QUARMEN
Erasmus Mundus Joint Master
QUANTUM SCIENCE & TECHNOLOGY

# Semester 2: Paris-Saclay University

# Plan of Studies

| COURSE | ECTS | HOURS |
|---|---|---|
| *Macroscopic Quantum Phenomena* | 6 | Lectures: 30h<br>Tutorials: 20h |
| *Advanced mathematics for physics* | 3 | Lectures: 20h<br>Practicals: 10h |
| *Machine learning for Quantum Technology* | 3 | Lectures: 20h<br>Tutorials: 10h |
| *Nanomaterials and electronics applications* | 3 | Lectures: 18h<br>Tutorials: 18h |
| *Quantum Hardware* | 3 | Lectures: 20h<br>Tutorials: 10h |
| *Research project* | 3 | One day per week |
| *Language course* | 3 | Lectures: 24h |
| *Internship* | 6 | 11 weeks |

# Macroscopic Quantum Phenomena

**ECTS: 6**
**Lectures: 30h**
**Tutorials: 20h**

**DESCRIPTION**

This course proposes an introduction to spectacular macroscopic manifestations of quantum physics in matter. In a first part, we will introduce the physics of superconductivity, superfluidity and condensates. At very low temperatures, various mechanisms can lead to macroscopic collective quantum states which have surprising properties such as zero-electrical resistance, magnetic levitation or absence of viscosity. We will show how a common phenomenon can give rise to these properties in very different systems such as boson gas, liquid helium or metals. In the second part of the course, we will show how the common classical law of electricity are modified at the mesoscopic scale where quantum effects do play an important role and may have macroscopic consequences. Finally the last part of the course will be devoted to an introduction to important modern applications of quantum mechanics in quantum communications and quantum computing which are very active fields at the crossroads between many disciplines such as information theory, mathematics and material science. This course will be based on many recent discoveries in this field which is one of the most active and innovative area in condensed matter physics today.

**Lecturers**

Charis Quay, Julien Basset

**SYLLABUS**

Chapter 1:
Superconductivity, superfluids and condensates
Bose-Einstein Condensation and superfluidity
Superconductivity: macroscopic aspects, microscopic theory, thermodynamics

Chapter 2:
Mesocopic physics
Quantization of conductance
Electronic transport in mesoscopic systems
Magnetism and persistent currents in mesoscopic rings
Josephson effect

Chapter 3:
Introduction to quantum information
Quantum Information : History, objectives, perspectives
Quantum bits and Bloch sphere
Simple examples of quantum computation
Quantum teleportation and EPR paradox

**Recommended textbooks:**

- Principles of Condensed Matter Physics (P. M. Chaikin and T. C. Lubensky)
- Superconductivity, Superfluids, and Condensates (J F Annett, Oxford Master Series in Condensed Matter Physics)
- S. Datta, Quantum Transport: Atom to Transistor, Cambridge University Press, New York (2005)
- M. Le Bellac, A short introduction to Quantum information and quantum computation, Cambridge University Press
- M. A. Nielsen, and I. L. Chuang, Quantum Computation and Quantum Information, Cambridge University press (2000)

**Course prerequisites and corequisites**

The prerequisites are usually taught at the level of the third year of university: Fundamentals of Quantum Mechanics (Book : Quantum Mechanics by C. Cohen-Tannoudi, B. Diu, F. Laloë - vol. I and II, Ed Wiley).

**Course concrete goals**

On completion of the course students should be able to:

- Take more formal courses at the level of second year of Master covering advanced concepts used in Solid State Physics, Quantum physics, Nanoelectronics (M2 Fundamental Concepts in Physics, M2 Nano, etc...)
- Be acquainted with the basics of superconductivity, superfluidity and quantum transport at the nanoscale
- Know how quantum mechanics can help to transmit information in a more secure way.

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# Advanced mathematics for physics

**ECTS: 3**
**Lectures: 20h**
**Practicals: 10h**

**DESCRIPTION**
These lectures allow to acquire familiarity and operational knowledge of the mathematics of symmetry groups, as a transversal and structuring notion of modern Physics, from condensed matter to particle physics.

**Lecturers**
Robin Zegers

## SYLLABUS

Chapter 1: General Group theory (definitions and main theorems)
Chapter 2: Finite and discrete groups
Examples include reflection groups and lattices in relation with crystallography, molecular physics etc. This chapter also introduces the notion of root systems as relevant to general Lie theory.
Chapter 3: Introduction to Lie groups and Lie algebras
Chapter 4: Introduction to the representation theory of Lie algebras
Special emphasis will be put on the Lie groups relevant to High Energy Physics such as the Poincaré and Lorentz groups; SU(2) and SU(3) in relation with particle physics.

**Recommended textbooks:**
- Fulton and Harris, Representation Theory
- Gilmore, Lie groups, Lie algebras and some of their applications
- Georgi, Lie algebras in particle Physics
- Hamermesh, Group theory and its applications to physical problems
- Kosmann-Schwartzbach, Groups and symmetries
- Sternberg, Group theory and physics

**Course prerequisites and corequisites**
- Elementary quantum mechanics (Hilbert spaces, operators);
- Elementary linear algebra (Vector spaces, matrices etc).

**Course concrete goals**
- On completion of the course students should be able to:
- Handle the physically relevant mathematics of group theory and representation theory
- Manipulate the classical Lie groups and their representations
- Follow any advanced M2 lecture involving or relying on those notions.

## Nanomaterials and electronics applications

**ECTS: 3**
**Lectures: 18**
**Tutorials: 18**

**DESCRIPTION**
This module introduces recent developments in the field of semiconducting nanomaterials based on silicon or carbon, as well as their principal electronic applications.
More precisely, the following topics are addressed:
• Disordered semiconductors: amorphous, nano- and polycrystalline silicon
• Silicon nanowires: structure and synthesis
• Carbon nanotubes
• Graphene
• Characterization techniques for nanomaterials: near-field and spectroscopies
• Electronic applications: photovoltaics, flat panel displays, electronic devices, detectors, sensors, etc.

**Lecturers**
Razvigor Ossikovski

**Syllabus**
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• Carbon nanotubes
• Graphene
• Characterization techniques for nanomaterials: near-field and spectroscopies
• Electronic applications: photovoltaics, flat panel displays, electronic devices, detectors, sensors, etc.

**Recommended textbooks:**
R. Ossikovski, Nanomatériaux et applications électroniques (Editions de l'Ecole polytechnique, 2018) R. A. Street, Hydrogenated Amorphous Silicon (Cambridge, 1991) S. M. Sze, Semiconductor Devices: Physics and Technology (Wiley, 2002) R. Saito, G. Dresselhaus, M. Dresselhaus, Physical Properties of Carbon Nanotubes (Imperial College, 2005) S. Datta, Electronic Transport in Mesoscopic Systems (Cambridge, 2007) (+ research articles).

**Course prerequisites and corequisites**
Fundamentals of quantum and statistical physics.

## Machine learning for Quantum Technology

**ECTS: 3**
**Lectures: 20h**
**Tutorials: 10h**

**DESCRIPTION**

Machine Learning methods are finding more and more applications in Quantum Science and Technology. This course aims at providing the basic elements of Machine Learning and examples of applications in prototype quantum science problems.

**Lecturers**

Filippo Gatti, Meydi Ayouz

**SYLLABUS**

Introduction to Machine Learning
Numerical resolution of the Schroedinger equation and applications to the HO system
Machine Learning for Quantum mechanics: applications to HO, Morse potential and the NH3 molecule.
Photoelectric effect in solids, its modelisation, and its solution using ML.
Computing photoionisation cross sections: predictions using ML.

**Course prerequisites and corequisites**

Fundamentals of quantum mechanics and basics of programming,

## Quantum Hardware

**ECTS : 3**
**Lectures : 20h**
**Tutorials : 10h**

**DESCRIPTION**

The course aims at providing an overview of the basic experimental approaches for quantum information

**Lecturers**

Nadia Belabas, Marino Marsi

**SYLLABUS**

Real and ideal qubits – manipulation and characterization
Initializing a qubit – decoherence – qubit state and its characterization – entanglement between two qubits – Di Vincenzo criterion
Quantum processors based on trapped ions Different types of qubits – clock type states - Paul trap and Penning trap – Cirac-Zoller door
Superconducting qubits - NV centers in diamond - Spin qubits - Rydberg atoms
Optomechanical resonators - Photonic qubits -Topological qubits

**Recommended textbooks:**

**Course prerequisites and corequisites**

Fundamentals of quantum mechanics, theoretical basics of quantum information

## Research project

**ECTS: 3**
**Project: 70h**

The Research project is an active participation in the activities of one of the research groups in the domain one day per week. It may be preliminary to an internship in the same group, but not necessarily.

## Language course

**ECTS: 3**
**Lectures: 24h**
**2 hours per week**

**French language courses:** the student will acquire the basic knowledge in the national language and a glimpse at national culture and heritage of the hosting country.
Developing language skills in order to be able to communicate. Oral and written understanding and oral and written expressions; practical aspects.

## Internship

**ECTS: 6**

The internship will take place between the end of April and the beginning of July. It should be with one of the Paris-Saclay groups working in the domain – either academic groups or companies / startups.