Overview

The theoretical physics of fundamental interactions focuses on the study of various relativistic field theories, such as those that compose the Standard Model of particle physics, General Relativity and String Theory. These theories have provided astonishingly precise predictions of many elementary particle phenomena and gravitational/cosmological phenomena, and have contributed a great deal of technological progress. Moreover, they have recently yielded new efficient approaches to tackle the physics of several strongly-coupled systems, hence opening new very promising avenues of research; for example, in the field of condensed matter, they have recently played an important role in the characterization of new innovative materials.

The present study plan will provide students with the most modern approaches to fundamental interactions. Students will be acquainted with the elegant and efficient formalism that characterizes the various relativistic field theories, and learn how to employ it to (analytically and/or numerically) compute relevant physical quantities, such as particle scattering amplitudes and effective actions entering in the evaluation of particle cross-sections, decay rates and other physical observables. However, most of the methodologies they will acquire are of broader use and are also employed in other physical theories, such as those modelling condensed matter systems and other strongly-coupled systems.

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.

Advanced quantum field theory

A follow-up course on Relativistic Quantum Field Theory introducing quantization of theories based on local (gauge) symmetry, which is the main ingredients of the Standard Model, the theory that describes with amazing precision the interactions of elementary particles. More advanced topics, including for instance Supersymmetry and/or BRST-BV formalism, will also be covered.

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.

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.

Close-up of a blackboard with the Lagrangian of the standard model.
Opportunities

This study plan is connected to ongoing research activities carried out by our scientists in collaboration with several research centres in the world, among which Istituto Nazionale di Fisica Nucleare (Bologna), University of California (Davis, USA), King’s College (London, UK), University of Michigan Ann Arbor (USA) and Keio University (Japan). The thesis project will be carried out within the group of theoretical physics of fundamental interactions of the FIM department and/or in the national and international collaborating research groups, some of which are listed above.

Notes

Students willing to deepen their formal training may want to choose courses from the Master program in mathematics, such as Equazioni alle Derivate Parziali or Metodi Matematici della Meccanica Quantistica (in Italian).

Students willing to see mathematical methods at work in applicative field may also enroll in Medical Physics, Numerical Algorithm for Signal and Images, or Deep Learning and Machine Learning.

Ask the Master coordinator for the full list of available courses.

Elementary particles

A course introducing the elementary constituents of matter and their interactions, as well as the role of symmetries and their violation, up to the most recent discoveries in the field (neutrino masses, Higgs boson, multi-quark states).

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.

Magnetism, spintronics, and quantum technologies

A course devoted to quantum and statistical description of magnetic phenomena, from atomic level to collective effects, experimental techniques for magnetic characterization, and advanced applications in spintronics and molecular magnetism. The course will offer an overview on some of the emerging quantum technologies for quantum computing, quantum sensing. Introducing basic concepts for the functioning of superconducting devices, on the use of spin resonance on colour centers and fundamentals of cryogenics.

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.

Relativity (as free choice course)

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.

Free choice course

See notes for several suggested courses.