT</td>
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<td>3</td>
<td>Research Module – Introduction to Working Science</td>
<td>Quantum Seminar S: 2 SWS</td>
<td>Colloquium / Theory Colloquium</td>
<td></td>
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<td></td>
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<tr>
<td>4</td>
<td>Specialized Scientific Seminar S: 2 SWS</td>
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<table>
<thead>
<tr>
<th>QT</th>
<th>Quantum Technologies</th>
<th>16 CP</th>
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<tbody>
<tr>
<td>LC</td>
<td>Laboratory Course in Advanced Quantum Technologies</td>
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<td>MB</td>
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<td>SE</td>
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<td>GE</td>
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<tr>
<td>RM</td>
<td>Research Module</td>
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<tr>
<td>MA</td>
<td>Master’s Thesis</td>
<td>30 LP</td>
</tr>
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</table>

SWS: weekly attendance time unit of 45 min = 0.75 h. (Semesterwochenstunde)
CP: credit (Leistungspunkt)
V: lecture (Vorlesung)
P: laboratory training (Praktikum)
S: seminar (Seminar)
1.3 Module Description
On the following pages you can find the module descriptions of the master study program Advanced Quantum Physics.

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<td>Module LC: Laboratory Course</td>
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<td>Module SE: Science Electives</td>
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<td>Module GE: General Electives</td>
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<td>Module RM: Research Module</td>
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<td>Module MT: Master’s Thesis</td>
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### Module QT: Quantum Technology

**Code:** QT  
**Module Coordinator:** Prof. Dr. Artur Widera

| Workload Total: 480 h | Credit Points (CP): 16 CP | Duration: 2 Semesters | Start (regular cycle): winter semester and summer semester |

#### 1. Parts of the module/courses:

| Attendance time: Private Study: CP: |
|---|---|
| CP: |

Optional compulsory courses listed below in the amount of 16 CP:

- **a)** Quantum Optics I*  
  V 2 SWS / 28 h 92 h 4
- **b)** Quantum Optics II*  
  V 2 SWS / 28 h 92 h 4
- **c)** Quantum Gases I  
  V 2 SWS / 28 h 92 h 4
- **d)** Quantum Gases II  
  V 2 SWS / 28 h 92 h 4
- **e)** Advanced Photonics I  
  V 2 SWS / 28 h 92 h 4
- **f)** Advanced Photonics II  
  V 2 SWS / 28 h 92 h 4
- **g)** Quantum Technology*  
  V 2 SWS / 28 h 92 h 4
- **h)** Quantum Information  
  V 2 SWS / 28 h 92 h 4
- **i)** Quantum Information Technology  
  V 2 SWS / 28 h 92 h 4
- **j)** Topological Systems I  
  V 2 SWS / 28 h 92 h 4
- **k)** Topological Systems II  
  V 2 SWS / 28 h 92 h 4
- **l)** Semiconductor Quantum Structures  
  V 2 SWS / 28 h 92 h 4
- **m)** Theoretical Semiconductor Optics  
  V 2 SWS / 28 h 92 h 4
- **n)** Coherent Optics  
  V 2 SWS / 28 h 92 h 4
- **o)** X-Ray Quantum Optics  
  V 2 SWS / 28 h 92 h 4
- **p)** Magnonics  
  V 2 SWS / 28 h 92 h 4
- **q)** Superconductivity  
  V 2 SWS / 28 h 92 h 4
- **r)** Laser-Matter-Interaction on ultrashort timescales  
  V 2 SWS / 28 h 92 h 4
- **s)** Intensive Week  
  VSP 120 h 4

*At least 8 CP must be completed in the courses Quantum Optics and/or Quantum Technology.*

#### 2. Impact on curriculum: optional compulsory modules

#### 3. Teaching Staff: members of the faculty of physics

#### 4. Content:

- **a)** and **b)** Quantum Optics I and II:  
  fundamentals of semi-classical atom-light interaction; laser radiation and fundamentals of photonics; coherent phenomena in multi-level atoms; quantized light fields; quantum states of light, their properties and their theoretical description; quantized atom-light interaction: Jaynes-Cummings model and dressed states; coherence and correlations; quantum correlations and entanglement; Bell inequalities and their violation; (quantum) theory of the laser; quantum effects in nonlinear optics.

- **c)** and **d)** Quantum Gases I and II:  
  fundamentals of quantum gases; laser cooling and cooling limits; magnetic and optical traps; ultracold interactions and evaporative cooling; detection of ultracold samples; Bose-Einstein condensation (BEC): experimental route to BEC, theoretical descriptions and approximations, Bogoliubov excitations; degenerate Fermi gases (DFG): experimental route to DFG, Feshbach resonances, BEC-BCS crossover, ultracold molecules; optical lattices and many-body lattice models; quantum gases in lower dimensions; quasi-spin systems; applications in optical clocks and atom interferometers.

- **e)** and **f)** Advanced Photonics I and II:  
  fundamentals of light-matter interaction; non-linear optics; dispersion relations; photonic bandstructures; band structure calculations (plane-wave method, finite-difference-time-domain); scattering matrix calculations; Monte-Carlo-
Simulation; photonic crystals, quasicrystals and disordered media; plasmonics: surface- and particle-plasmon-polaritons; plasmonic antennas; photonic metamaterials: negative refractive index; metasurfaces; all-dielectric metamaterials; transformation optics.

q) Quantum Technology:
introduction to quantum properties: matter waves, quantum statistics and entanglement; matter wave applications and sub-wavelength microscopy; applications in time-keeping: optical clocks and squeezed states; superconductivity and superfluidity, and their applications.

h) Quantum Information:
quantum states; entanglement and its measures; teleportation; qubits and diVincenzo criteria; single qubit gates and realizations; quantum correlations and two-qubit gates.

i) Quantum Information Technology:
quantum computation and simple algorithms; quantum cryptography and quantum communication; quantum error correction; experimental implementations of quantum computation; quantum repeaters; quantum algorithms: Grover’s algorithm, Shor’s algorithm.

j) Topological Systems I and II:
integer quantum Hall effect and lattice realizations; topological invariants and general classification of topological phases in non-interacting fermion systems (Berry phase and Chern number, “ten-fold way”); quantum spin-Hall effect and topological insulators, graphene and Haldane model; symmetry-protected topological systems in 1D; phenomenology of the fractional quantum Hall effect and introduction to composite fermion theory.

k) Semiconductor Quantum Structures:
nanostructures; future of electronic chips; fundamentals of micromechanics and microfluidics; scaling laws; heterostructures and p-n junctions; quantum mechanical confinement: quantum wells, wires, and dots; quantum cascade lasers; Fermi’s Golden Rule; self-organized nanostructures; nanoscopic measuring techniques.

l) Theoretical Semiconductor Optics:
optical fields in semiconductors; semiconductor Bloch equations; excitons; optical nonlinearities in semiconductors; semiconductor laser physics.

m) Coherent Optics:
principles of lasers; laser resonators; laser modes; interference and coherence; short and ultrashort optical pulses; overview of nonlinear optics; wave optics; Fourier optics and diffraction; speckles; holography and holographic interferometry; coherent Fourier-optical spatial frequency filtering; broad-area semiconductor lasers; optical waveguides.

n) X-Ray Quantum Optics:
X-ray light sources, particles accelerators, insertion devices; 3rd generation synchrotrons and X-ray free electron lasers (XFEL) including novel concepts like XFEL-oscillators (XFELO); precision X-ray optics; coherent and incoherent effects in nuclear resonance scattering; single-photon superradiance, collective Lamb shift, coherent control, electromagnetically induced transparency (EIT), resonance fluorescence; coherent control of γ-ray photons with incoherent γ-sources

p) Magnonics:
fundamentals of spin waves in confined structures; basic elements of magnonics; parametric and nonlinear phenomena; advanced properties and applications.

q) Superconductivity:
Phenomenology: Historical introduction, critical temperature, Meissner-Ochselfeld effect, type I and type II superconductor, thermodynamics of superconductors, London theory, flux quanta
5. Competences and intended learning outcomes:
Successful completion of this module will develop the following skills, knowledge and expertise:

- The student will know and understand the fundamental concepts, methods and approaches of quantum optics and optical technologies.
- The student will have acquired a structured and specific knowledge of those subjects in quantum optics and optical technologies which are treated by the particular courses that the student has taken.
- The student will understand the close interaction between theoretical predictions and experiments in (quantum) optics, and the importance of this close interaction for developing technological applications.
- The student will be able to understand and interpret discrepancies between theoretical predictions and experimental results.
- The student will have an overview of current fundamental problems in quantum optics, quantum technologies and optical technologies.
- The student will be aware of how quantum optics theory and optical technologies were developed historically.
- The student will appreciate how the discoveries in quantum optics and the inventions of optical technologies have contributed to the development of the fundamental concepts of modern physics in general.
- The student will also be able to apply the essential working strategies and paradigms that are specific to quantum optics and optical technologies, in order to recognize and solve common (quantum) optical problems.
- The student will conversely understand how the specific concepts and strategies of quantum optics relate to the basic principles of physics in general.

6. Prerequisites for attending:

Formal admission requirements: none
Contentual prerequisites: none

7. Requirements for receiving credit points: successful completion of all sub-module examinations
The following examinations and courseworks have to be fulfilled:

Examination(s): oral examination(s)
Coursework(s): regular and active participation in course, the conditions for the regular and active participation are made public at the beginning of the course
The coursework is prerequisite for the module examination.

Determination of grade: The grade of the module exam is also the module grade. In the case of sub-module examinations, all sub-module examinations must be passed. The module grade results from the arithmetic average of the grades of the sub-module examinations.

8. Applicability of the module/suitability:
Master program Advanced Quantum Physics
### Hints for preparation:

#### Recommended literature:

<table>
<thead>
<tr>
<th>Category</th>
<th>Books</th>
</tr>
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<tbody>
<tr>
<td>e) and f) Advanced Photonics I and II:</td>
<td>Saleh, Teich: Fundamentals of Photonics, Wiley&amp;Sons&lt;br&gt;Maier: Plasmonics: Fundamentals and Applications, Springer</td>
</tr>
<tr>
<td>h) - l): as announced in lecture</td>
<td></td>
</tr>
<tr>
<td>o) X-Ray Quantum Optics:</td>
<td>Röhrsberger: Nuclear Condensed Matter Physics with Synchrotron Radiation, Springer</td>
</tr>
<tr>
<td>p): as announced in lecture</td>
<td></td>
</tr>
<tr>
<td>r) - s): as announced in lecture</td>
<td></td>
</tr>
</tbody>
</table>

#### Available documents:

Up-to-date information and lecture-accompanying materials will be announced in the lecture or on the internet pages of the course.

### Registration procedure:

Registration for lectures a) – r) is not required.
A possibly required registration procedure for exercises will be announced in the belonging lecture. flock s): will be announced by the organizing lecturer.

| 11. **Language:** | English |
### Module MB: Many-Body Quantum Systems

**Code:** MB  
**Module Coordinator:** Prof. Dr. Michael Fleischhauer

<table>
<thead>
<tr>
<th>Workload Total:</th>
<th>Credit Points (CP):</th>
<th>Duration:</th>
<th>Start (regular cycle):</th>
</tr>
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<tbody>
<tr>
<td>600 h</td>
<td>20 CP</td>
<td>2 Semesters</td>
<td>winter semester and summer semester</td>
</tr>
</tbody>
</table>

### 1. Parts of the module/courses:

<table>
<thead>
<tr>
<th>Attendance time: (SWS x 14)</th>
<th>Private Study:</th>
<th>CP:</th>
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</thead>
<tbody>
<tr>
<td>Optional compulsory courses listed below in the amount of 20 CP:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Advanced Quantum Mechanics I*</td>
<td>V 2 SWS / 28 h 92 h</td>
<td>4</td>
</tr>
<tr>
<td>b) Advanced Quantum Mechanics II*</td>
<td>V 2 SWS / 28 h 92 h</td>
<td>4</td>
</tr>
<tr>
<td>c) Many-Body Quantum Theory I*</td>
<td>V 2 SWS / 28 h 92 h</td>
<td>4</td>
</tr>
<tr>
<td>d) Many-Body Quantum Theory II*</td>
<td>V 2 SWS / 28 h 92 h</td>
<td>4</td>
</tr>
<tr>
<td>e) Quantum Gases I</td>
<td>V 2 SWS / 28 h 92 h</td>
<td>4</td>
</tr>
<tr>
<td>f) Quantum Gases II</td>
<td>V 2 SWS / 28 h 92 h</td>
<td>4</td>
</tr>
<tr>
<td>g) Quantum Information</td>
<td>V 2 SWS / 28 h 92 h</td>
<td>4</td>
</tr>
<tr>
<td>h) Quantum Information Technology</td>
<td>V 2 SWS / 28 h 92 h</td>
<td>4</td>
</tr>
<tr>
<td>i) Quantum Field Theory I</td>
<td>V 2 SWS / 28 h 92 h</td>
<td>4</td>
</tr>
<tr>
<td>j) Quantum Field Theory II</td>
<td>V 2 SWS / 28 h 92 h</td>
<td>4</td>
</tr>
<tr>
<td>k) Solid State Theory I</td>
<td>V 2 SWS / 28 h 92 h</td>
<td>4</td>
</tr>
<tr>
<td>l) Solid State Theory II</td>
<td>V 2 SWS / 28 h 92 h</td>
<td>4</td>
</tr>
<tr>
<td>m) Quantum Technology</td>
<td>V 2 SWS / 28 h 92 h</td>
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</tr>
<tr>
<td>n) Ab-Initio Methods of Condensed Matter Theory I</td>
<td>V 2 SWS / 28 h 92 h</td>
<td>4</td>
</tr>
<tr>
<td>o) Ab-Initio Methods of Condensed Matter Theory II</td>
<td>V 2 SWS / 28 h 92 h</td>
<td>4</td>
</tr>
<tr>
<td>p) Non-Equilibrium Statistical Mechanics</td>
<td>V 2 SWS / 28 h 92 h</td>
<td>4</td>
</tr>
<tr>
<td>q) Superconductivity</td>
<td>V 2 SWS / 28 h 92 h</td>
<td>4</td>
</tr>
<tr>
<td>r) Topological Systems I</td>
<td>V 2 SWS / 28 h 92 h</td>
<td>4</td>
</tr>
<tr>
<td>s) Topological Systems II</td>
<td>V 2 SWS / 28 h 92 h</td>
<td>4</td>
</tr>
</tbody>
</table>

*At least 8 CP must be completed in the courses Advanced Quantum Mechanics and/or Many-Body Quantum Theory.*

### 2. Impact on curriculum: optional compulsory modules

### 3. Teaching Staff: members of the faculty of physics

### 4. Content:

**a) and b) Advanced Quantum Mechanics I and II:**  
discrete groups, including application to eigenvalue spectra; continuous (Lie) groups, including application to electron spin and other elementary particle properties; quantum mechanics of open systems; scattering theory; relativistic quantum mechanics: Klein-Gordon and Dirac equations, nonrelativistic limit; many-body theory of quantum liquids; finite temperatures; elementary quantum field theory: quantization of the electromagnetic field.

**c) and d) Many-body Quantum Theory I and II:**  
troduction to many-body models (fermionic and bosonic systems, spin models); approximation methods (Hartree-Fock, Bogoliubov transformations); equation-of motion-methods; polarons; Green-functions-based methods; Feynman diagrams, including applications to excitations in many-fermion systems; introduction to non-equilibrium techniques.

**e) and f) Quantum Gases I and II:**  
fundamentals of quantum gases; laser cooling and cooling limits; magnetic and optical traps; ultracold interactions and evaporative cooling; detection of ultracold samples; Bose-Einstein condensation (BEC): experimental route to BEC, theoretical descriptions and approximations, Bogoliubov excitations; degenerate Fermi gases (DFG): experimental route
to DFG, Feshbach resonances, BEC-BCS crossover, ultracold molecules; optical lattices and many-body lattice models; quantum gases in lower dimensions; quasi-spin systems; applications in optical clocks and atom interferometers.

g) Quantum Information:
quanta states; entanglement and its measures; teleportation; qubits and DiVincenzo criteria; single qubit gates and realizations; quantum correlations and two-qubit gates.

h) Quantum Information Technology:
quanta computation and simple algorithms; quantum cryptography and quantum communication; quantum error correction; experimental implementations of quantum computation; quantum repeaters; quantum algorithms: Grover's algorithm, Shor's algorithm.

i) and j) Quantum Field Theory I and II:
classical field theory; canonical field quantization; Noether theorem; Schrödinger field, Klein-Gordon field, Maxwell field, Dirac field; quantum electrodynamics; perturbation theory; Wick theorem, Feynman diagrams; scattering processes; renormalization; quantization of gauge fields; introduction to the standard model.

k) and l) Solid State Theory I and II:
Drude model; failures of the free electron model; crystal lattices; band structure theory; phonons; Matsubara formalism; exactly solvable models; strong electronic correlations and magnetism; superconductivity.

m) Quantum Technology:
introduction to quantum properties: matter waves, quantum statistics and entanglement; matter wave applications and sub-wavelength microscopy; applications in time-keeping: optical clocks and squeezed states; superconductivity and superfluidity and applications; quantum information processing and applications.

n) X-Ray Quantum Optics:
X-ray light sources, particles accelerators, insertion devices; 3rd generation synchrotrons and X-ray free electron lasers (XFEL) including novel concepts like XFEL-oscillators (XFELO); precision X-ray optics; coherent and incoherent effects in nuclear resonance scattering; single-photon superradiance, collective Lamb shift, coherent control, electromagnetically induced transparency (EIT), resonance fluorescence; coherent control of γ-ray photons with incoherent γ-sources

n) and o) Ab-Initio Methods of Condensed Matter Theory I and II:
thoerems of density functional theory (DFT); LAPW (linearized augmented plane wave) method; Brillouin zone integration; spin-orbit coupling; DFT for structure optimization; DFT for magneto-optics; quantum chemistry with Gaussian orbitals; relativistic effective core potentials; multi-component relativistic methods; spin dynamics in extended systems; multicenter localized systems.

p) Non-Equilibrium Statistical Mechanics:
open systems and quantum master equations; kinetic theory, Boltzmann equation; general linear response theory; correlation functions and memory kernels.

q) Superconductivity:
Phenomenology: Historical introduction, critical temperature, Meissner-Ochselfeld effect, type I and type II superconductor, thermodynamics of superconductors, London theory, flux quanta

Ginzburg-Landau theory: Wave function of superconductivity, inhomogeneous superconductor, Ginzburg-Landau equations, London penetration depth and coherence length, critical magnetic fields, magnetization curve, interaction between flux quanta, critical current

Bardeen-Cooper-Schrieffer-Theorie: Josephon effects, Feynman theory, SQUID, Cooper problem, Jellium model of electron gases, Coulomb interaction, lattice vibrations, electron-phonon interaction, BCS ground state, energy gap, excited states, Gorkov derivation of Ginzburg-Landau theory

r) and s) Topological Systems I and II:
integer quantum Hall effect and lattice realizations; topological invariants and general classification of topological phases in non-interacting fermion systems (Berry phase and Chern number, “ten-fold way”); quantum spin-Hall effect and topological insulators, graphene and Haldane model; symmetry-protected topological systems in 1D; phenomenology of the fractional quantum Hall effect and introduction to composite fermion theory.

5. Competences and intended learning outcomes:
Successful completion of this module will develop the following skills, knowledge and expertise:
- The student will know and understand the fundamental concepts, methods and approaches of many-body quantum systems.
- The student will have acquired a structured specific knowledge on those sub-fields and topics of many-body quantum systems which are treated by the particular courses that the student has taken.
- The student will understand essential aspects of interactions among large numbers of quantum particles, and their implications for technological applications.
- The student will acquire an overview of current fundamental problems in many-body quantum systems.
- The student will be able to understand and interpret discrepancies between theoretical predictions and experimental results.
- The student will be aware of how modern quantum many-body theory and experimental techniques were developed historically.
- The student will appreciate how progress on the quantum many-body problem has contributed to the development of the fundamental concepts of modern physics in general.
- The student will be able to apply fundamental scientific methods, such as induction, model construction, and experimental testing, to solve scientific problems and develop new scientific insights, especially in the contexts of many-body quantum systems.
- The student will also be able to apply the essential working strategies and paradigms that are specific to many-body quantum systems, in order to recognize and solve typical problems involving quantum systems of many interacting particles.
- The student will conversely understand how the specific concepts and quantum many-body physics relate to the basic principles of physics in general.

6. Prerequisites for attending:
Formal admission requirements: none
Contentual prerequisites: none

7. Requirements for receiving credit points: successful completion of all sub-module examinations
The following examinations and coursework have to be fulfilled:
Examination(s): oral examination(s)
Coursework(s): regular and active participation in course, the conditions for the regular and active participation are made public at the beginning of the course,
The coursework is prerequisite for the module examination.

8. Determination of grade: The grade of the module exam is also the module grade. In the case of sub-module examinations, all sub-module examinations must be passed. The module grade results from the arithmetic average of the grades of the sub-module examinations.

9. Applicability of the module/suitability:
Master program Advanced Quantum Physics
### 10. Hints for preparation:

#### Recommended literature:

**a) and b) Advanced Quantum Mechanics I and II:**  
- Sakurai: Advanced Quantum Mechanics, Addison-Wesley.  
- Dyson: Advanced Quantum Mechanics, World Scientific Publishing

**c) and d) Many-body Quantum Theory I and II:**  
- Roessler: Solid-State Theory, Springer  
- Lippariini: Modern Many-Particle Physics, World Scientific  
- Doniach, Sondheimer: Green's Functions in Solid State Physics, Imperial College Press  
- Haug, Jauho: Quantum Kinetics in Transport and Optics of Semiconductors, Springer  
- Wen: Quantum Field Theory and Many-Body Systems

**e) and f) Quantum Gases I and II:**  
- Metcalf, van der Straten: Laser Cooling and Trapping, Springer  
- Pethick, Smith: Bose-Einstein Condensation in Dilute Gases, Cambridge University Press  
- Zwerger: The BEC-BCS Crossover and the Unitary Fermi Gas, Springer Lecture Notes 836, Springer

**g) and h) Quantum Field Theory I and II:**  
- Peskin, Schroeder: An Introduction to Quantum Field Theory, Westview Press  
- Dyson: Advanced Quantum Mechanics, World Scientific Publishing.  
- Gross: Relativistic Quantum Mechanics and Field Theory, Wiley  
- Mandl, G. Shaw: Quantum Field Theory, Wiley

**i) and j) Solid State Theory I and II:**  
- Ashcroft, Mermin: Solid state physics, Cengage Learning  
- Mahan: Many-Particle Physics, Springer

**m) Quantum Technology:**  
- Pethick, Smith: Bose-Einstein Condensation in Dilute Gases, Cambridge University Press  
- Gerry, Knight: Introductory Quantum Optics, Cambridge University Press

**n) and o) Non-Equilibrium Statistical Mechanics:**  
- Schlosshauer: Decoherence and the Quantum-to-Classical Transition, Springer  
- Breuer, Petruccione: The theory of open quantum systems, Oxford University Press  
- Röpke: Nonequilibrium Statistical Physics, Wiley  
- Bikkin, Lyapilin: Non-equilibrium Thermodynamics and Physical Kinetics, de Gruyter

**q) Superconductivity:**  
- Annett: Superconductivity, Superfluids, and Condensates, Oxford University Press  
- Bennemann, Ketterson (Eds.): The Physics of Superconductors: Vol. II Novel Superconductors, Springer  
- Blundell: Superconductivity - a Very Short Introduction, Oxford  
- Kleiner, Buckel: Superconductivity - Fundamentals and Application, Wiley VCH  
- De Gennes: Superconductivity of Metals and Alloys, Taylor & Francis  
- Tinkham: Introduction to Superconductivity, Dover

**r) – s) as announced in lecture**
Available documents: Up-to-date information and lecture-accompanying materials will be announced in the lecture or on the internet pages of the course.

11. **Registration procedure:**
   - Registration for lectures a) – s) is not required.
   - A possibly required registration procedure for exercises will be announced in the belonging lecture.

12. **Language:** English
## Module LC: Laboratory Course

<table>
<thead>
<tr>
<th>Code: LC</th>
<th>Module Coordinator: Dr. Christoph Döring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workload Total: 210 h</td>
<td>Credit Points (CP): 7 CP</td>
</tr>
<tr>
<td>Duration: 1 Semesters</td>
<td>Start (regular cycle): winter semester and summer semester</td>
</tr>
</tbody>
</table>

1. **Parts of the module/courses:**
   - (P: laboratory, S: seminar)
   - Advanced Laboratory course with seminar

2. **Impact on curriculum:** optional compulsory module

3. **Teaching Staff:** members of the faculty of physics

4. **Content:**
   Complex experiments are performed and analyzed, dealing with fundamental phenomena and techniques of modern physics, particularly in the field of quantum optics. A total of two experiments are to be performed successfully. The current list of experiments may be found at [https://www.physik.uni-kl.de/fp/](https://www.physik.uni-kl.de/fp/).

5. **Competences and intended learning outcomes:**
   Successful completion of this module will develop the following skills, knowledge and expertise:
   - Students will have learned to acquaint themselves rapidly with special subjects and techniques.
   - Students will have learned to work in a scientific team.
   - Students will have learned to set up and operate complex modern measurement apparatus.
   - Students will have learned to plan and perform experiments.
   - Students will have learned to analyze and critically evaluate experimental results.
   - Students will have learned to present scientific results graphically, orally, and in written reports, according to good scientific practice.

6. **Prerequisites for attending:**
   - Formal admission requirements: none
   - Contentual prerequisites: Modules QT and MB

7. **Requirements for receiving credit points:** successful participation
   - The following examinations and courseworks have to be fulfilled:
     - Examination(s): none
     - Coursework(s): successful participation of all experiments within attestation
     - In an accompanying seminar a talk about the first experiment has to be given.

8. **Determination of grade:** ungraded

9. **Applicability of the module/suitability:**
   - Master program Advanced Quantum Physics
## Hints for preparation:

<table>
<thead>
<tr>
<th>Recommended literature:</th>
<th>As provided in the description of each experiment.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available documents:</td>
<td>A description of each experiment is given in advance.</td>
</tr>
</tbody>
</table>

## Registration procedure:
Registration has to be done at the module coordinator.

## Language:
English

## Further Information:
The Laboratory Course is offered twice in each year: from February to April, and from August to October. Both versions of the course are identical, and students are free to choose which one to attend.
Credit for the Laboratory Course in Advanced Quantum Physics is not normally valid in any other Master's program.
# Module SE: Science Electives

**Code:** SE  
**Module Coordinator:** Prof. Dr. Herwig Ott

<table>
<thead>
<tr>
<th>Workload Total: (30 h = 1 CP)</th>
<th>Credit Points (CP):</th>
<th>Duration:</th>
<th>Start (regular cycle):</th>
</tr>
</thead>
<tbody>
<tr>
<td>240 h</td>
<td>8 CP</td>
<td>2 Semesters</td>
<td>winter semester and summer semester</td>
</tr>
</tbody>
</table>

1. **Parts of the module/courses:**

Elective courses as selected by the student  

The choice of the courses requires the approval of the examination board.  

*At least 6 CP must be completed as examination(s), remaining CP can be provided as coursework(s)!*

2. **Impact on curriculum:** elective modules

3. **Teaching Staff:** members of the university

4. **Content:**

Overviews of elective course contents are available from the departments offering the elective courses. A list of courses already approved by the examination board is given in the section Recommendations for Science Electives.

5. **Competences and intended learning outcomes:**

The students deepen and broaden their knowledge in diverse fields of science, and develop general skills that are required for interdisciplinary and professional work.

6. **Prerequisites for attending:**

- **Formal admission requirements:** none  
- **Contentual prerequisites:** depending on the chosen courses, see course description

7. **Requirements for receiving credit points:** successful completion of all sub-module examinations  

The following examinations and courseworks have to be fulfilled:

- **Examination(s):** depending on the chosen courses  
- **Coursework(s):** depending on the chosen courses

8. **Determination of grade:** The grade of the module exam is also the module grade. In the case of sub-module examinations, all sub-module examinations must be passed. The module grade results from the arithmetic average of the grades of the sub-module examinations.

9. **Applicability of the module/suitability:**  

Master program Advanced Quantum Physics

10. **Hints for preparation:**

- **Recommended literature:** As recommended by course instructors.  
- **Available documents:** As recommended by course instructors.

11. **Registration procedure:**

depending on the chosen courses

12. **Language:** English
# Module GE: General Electives

**Code:** GE  
**Module Coordinator:** Prof. Dr. Artur Widera

<table>
<thead>
<tr>
<th>Workload Total: (30 h = 1 CP)</th>
<th>Credit Points (CP):</th>
<th>Duration:</th>
<th>Start (regular cycle):</th>
</tr>
</thead>
<tbody>
<tr>
<td>180 h</td>
<td>6 CP</td>
<td>2 Semesters</td>
<td>winter semester and summer semester</td>
</tr>
</tbody>
</table>

1. **Parts of the module/courses:**
   - Diverse elective courses

2. **Impact on curriculum:** elective modules

3. **Teaching Staff:** members of the university

4. **Content:**
   - Overviews of elective course contents are available from the departments offering the elective courses. Courses may also be found by searching on the KIS webpage: [http://www.kis.uni-kl.de/campus/all/fields.asp](http://www.kis.uni-kl.de/campus/all/fields.asp)

5. **Competences and intended learning outcomes:**
   - Students deepen and broaden their knowledge in diverse subjects, and acquire interdisciplinary skills and competences that are required for professional work.

6. **Prerequisites for attending:**
   - Formal admission requirements: none
   - Contentual prerequisites: depending on the chosen courses, see course description

7. **Requirements for receiving credit points:** successful completion of all sub-module examinations
   - Examination(s): depending on the chosen courses
   - Coursework(s): depending on the chosen courses

8. **Determination of grade:** ungraded

9. **Applicability of the module/suitability:**
   - Master program Advanced Quantum Physics

10. **Hints for preparation:**
    - Recommended literature: As recommended by course instructors.
    - Available documents: As recommended by course instructors.

11. **Registration procedure:**
    - depending on the chosen courses

12. **Language:** English
# Module RM: Research Module

**Code:** RM  
**Module Coordinator:** Prof. Dr. Herwig Ott

<table>
<thead>
<tr>
<th>Workload Total: (30 h = 1 CP)</th>
<th>Credit Points (CP):</th>
<th>Duration:</th>
<th>Start (regular cycle):</th>
</tr>
</thead>
<tbody>
<tr>
<td>990 h</td>
<td>33 CP</td>
<td>2 Semesters</td>
<td>winter semester and summer semester</td>
</tr>
</tbody>
</table>

1. **Parts of the module/courses:** (S: seminars, P: laboratory, K: colloquium)

   a) Introduction to Scientific Practice  
   Attendance time:  
   (SWS x 14)  
   Private Study:  
   CP:  
   total 780 h 26

   b) Quantum Seminar  
   S  
   2 SWS / 28 h 62 h 3

   c) Specialized Scientific Seminar  
   S  
   2 SWS / 28 h 62 h 3

   d) (Theory) Colloquium (5 events)  
   K  
   10 h 20 h 1

2. **Impact on curriculum:** mandatory modules

3. **Teaching Staff:** members of the faculty of physics

4. **Content:**  
Each of the department's research groups provides overviews of its research projects.

5. **Competences and intended learning outcomes:**  
The students acquire in-depth knowledge of the experimental or theoretical methods for selected research topics within the field of quantum physics. By working under close supervision of faculty members, they learn to plan and perform scientific experiments while understanding the theoretical basis of the experiments, or to pursue theoretical research while understanding the experimental realization of the theoretical ideas. They learn to present, interpret and discuss their results, both orally and in writing.

6. **Prerequisites for attending:**  
Formal admission requirements: none  
Contentual prerequisites: Modules QT and MB

7. **Requirements for receiving credit points:** regular and successful participation  
The following examinations and courseworks have to be fulfilled:  
Examination(s): none  
Coursework(s): regular and active participation in course

8. **Determination of grade:** ungraded

9. **Applicability of the module/suitability:**  
Master program Advanced Quantum Physics

10. **Hints for preparation:**  
Recommended literature: as announced by the respective lecturer / group leader  
Available documents: as announced by the respective lecturer / group leader

11. **Registration procedure:**  
Registration for a) and c) has to be done in consultation with the respective group leader. Information on the registration procedure for b) is given in the first seminar session.

12. **Language:** English
**Module MT: Master's Thesis**

**Code:** MT  
**Module Coordinator:** Prof. Dr. Artur Widera

<table>
<thead>
<tr>
<th>Workload Total:</th>
<th>Credit Points (CP):</th>
<th>Duration:</th>
<th>Start (regular cycle):</th>
</tr>
</thead>
<tbody>
<tr>
<td>900 h</td>
<td>30 CP</td>
<td>1 Semesters</td>
<td>winter semester and summer semester</td>
</tr>
</tbody>
</table>

1. **Parts of the module/courses:**
   - Master's Thesis with Oral Presentation

2. **Impact on curriculum:** mandatory module

3. **Teaching Staff:** members of the faculty of physics

4. **Content:**
   The subject of the Master's Thesis will be the student's own research project, completed under the supervision of a faculty member while working within one of the department's research groups. The research project and its presentation will involve learning about the research topic; planning the work; executing the plan; documenting all results according to the formal criteria of an audit committee; explaining the project and its results in the written Thesis; and finally presenting the results in a half-hour talk followed by a fifteen-minute discussion.

5. **Competences and intended learning outcomes:**
   Writing and presenting a Master's Thesis develops the ability to plan and carry out a theoretical or experimental research project in a specialized field of physics, and to explain it clearly to others. During this final phase of the Master's Program, students will attain a professional level of scientific expertise on their specific topic, as well as mastering the essential professional skills of interdisciplinary teamwork and proper scientific conduct.

6. **Prerequisites for attending:**
   - Formal admission requirements: Modules QT, MB, LC, SE GE and RM (expect “Specialized Scientific Seminar”; resolution of the examination board)
   - Contentual prerequisites: Modules QT, MB, LC, SE GE and RM

7. **Requirements for receiving credit points:** successful completion of module examination
   - The following examinations and coursework have to be fulfilled:
     - Examination(s): written Master's Thesis
     - Coursework(s): successful participation of all experiments within attestation
     - In an accompanying seminar a talk about the first experiment has to be given.

8. **Determination of grade:** ungraded

9. **Applicability of the module/suitability:**
   Master program Advanced Quantum Physics
10. **Hints for preparation:**

<table>
<thead>
<tr>
<th>Recommended literature:</th>
<th>As provided by the respective group leader.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available documents:</td>
<td>As provided by the respective group leader.</td>
</tr>
</tbody>
</table>

11. **Registration procedure:**

Registration has to be done in accordance with the examination regulations (§ 16) and in consultation with the respective group leader.

12. **Language:** English
1.4 Recommendations for Science Electives

In the module Science Electives students can select courses in the amount of at least 8 CP from any non-physics science curriculum at TU Kaiserslautern. The choice of the courses requires the approval of the examination board. The following list shows courses already approved by the examination board, it is not final.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4.1 COMPUTER SCIENCE</td>
<td>24</td>
</tr>
</tbody>
</table>
### 1.4.1 Computer Science

#### 1. Parts of the module/courses:

<table>
<thead>
<tr>
<th>Course</th>
<th>Turnus</th>
<th>Attendance time: (SWS x 14)</th>
<th>Private Study:</th>
<th>CP</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Advanced Automata Theory</td>
<td>SS</td>
<td>V 4 SWS / 56 h, Ü 2 SWS / 28 h</td>
<td>156 h</td>
<td>8</td>
</tr>
<tr>
<td>b) Concurrency Theory</td>
<td>WS</td>
<td>V 4 SWS / 56 h, Ü 2 SWS / 28 h</td>
<td>156 h</td>
<td>8</td>
</tr>
<tr>
<td>c) Prozessorarchitektur</td>
<td>WS</td>
<td>V 2 SWS / 28 h, Ü 1 SWS / 14 h</td>
<td>78 h</td>
<td>4</td>
</tr>
<tr>
<td>d) Parallel Computing</td>
<td>SS</td>
<td>V 2 SWS / 28 h, Ü 1 SWS / 14 h</td>
<td>78 h</td>
<td>4</td>
</tr>
<tr>
<td>e) Datenbanksysteme</td>
<td>WS</td>
<td>V 4 SWS / 56 h, Ü 2 SWS / 28 h</td>
<td>156 h</td>
<td>8</td>
</tr>
<tr>
<td>f) Machine Learning I - Foundations</td>
<td>SS</td>
<td>V 4 SWS / 56 h, Ü 2 SWS / 28 h</td>
<td>156 h</td>
<td>8</td>
</tr>
<tr>
<td>g) Collaborative Intelligence</td>
<td>SS</td>
<td>V 2 SWS / 28 h, Ü 1 SWS / 14 h</td>
<td>78 h</td>
<td>4</td>
</tr>
<tr>
<td>h) 3D Computer Vision</td>
<td>WS</td>
<td>V 2 SWS / 28 h, Ü 1 SWS / 14 h</td>
<td>78 h</td>
<td>4</td>
</tr>
<tr>
<td>i) Foundations of Software Engineering</td>
<td>SS</td>
<td>V 2 SWS / 28 h, Ü 1 SWS / 14 h</td>
<td>78 h</td>
<td>4</td>
</tr>
<tr>
<td>j) Funktionale Programmierung</td>
<td>SS</td>
<td>V 4 SWS / 56 h, Ü 2 SWS / 28 h</td>
<td>156 h</td>
<td>8</td>
</tr>
<tr>
<td>k) Automotive Software and Systems Engineering</td>
<td>SS</td>
<td>V 2 SWS / 28 h, Ü 1 SWS / 14 h</td>
<td>78 h</td>
<td>4</td>
</tr>
<tr>
<td>l) Human Computer Interaction</td>
<td>WS</td>
<td>V 2 SWS / 28 h, Ü 1 SWS / 14 h</td>
<td>78 h</td>
<td>4</td>
</tr>
<tr>
<td>m) Data Visualization</td>
<td>WS</td>
<td>V 2 SWS / 28 h, Ü 1 SWS / 14 h</td>
<td>78 h</td>
<td>4</td>
</tr>
</tbody>
</table>

#### 2. Teaching Staff: members of the faculty of computer science

#### 3. Further Information:

[see respective module description](https://www.cs.uni-kl.de/studium/lehrveranstaltungen/modulhb/)