Study plan in

Theoretical Condensed Matter Physics

UNIMORE
UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA
Dipartimento di Scienze Fisiche, Informatiche e Matematiche

M.Sc. program in Physics – Curriculum Theoretical and Computational physics

Overview

This study plan is tailored to educate students in the fascinating realm of **condensed matter quantum theory**. It integrates foundational teachings covering advanced quantum theories, statistical mechanics, and relativistic physics, with specialized courses delving into the fundamental phenomena within condensed matter systems and their applications. Through this program, students gain a deep understanding of the theoretical modelling that underpin captivating physics phenomena, such as **superconductivity**, **quantum matter**, and **topological effects**, with a particular focus on **revolutionary materials systems** at the nanoscale.

Goal

To acquire a comprehensive understanding of the intricate and fascinating mechanisms governing advanced materials properties. The attendees will be able to critically analyze **excitations** triggered by external probes, enabling them to make precise quantitative predictions of their **spectral features**. Mastery of **cutting-edge theoretical methods** and investigative protocols will equip students to delve into material properties and engage in material engineering with precision and expertise.

More info and suggestions from

Study plan coordinator
Prof. Guido Goldoni

Program director
Prof. Paolo Bordone

Program website
`www.fim.unimore.it/LM/FIS`

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Fist year

Advanced quantum mechanics **(M)** – M Gibertini

A self-contained course addressing several aspects of quantum mechanics relevant to modern developments of physics, from condensed-matter theory to particle physics and their fundamental interactions. Emphasis will be given to the concept of Berry phase, the path integral formulation, and scattering theory.

Quantum field theory **(M)** – D Trancanelli, E Bertuzzo

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 4, Yukawa and QED theory. The course also provides a first discussion of radiative correction and renormalization.

Statistical mechanics and phase transitions **(M)** – G Goldoni

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

Quantum physics of matter **(M)** – R Magri

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.

Solid state physics **(D)** – G Goldoni, F Grasselli

A course on the quantum theory of solid matter which is behind modern material science and semiconductor technology which shape the technological world. From electronic properties and transport phenomena to interaction with radiation, topological properties and advanced phenomena like superconductivity.

Quantum many-body theory **(D)** – A Ferretti

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.

Nanoscience and quantum materials **(D)** – E Molinari

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.

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Fields of specialization

- Modeling of quantum processes
- Topological quantum matter
- Nano-physics
- 2D materials
- Quantum technologies
- Quantum many-body physics

Opportunities

Our research groups, led by internationally recognized scientists in **theoretical condensed matter physics**, have unique expertise in specialized areas of theoretical research on materials. Research activities are carried out in collaboration with **research and computational centers** in Europe, and world-wide, as well as with the Institute of nanoscience **CNR-NANO** in Modena. Collaborations are supported by European agencies through, e.g. **EU framework programs**, **Marie-Curie networks**, and drive **thesis projects** at the forefront of current theoretical-computational research. Students may also opt for the **Double Degree program** and spend one year on a research project at the Radboud University (NL).

Employment

Our students often pursue employment in research on advanced materials at international **private and public laboratories**, in industrial **R&D sectors**, or proceed for a PhD, both within the **Graduate School in Physics and Nanoscience** in Modena or worldwide.

Notes

Interested students may deepen the computational aspects of the field choosing from a list of modern courses in computational techniques.

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Quantum information processing **(R)** – P Bordone

An introduction to the theory behind quantum computers and QIP in general. Topics range from the basic concepts of QIP such as quantum entanglement and generalized quantum dynamics, to fundamental QIP algorithms, such as Shor's factoring, and quantum cryptography.

Physics of semiconductors **(R)** – S D'Addato

A course providing all the necessary ingredients to understand the fascinating physical properties of semiconductors, from their electronic structure description to transport phenomena, and how to exploit them in devices like transistors, or to observe novel states of matter like the quantum Hall liquid.

Relativity **(R)** – D Trancanelli

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.

Second year

Synchrotron radiation: basics and applications **(D)** – S D'Addato

A course on the working principles of synchrotrons and the use of emitted radiation, from description of single ultra-relativistic particles sources to essentials of storage rings, bending magnets, wigglers and undulators, free electron lasers, beam lines. Examples of ensuing popular techniques, as X-ray diffraction, scattering, absorption and X-ray microscopy, are discussed and a visit to to ELETTRA labs in Trieste ends the course.

Laboratory of Quantum Simulation of Materials **(F)** – A Ruini

Frontal lectures and hands-on tutorial sessions introduce attendees to 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.

Magnetism, spintronics, and quantum technologies **(F)** – M Affronte

A course on quantum and statistical description of magnetic phenomena, experimental techniques for magnetic characterization, and advanced applications in spintronics and molecular magnetism. The course offers an overview on some of the emerging quantum technologies for quantum computing and quantum sensing, introducing basic concepts for the functioning of superconducting devices, on the use of spin resonance on color centers and fundamentals of cryogenics.

Legend: (M) mandatory course for this curriculum; (D) chosen within distinctive (*caratterizzanti*) courses; (R) chosen within related (*affini*) courses; (F) selected as a free choice course

This study plan is a suggested set of courses, chosen within the curriculum, to ensure an in-depth professional training combined with the broad spectrum of skills required to modern scientists. Mandatory, distinctive and related courses provide the natural background of this study plan. However, the study plan can also be tailored to the students' scientific interests. Ask the study plan coordinator for further indications.