Study plan in

Theoretical and Computational Condensed Matter Physics

Master’s Degree Program in Physics – Curriculum Theoretical and computational physics

Overview

This study plan is designed to train students in the methods of theoretical and computational material modeling. The knowledge and practice of advanced concepts and computational tools will enable the attendees to reach a working understanding of the many new fascinating quantum phenomena occurring in materials, especially at the nanoscale, and in the low-dimensional quantum systems.

Fields of specialization
- Theoretical modeling of physical and quantum processes in materials
- Computational nanoscience
- Computational bio-physics
- Materials for quantum technologies
- Materials for nanophotonics

Scope
At the end of this program students will be able to understand the physics and functioning principles of advanced materials, and of the interaction between materials and external probes (waves and particles), make quantitative predictions of material properties by mastering the most advanced theoretical and computational methods and protocols for the investigation of material properties and for (nano-)material engineering.

First Year

Advanced quantum mechanics
A self-contained course addressing several aspects of quantum mechanics that are relevant for modern developments in physics, ranging from condensed-matter theory to particle physics and their fundamental interactions. Particular emphasis will be given to the concept of Berry phases, the path integral formulation of quantum mechanics, and scattering theory.

Quantum field theory
An introductory course on QFT, providing the quantization of scalar, spinor and vector fields and covering the computation of scattering processes and decay rates in theories like $\phi^4$, Yukawa and QED. The course also provides a first discussion of radiative correction and renormalization.

Quantum physics of matter
An advanced course on matter-light and matter-electron interactions, using quantum linear response theory to discuss elementary excitations of material systems and their spectral features: electronic and phonon excitations, excitons, plasmons, polaritons.

Relativity
In this course students learn the elegant mathematical framework behind Special and General Relativity and apply it to fascinating physical problems, including GR effects on planetary motion, the physics of black holes, gravitational waves and cosmology. The course also provides a first discussion of quantum gravity.

Statistical mechanics and phase transitions
An advanced course in classical and quantum statistical mechanics, from the theoretical foundations to phase transitions and critical phenomena, including quantum condensates (BEC, superfluids, superconductors). Attendees are introduced to modern theoretical methods, from mean-field methods to statistical field theory and renormalization group theory.

Laboratory of Quantum Simulation of Materials
A course with both frontal lectures and hands-on tutorial sessions, dealing with theoretical/computational techniques for the electronic structure simulation of condensed matter systems. Special emphasis is given to Density Functional Theory, the present state-of-the-art, parameter-free and atomistic scheme for the predictive description of materials.

Image: Energy dispersion of quasi-particles states from a three-body scattering calculation
Opportunities

The FIM Department hosts internationally recognized scientists in theoretical and computational condensed matter physics. Each research group has unique worldwide expertise in specialized areas of material theoretical research. The ongoing research activities are carried out in collaboration with several research and computational centers in Italy, Europe, and worldwide, including Stanford University, Princeton University, Arizona State University, Paul Drude Institute (Berlin). Many research activities are also carried out in close collaboration with the Institute of nanoscience CNR-NANO in Modena (www.nano.cnr.it).

Employment

The acquired skills will enable the student to pursue employment in research on advanced new materials at international private and public laboratories, at High Performance Computing Centers, in industrial R&D sectors, or to proceed for a PhD, both within the Graduate School in Physics and Nanoscience in Modena and worldwide.

Notes

For up-to-date technical HPC competences you may want to take Machine learning and deep learning, and/or High-Performance-Computing from the M.Sc. in Mathematics.

Quantum Information Processing

A graduate-level introduction to the theory behind quantum computers and quantum information processing (QIP) in general. The topics will range from basic QIP primitives e.g., teleportation, to quantum error correction passing through fundamental quantum computing algorithms e.g., Shor’s factoring.

Fundamentals of nanoscience

Nanosystems are both quantum worlds with astonishingly new properties and the basis of new nanodevices. The course provides a conceptual and practical framework dealing with the physics and description of a set of prototype nanosystems, from nanotubes and graphene structures to nanocrystals, quantum wells, wires and dots.

Quantum many-body theory

A course covering concepts and physical pictures behind various phenomena that appear in vast assemblies of interacting quantum particles. The most widely used many-body methods are presented (many-body perturbation theory, large-scale diagonalization methods, Feynman diagram, and Green’s function approaches) and applied to selected physical systems.

Atomistic simulation methods

The aims are to master the fundamental techniques underlying the numerical approaches to simulate microscopic models in Statistical Mechanics and Quantum Physics, developing the abilities needed to write (simple) Monte Carlo or Molecular Dynamics codes and to perform a thorough numerical investigation for a given case study.

Second Year

Laboratory of condensed matter physics

A lab course to become familiar with a few of the most used experimental techniques in material research (electron microscopies, X-ray diffraction and electronic spectroscopies) and challenge your experimental skills by designing and performing experiments from scratch.

Chemical Physics of Biomolecules (as free choice course)

A unique and multidisciplinary course for students interested in acquiring advanced theoretical understanding of chemical physics, with an emphasis on biomolecules, colloids and their application to nano-biophysics and nano-medicine.

Physics of semiconductors (as free choice course)

Semiconductors have played a key role both in the observation of unprecedented physical phenomena and in the development of modern electronic devices. This course, suitable to students following both a curriculum with a theoretical or an experimental character, provides all the necessary ingredients to understand the fascinating physical properties of semiconductors, from their band structure description to transport phenomena, and how to exploit them in devices like transistors or to observe novel phenomena like the quantum Hall effect.