Master of Fundamental Physics and Applications:
Quantum and photonic technologies Master Track

Département de Physique - Université de Lille

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Syllabus

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ADVANCED QUANTUM PHYSICS

UE : ADVANCED QUANTUM PHYSICS

BCC2 : RÉSOUDRE DES PROBLÈMES COMPLEXES EN QUANTIQUE ET PHOTONIQUE

Enseignement ob
Modalité d'enseignement : présentiel
Langue de l'enseignement : anglais
Responsable : Adam Rançon
Enseignants potentiels : A. Rançon, G. Patera, A. Feller, C. Hainaut, R. Chicireanu

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		24				24

UE(s) prérequise(s) :

Lectures conseillées :

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Syllabus :

This advanced quantum physics course explores key concepts of modern quantum physics such as time-dependent perturbation theory, density matrices, entanglement, and the dynamics of two-level systems. It provides a deep understanding of fundamental quantum phenomena and their applications.

Prerequisite:

Equivalent of Cohen-Tannoudji's book volume 1 and part of 2 : Schrodinger equation, Heisenberg and Schrodinger picture, Harmonic oscillator, Hydrogene atom, Angular momentum and addition of angular momenta.

Objectives:

This course aims to equip students with advanced skills in quantum physics, focusing on mastering time-dependent perturbation theory for analyzing complex quantum systems. Students will learn to manipulate density matrices, understand quantum entanglement, and analyze the behavior of two-level systems using tools like Bloch spheres and Rabi oscillations. By the end, they will be proficient in applying these concepts to solve advanced problems in quantum mechanics and quantum information science.

Program :

- Dirac Equation (4h CTD)
- Density Matrix Formalism: pure vs mixed state ; entanglement and partial trace (e.g. EPR, Bell) ; Boltzmann distribution (6h)
- 2nd quantization (6h) : find a nice application (Bose/Fermi distribution ?)
- Time-Dependent Perturbation Theory (6h) : application using 2nd quantization (coupling of descrete system to a

continuum)

- Introduction to the path integral formalism (4h CTD) : construction of path integral + application to free particle and harmonic oscillator
-

Aquired skills:

Direct skills include proficiency in time-dependent perturbation theory, manipulation of density matrices for quantum systems, and analysis of two-level quantum systems using geometric representations like the Bloch sphere. Indirectly, students will develop problem-solving abilities in complex quantum scenarios and enhance their understanding of foundational quantum concepts essential for advanced research and applications in quantum technology.

Modalités d'évaluation

Evaluation : isolée
CC, CT, rapport, soutenance orale,... + pondérations

MASTER mention PHYSIQUE FONDAMENTALE ET APPLIQUÉE parcours QUANTUM AND PHOTONIC TECHNOLOGIES

S1

LINEAR SYSTEMS

UE : LINEAR SYSTEMS

BCC2 : RÉSOUDRE DES PROBLÈMES COMPLEXES EN QUANTIQUE ET PHOTONIQUE

Enseignement ob
Modalité d'enseignement : présentiel
Langue de l'enseignement : anglais
Responsable : Pierre Suret
Enseignants potentiels : Pierre Suret, Francois Anquez, Serge Bielawski

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		24		12		36

UE(s) prérequise(s) :

Lectures conseillées :

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Syllabus :

Explore the core mathematical tools behind waves and linear systems: from spectral analysis and transfer functions to eikonal approximations and ray dynamics in complex media.

Objectives:

This course will give students a solid foundation in the analysis of linear systems using Fourier techniques and impulse response theory.

They will learn how to solve linear partial differential equations using spectral methods. The course introduces dispersion relations to understand wave behavior in various media. Students will explore the high-frequency limit of wave propagation and its geometric interpretation. By the end, they will be able to model, analyze, and interpret a broad range of wave phenomena across physics.

Program:

Chapter 1 – Harmonic Analysis and System Characterization

1.1 Fourier Transform and Spectral Representation

- Fourier transform of signals
- Frequency-domain representation

1.2 Impulse Response

- Definition and properties: linearity, time-invariance

- Principle of superposition and impulse response

1.3 Transfer Function

- Definition: H(ω) = \frac{out(\omega)}{in(\omega)}
- Relationship between impulse response and transfer function
- Kramers–Kronig relations
- Examples: RC low-pass filter, damped oscillator, Bode plots

Chapter 2 – Solving Linear Partial Differential Equations

2.1 Overview of Linear PDEs in Physics

- Definition and examples: heat equation, wave equation, Helmholtz equation
- Linearity and superposition principle
- Role of initial and boundary conditions

2.2 Fourier Transform Methods

- Solving linear PDEs using Fourier transforms
- Examples

2.3 Green's Functions

1. Definition and physical interpretation
1. General solution of L\psi=f \psi
1. Examples (Wave equation and retarded Green's function)

2.4 Dispersion Relations

- Definition and derivation from the wave equation and other PDEs
- Physical meaning of phase and group velocities:

vp=ω/k, v_g = \frac{d\omega}{dk}vp

- Examples: vibrating string, optical fibers

Chapter 3 – Geometrical Approximation of Wave Propagation

3.1 Motivation and Context

- Physical motivation: wave behavior in the short-wavelength (high-frequency) limit.
- Typical situations: optics, acoustics, quantum mechanics (WKB), seismology.
- Goal: extract the main behavior (phase and direction) without solving full wave equations.

3.2 From the Wave Equation to the Eikonal Equation

- WKB ansatz: for a time-harmonic wave,

psi(x) = A(x) e^{i \phi(x)/\varepsilon}, \quad \varepsilon \ll 1

- Inserting into the Helmholtz equation and expanding in powers of ε

- Eikonal equation (leading order) : wavefronts
- Transport equation (next order): governs how amplitude A(x) evolves along rays.

3.3 Fermat’s Principle and its Generalization

Rays are solutions to a variational problem

- In optics: light travels along the path that extremizes optical length:
- In the eikonal framework: rays extremizes the action functional
- The generalized Fermat principle applies to any high-frequency wave phenomenon governed by a Hamiltonian-type structure.

Modalités d'évaluation
Evaluation : isolée *CC, CT, rapport, soutenance orale,... + pondérations* CT

CLASSICAL FIELD THEORY

UE : CLASSICAL FIELD THEORY

BCC2 : RÉSOUDRE DES PROBLÈMES COMPLEXES EN QUANTIQUE ET PHOTONIQUE

Enseignement ob
Modalité d’enseignement : présentiel
Langue de l’enseignement : anglais
Responsable : Alexandre Feller
Ensiegnants potentiels : Alexandre Feller, Adam Rançon, Stephane Randoux

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		24				24

UE(s) prérequise(s) :

Lectures conseillées :

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Syllabus :

This course aims to develop the formalism of classical field theory, which is the basis of all our current fundamental theories, in its quantum extension. This module is divided into two parts. The first aims to present the general formalism for defining and studying a field theory, via a Lagrangian or Hamiltonian description. A major result of modern physics will be established: Noether's theorem, linking symmetries and conserved quantities. The second part of the course will be dedicated to studying classical electromagnetism as a relativistic classical field theory. This will lay the foundation stone for its quantum version, quantum electrodynamics, which is currently the most precise physical theory ever tested.

Objectives :

1. Master the Lagrangian and Hamiltonian formalism of classical field theories.
2. Deduce general physical features from fundamental symmetries.
3. Master the relativistic formulation of electrodynamics and its Hamiltonian formulation.

Program :

Prerequisites : Special Relativity, Analytical Mechanics, Basis of Electromagnetism

1. Space-time and observers
   Spacetime as Minkowskian geometry : four dimentional spacetime, metric

   Observers : worldine, proper time

Change of observers : Lorentz transformations, Lorentz group

2. Classical field theory: Lagrangian formulation, action, Euler-Lagrange equation
3. Symmetries in Lagrangian formulation: Noether's theorem.
4. Classical field theory: Hamiltonian formualtion
5. Symmetries in Hamiltonian formulation
6. Electrodynamics: covariant, Lagrangian, and Hamiltonian formulation
7. Complements: Tensors, geometry and group theory

Acquired skills :

The student will be able to :

1. Define a field theory and deduce its main features from symmetries
2. Buils some field theory models from general arguments like symmetries
3. Define and/or deduce an Hamiltonian formalism as a first step to build quantum models

Modalités d'évaluation
Evaluation : isolée *CC, CT, rapport, soutenance orale,... + pondérations* CT

MASTER mention **PHYSIQUE FONDAMENTALE ET APPLIQUÉE** parcours

QUANTUM AND PHOTONIC TECHNOLOGIES

S1

STATISTICAL PHYSICS AND CRITICAL PHENOMENA

UE : STATISTICAL PHYSICS AND CRITICAL PHENOMENA

BCC3 : RÉSOUDRE DES PROBLÈMES COMPLEXES EN MOBILISANT LES CONCEPTS DE LA PHYSIQUE FONDAMENTALE

Enseignement **Ob**

Modalité d’enseignement : **présentiel**
Langue de l’enseignement : anglais

Responsable de l’enseignement : *Adam Rançon* – `adam.rancon@univ-lille.fr`
Autres enseignants potentiels : Laurent Carpentier, Adam Rançon, Radu Chicireanu, Abdelkader, Frederic, Alexandre Feller

volume horaire	**CM**	**C-TD**	**TD**	**TP**	**A distance**	**Total**
Heures d'enseignement encadrées		**24**				**24**

UE(s) prérequise(s) : None

Lectures conseillées :
- Goldenfeld, Lectures On Phase Transitions And The Renormalization Group (Frontiers in Physics)

Syllabus :

This course introduces fundamental concepts in statistical physics, focusing on phase transitions, critical phenomena, and the renormalization group. It covers key models like the Ising model and Landau theory, providing tools for analyzing quantum gases and critical phenomena. Standard tools such as statistical field theory and the renormalization group will be introduced.

Prerequisites
Probabilistic description, ensembles (micro, cano, grand cano) ; Partition function, thermodynamic potentials.

Course outline
What are a phase transition ? Order paramter, spontanueous symmetry breaking and thermodynamic limit
Critical phenomena, Landau theory, mean field, with application to the Ising model
Introduction to statistical field theory, correlation functions and gaussian fluctuations
Introduction to the renormalisation group : breakdown of mean-field theory, Ising 1D and decimation, Kadanoff block-spins

Modalités d'évaluation
Evaluation : isolée *CC, CT, rapport, soutenance orale,... + pondérations*

ATOMIC PHYSICS

UE : ATOMIC PHYSICS

BCC3 : RÉSOUDRE DES PROBLÈMES COMPLEXES EN MOBILISANT LES CONCEPTS DE LA PHYSIQUE FONDAMENTALE

Enseignement Ob
Modalité d'enseignement : présentiel
Langue de l'enseignement : anglais

Responsable de l'enseignement : *Céline Toubin* – celine.toubin@univ-lille.fr
Autres enseignants potentiels : Céline Toubin, Thèrèse Huet, Hervé Herbin, Claire Pirim

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		24				24

UE(s) prérequise(s) :

Lectures conseillées :
- Mécanique quantique, C. Cohen-Tannoudji, B. Diu, F. Laloë (Hermann).
- Molecular quantum mechanics / Atkins
- Physics of atoms and molecules / Bransden
- Atoms and molecules interacting with light / Van der Straten

Syllabus :

This course provides an introduction to atomic physics. You will explore the quantum mechanical description of both single and multi-electron atoms. By studying the fundamental properties of atoms, you will gain a deeper understanding of the periodic table's structure. Furthermore, you will investigate how atoms interact with light and how their spectra provide insights into these systems.

Prerequisites:
Basics of quantum physics (L3); hydrogen atom; quantization of angular momentum; harmonic oscillator; Special relativity; electromagnetism ; Hamiltonian mechanics

Objectives:
This advanced course delves into the intricate interactions between light and matter at atomic scales. We will explore fundamental concepts based on quantum physics to describe the structure of atoms containing several electrons and the spectral signatures resulting from their interactions with electromagnetic fields.

Course outline
- Atom with 1 electron : Interaction with an external electric or magnetic field,
    - Fine structure
    - The Zeeman effect,
    - The Stark effect
    - Hyperfine structure
- Atom with two electrons :

  - The Schrödinger equation of 2-electron atoms, ortho and para states
  - Spin wave functions and the Pauli exclusion principle
  - The independent particle model
  - The ground state of the 2-electron atoms
  - Excited states of the 2-electron atoms
- Atom with many electron
  - (Slater determinants), variational method, Hartree-Fock
  - The central field approximation
  - The periodic classification of the elements
  - The Hartree-Fock method
  - Corrections to the central field approximation
- The interaction of many-electron atoms with electromagnetic fields
- Selection rules (if times allows, otherwise fairly Light-matter interaction)

Skills acquired

- Apply fundamental quantum mechanical concepts and methods to problems in atomic physics.
- Analyze basic atomic spectra.
- Solve complex theoretical and numerical problems using advanced quantum and mathematical methods.
- Relate examples to current research in atomic physics.
- Evaluate the applicability and limitations of physical models relevant to atomic physics.

Modalités d'évaluation

Evaluation : isolée
Final exam

CONDENSED MATTER I – ELECTRONS

UE : CONDENSED MATTER I – ELECTRONS

BCC3 : RÉSOUDRE DES PROBLÈMES COMPLEXES EN MOBILISANT LES CONCEPTS DE LA PHYSIQUE FONDAMENTALE

Enseignement Ob
Modalité d'enseignement : présentiel
Langue de l'enseignement : anglais

Responsable de l'enseignement : *Gaëtan Lévêque* – `gaetan.leveque@univ-lille.fr`
Autre enseignants potentiels : Laurent, Gaëtan, Alexandre Feller, Yan, Matthieu Touzin, Philippe

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		24				24

UE(s) prérequise(s) :

Lectures conseillées :

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Syllabus :

Basics on electronic properties in solid state physics, covering equilibrium and transport properties of crystalline solids, from the Sommerfeld model to semi-conductors.

Prerequisites
Basics on crystallography and Bravais lattices, quantum mechanics and statistical physics at bachelor level.

Objectives
Students will learn how to connect microscopic properties of electrons in solids from quantum mechanics and macroscopic properties (internal energy, heat capacity, electrical and thermal conductivity) from statistical physics. Starting from the simplest model of free electrons, we will expand it to crystalline solids to cover band theory, finally making the distinction between metals, insulators and semi-conductors.

Course outline

- Context, Born-Oppenheimer and single-electron approximation (3/4h)
- Sommerfeld model (density of states, Fermi sphere, chemical potential, internal energy, heat capacity) (3 1/4h)
- Band theory : nearly-free electrons, metal/insulators/semi-conductors, tight-binding model if time. (3,5h)
- Semi-conductors : electrons and holes description, intrinsic/extrinsic SC, homogeneous/heterogeneous SC, PN junction (3,5 h)

Skills acquired

Modalités d'évaluation
Evaluation : isolée Final exam

CONTINUUM MECHANICS

UE : CONTINUUM MECHANICS

BCC3 : RÉSOUDRE DES PROBLÈMES COMPLEXES EN MOBILISANT LES CONCEPTS DE LA PHYSIQUE FONDAMENTALE

Enseignement Ob
Modalité d'enseignement : présentiel
Langue de l'enseignement : anglais

Responsable de l'enseignement : *Philippe Carrez* – philippe.carrez@univ-lille.fr
Autres enseignants potentiels : Philippe, Sebastien, Frederic, Valerie, Franck, Mathieu, Patrick

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		24				24

UE(s) prérequise(s) :

Lectures conseillées :

-

Syllabus :

Continuum mechanics is a fundamental theory of many fields of science and engineering. This course will give an introduction to the principles of stress, strain, anisotropic and isotropic elasticity with applications covering a broad area relating to the mechanical behavior of materials.

Requires

- Basis of linear algebra and crystallography

Objectives :

- acquire the basic concepts of continuum mechanics
- Define and manipulate stress and strain tensor, apply tensor transformation
- Analytically solve simple problems of elasticity

Course outline

- Stress and strain as a second-rank tensor
- Fondamental equations of elasticity, Hooke's law
- Navier equations
- Review of mascroscopic plastic behavior of matter
- Principles stresses and yield criterion

Skills aquired

- Students will be able to manipulate fundamental equations of elasticity theory and acquire

knowledge of several techniques of resolution of different problems at different length scales.

Modalités d'évaluation
Evaluation : isolée *CC, CT, rapport, soutenance orale,... + pondérations*

FACULTÉ DES SCIENCES ET TECHNOLOGIES
Université de Lille

MASTER mention PHYSIQUE FONDAMENTALE ET APPLIQUÉE parcours
QUANTUM AND PHOTONIC TECHNOLOGIES

S1

AI AND ADVANCED COMPUTATIONAL METHODS IN PHYSICS

UE : AI AND ADVANCED COMPUTATIONAL METHODS IN PHYSICS

BCC1 : METTRE EN ŒUVRE DES OUTILS ET DES DÉMARCHES DE PHYSIQUE FONDAMENTALE POUR PRODUIRE DES SAVOIRS HAUTEMENT SPÉCIALISÉS

Enseignement Ob
Modalité d'enseignement : présentiel
Langue de l'enseignement : anglais

Responsable de l'enseignement : *Quentin Coopman* – quentin.coopman@univ-lille.fr
Enseignants potentiels : Quentin Coopman, Jérôme Riedi

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		10		15		25

UE(s) prérequise(s) :

Lectures conseillées :

-

Syllabus :

Explore the intersection of AI, Machine Learning, and Physics in this class. Gain hands-on experience with cutting-edge techniques and applications tailored for the world of physics.

Objectives :
This class introduces AI and Machine Learning, focusing on their applications in physics. It covers fundamental concepts like supervised and unsupervised learning, regression, and classification, as well as advanced topics such as neural networks and deep learning. Students will explore classification techniques, clustering algorithms, and data preprocessing methods tailored for physics data. The course also delves into dimensionality reduction and advanced subjects like physics-informed machine learning. By the end, students will be equipped to apply AI and ML techniques effectively in the field of physics.

Course outline
- Courses (10H):
  - I - Introduction to Artificial Intelligence and Machine Learning (1H)
    - Overview of AI and ML
    - Applications in physics
    - Key concepts and terminology
  - II - Fundamentals of Machine Learning (1H)
    - Supervised vs. unsupervised learning
    - Regression, classification, prediction
    - Evaluation metrics

  - III - Classification/Clustering algorithms (1H30)
    - Linear Models and Regularization (Linear regression)
    - Decision Trees and Ensemble Methods (Decision trees, Random, Gradient boosting regression tree forests)
    - K-means
  - IV - Dimensionality reduction (e.g., Principal Component Analysis) (45 mins)
  - V - Neural Networks and Deep Learning (2H15)
    - Introduction to neural networks
    - Activation functions
    - Training neural networks
    - Encodeur/Decodeur
  - VI - Data Preprocessing (1H)
    - Handling physics data
    - Feature selection and extraction
    - Data normalization and scaling
    - Datacentric methods
  - VII - Introduction Advanced Topics in Machine Learning for Physics (2H)
    - Physics-informed machine learning
    - Interpretable AI models
- Practicals (15H):
  - The practical sessions (TDs/TPs) will be conducted with the assistance of the CRI and the MesoNET program to access the notebooks. The practical sessions will cover the themes discussed in the lecture courses, namely:
    - Linear models (3H)
    - K-means (2H)
    - Principal Component Analysis (2H)
    - Neural Networks (3H)
    - Deep Learning (3H)
    - Data Preprocessing (2H)

Skills acquired

- Grasp the fundamental principles of artificial intelligence and machine learning.
- Learn key terminology and concepts used in AI and ML.
- Apply AI and ML techniques to solve problems in the field of physics.
- Differentiate between and apply supervised and unsupervised learning techniques.
- Implement regression, classification, and prediction models.
- Use popular ML libraries and tools such as TensorFlow, PyTorch, and scikit-learn.
- Implement AI and ML techniques in practical, hands-on projects and case studies.
- Use advanced digital tools autonomously for one or more professions or research sectors in the field.
- Conduct a reflective and distanced analysis, considering the issues, challenges, and complexity of a request or situation, to propose appropriate and/or innovative solutions in compliance with regulatory developments.
- Develop predictive tools based on validated models describing complex physical problems.
- Program digital tools to process physical measurements in a relevant manner (potentially using machine learning and AI approaches).

Modalités d'évaluation

Evaluation : isolée

Continuous assessment and project

The course evaluation will consist of two main parts:

- *Multiple Choice Quiz at the beginning of some lectures (30%)*
- *Project leading to a written report of analysis and interpretation of a dataset (70%)*

TUTORED TRAININGS

UE : TUTORED TRAININGS

BCC2 : PRODUIRE ET COMMUNIQUER DES SAVOIRS HAUTEMENT SPÉCIALISÉS, Y COMPRIS DANS UN CONTEXTE PROFESSIONNEL

Enseignement Ob
Modalité d’enseignement : présentiel
Langue de l’enseignement : anglais

Responsable de l’enseignement : *Sébastien Merkel* – `sebastien.merkel@univ-lille.fr`

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		4.5	6			10.5

UE(s) prérequise(s) :

Lectures conseillées :

-

Syllabus :

Discovery of new topics in physics based on the scientific literature and develop your teaching and presentation skills in front of your peers.

Objectives
Promote scientific openness among Physics Masters students. Complement their training in subjects not covered in traditional courses. Develop students' ability to work independently using information from the literature. Develop professional skills (oral presentation, scientific writing, and poster presentation

Course outline
Students choose 1 work topic in pairs. Topics are proposed by department staff, based on scientific articles, books, etc and can cover any field of physics.
The teaching consists in 6 in-person session guided by a main instructor, assistance from tutors, and significant personal work from the students based on information found in the University library and the scientific literature.
In person activities:

- Class 1 (1h30 CTD) Introduction, choice of subject, expectations
- Class 2 (1h30 TD, 3 groups QPT, PMM, BIOPHAM): Mid-course presentation, 10 minutes per pair, plan
- Class 3 (1h30 TD, 3 groups) Presentation analysis session (based on students reports on the presentations of others, and on their own)
- Class 4 (1h30 CTD) Latex and overleaf
- Class 5 (1h30 CTD) Report preparation
- Class 6 (1h30 TD, 3 groups) Final oral

Tutor activities

- propose a lead for topic (title, keywords, and references)
- 3 individual meetings with the student pair they supervise
  - First contacts, first publications
  - Assessment of students' individual research and understanding of the topic

- Detailed plan of report
- Proofreading and evaluation of reports
- Participation in evaluation of oral defenses

Acquired skills
Develop advanced and critical expertise at the edge of knowledge in a sub-field of physics based on documents from the recent scientific literature
Identify, select, and critically analyze specialized resources to document a topic and make a synthesis and exploit their content
Present advanced scientific content in front of your peers

Modalités d'évaluation

Evaluation : isolée
Report (1/3)
Oral defense (1/3)
Response to questions (1/3)

2 First year - Semester 2

Semester 2	ECTS
Condensed matter II - Phonons	3
Light-matter interaction	3
Out of equilibrium stat. physics	3
Non-linear dynamics	3
Classical and quantum coherences	3
Large instruments	3
Projects (Open lab)	3
Tutored training	3
Internship	6

MASTER mention PHYSIQUE FONDAMENTALE ET APPLIQUÉE parcours QUANTUM AND PHOTONIC TECHNOLOGIES

S2

LIGHT-MATTER INTERACTION

UE : LIGHT-MATTER INTERACTION

BCC2 : RÉSOUDRE DES PROBLÈMES COMPLEXES EN QUANTIQUE ET PHOTONIQUE

Enseignement ob
Modalité d'enseignement : présentiel
Langue de l'enseignement : anglais
Responsable : Giuseppe Patera
Enseignants potentiels : A. Rançon, G. Patera, A. Feller, C. Hainaut, R. Chicireanu

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		24				24

UE(s) prérequise(s) :

Lectures conseillées :

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Syllabus :

This course focuses on the quantization of light and its interaction with matter, specifically an atom modeled as a two-level system. It provides an in-depth understanding of the quantum dynamics involved in light absorption, emission, and coherent processes.

Objectives:

Students will learn the principles of light quantization and how light interacts with an atom modeled as a two-level system. They will gain skills in analyzing photon-atom interactions, including processes like absorption, stimulated emission, and Rabi oscillations. The course also covers the role of these interactions in phenomena such as quantum coherence and the development of quantum technologies.

Prerequisite :

Bachelor quantum physics + advanced quantum physics

Program:

- Quantization of Light (2h)
- Interaction Between a Two-Level Atom and a Single Photon Field (6h)
- Two-Level Atom Model (6h): dressed atom, Bloch Sphere, Rabi Frequency, state manipulation (basic quantum gates)
- Coherent Processes (6h): Absorption, Emission, and Rabi Oscillations, spontaneous émission (TD based on S1 course Advanced quantum physics)
- Maxwell Bloch optics equation (4h)

Acquired skills :

Direct skills include the ability to model and analyze light-atom interactions, solve problems related to Rabi oscillations and spontaneous emission, and understand quantum coherence in atomic systems. Indirectly, students will develop critical thinking and problem-solving abilities, applicable to quantum optics and emerging technologies such as quantum computing and laser development.

Modalités d'évaluation

Evaluation : isolée
CC, CT, rapport, soutenance orale,... + pondérations

MASTER mention **PHYSIQUE FONDAMENTALE ET APPLIQUÉE** parcours

QUANTUM AND PHOTONIC TECHNOLOGIES

S2

CONDENSED MATTER II - PHONONS

UE : CONDENSED MATTER II - PHONONS

BCC1 : MODÉLISER ET CARACTÉRISER LA MATIÈRE À L'ÉCHELLE ATOMIQUE, MOLÉCULAIRE ET DU MATÉRIAU

Enseignement **Ob**

Modalité d'enseignement : **présentiel**
Langue de l'enseignement : anglais

Person in charge: Yan Pennec – yan.pennec@univ-lille.fr
List of potential teachers: Yan, Frederic, Gaetan, Laurent

volume horaire	**CM**	**C-TD**	**TD**	**TP**	**A distance**	**Total**
Heures d'enseignement encadrées		**24**				**24**

UE(s) prérequise(s) :

Lectures conseillées :

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Syllabus :

This lecture explores the vibrational properties of crystalline solids, from lattice symmetries and phonon dispersion to thermodynamic behavior. It provides the fundamental tools to understand heat capacity, thermal transport, and the quantum nature of lattice vibrations in condensed matter systems.

Prerequisites

Condensed Matter I (S1), Statistical Physics (L3), Crystallography. Bravais Lattices / Reciprocal Lattices / Brillouin Zone / Sum Rule, Fourier Analysis

Objectives

This course provides a rigorous introduction to the vibrational properties of crystalline solids. It develops the theoretical framework for lattice dynamics using classical and quantum models. It explains phonon dispersion, density of states, and their influence on thermodynamic properties. It analyzes how phonons govern specific heat, thermal conductivity, and electron interactions. It lays the foundation for understanding thermal and vibrational phenomena in condensed matter physics.

Course outline

- Chapter 2: Dynamics of the Crystal Lattice : Introduction / Harmonic Approximation / Vibrations of a One-Dimensional Atomic Lattice / Extension to Two andThree Dimensions / Quantification of Vibrations: Phonons / Conclusion

- Chapter 3: Crystal Lattice Dynamics II Introduction / Density of States / Thermodynamic Properties / Einstein Model of Specific Heat / Debye Model of Specific Heat / Phonon Scattering and Thermal Conductivity
- Chapter 4 : Phonon Transport / Anharmonic Effects / Thermal dilatation (Grüneisen coefficient).

Acquired skills
At the end of the course, students are able to acquire and analyze phonon dispersion relations derived from lattice
dynamics in one, two, and three dimensions. They can interpret how phonons influence the thermal and electronic
properties of solids, including specific heat and thermal conductivity. They understand and apply the Debye and
Einstein models to explain the temperature dependence of specific heat, and can evaluate the role of electron-
phonon interactions in condensed matter systems. They are also proficient in using theoretical frameworks—such
as the harmonic approximation and the Brillouin zone formalism—to model and interpret the vibrational behavior
of crystalline solids

Modalités d'évaluation

Evaluation : isolée
CC, CT, rapport, soutenance orale,... + pondérations

OUT OF EQUILIBRIUM STATISTICAL PHYSICS

UE : OUT OF EQUILIBRIUM STATISTICAL PHYSICS

BCC4 : CONDUIRE ET COMMUNIQUER SUR DES PROJETS EXPÉRIMENTAUX, NUMÉRIQUES OU DE MODÉLISATION EN PHYSIQUE

Enseignement ob
Modalité d'enseignement : présentiel
Langue de l'enseignement : anglais
Responsable : François Anquez
Enseignants potentiels : F. Anquez and S. Randoux

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		24				24

UE(s) prérequise(s) :

Lectures conseillées :

-

- Syllabus :

Many natural and engineered systems operate away from thermal equilibrium. This course introduces the conceptual frameworks and tools needed to describe the time evolution of systems driven slightly out of equilibrium. Emphasis is placed on linear response theory, stochastic dynamics, and kinetic descriptions. Examples will be drawn from various areas of physics, including electrical conductors, reaction–diffusion systems, active and living matter, and optical systems.

Program :

1. Reminders
   - Probabilities
   - Results from Equilibrium Statistical Thermodynamics
2. Continuous Markov Processes :
   - Application to Brownian Motion and Johnson noise
3. Stochastic Processes and master equations
4. Kubo Linear Response Theory
5. Transport Coefficient

Modalités d'évaluation

Evaluation : isolée
CC, CT, rapport, soutenance orale,... + pondérations

MASTER mention PHYSIQUE FONDAMENTALE ET APPLIQUÉE parcours QUANTUM AND PHOTONIC TECHNOLOGIES

S2

NON-LINEAR PHYSICS

UE : NON-LINEAR PHYSICS

BCC4 : CONDUIRE ET COMMUNIQUER SUR DES PROJETS EXPÉRIMENTAUX, NUMÉRIQUES OU DE MODÉLISATION EN PHYSIQUE

Enseignement ob
Modalité d'enseignement : présentiel
Langue de l'enseignement : anglais
Responsable : Marc Lefranc et Serge Bielawski
Enseignants potentiels : Marc Lefranc, Serge Bielawski, Pierre Suret, Stéphane Randoux, Christophe Szwaj, François Copie, Saliya Coulibaly,

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		24		6		30

UE(s) prérequise(s) :

Lectures conseillées :

-

Syllabus :

Nonlinear dynamical systems can generate complex dynamical behaviors resulting from the collective interaction of their constituents, such as multi-stability, self-sustained oscillations or deterministic chaos. Their mathematical description is remarkably simple and universal.

Prerequisite :

Basic linear algebra, including eigenvalues and eigenvectors.

Objectives :

This course aims at introducing the basic concepts of nonlinear dynamics and showing how simple model systems recapitulate phenomena observed in a wide range of natural systems. Students will first learn to switch to a geometric description of the dynamics, using the notion of state space, and to discover how the asymptotic dynamics is associated with invariant sets in this state space.

The next step is to realize how qualitative changes of the dynamical behavior are associated with modifications of the stability or existence of these invariant sets. Through such changes, also known as bifurcations, complex behaviors such as self-sustained oscillations, quasi-periodic or chaotic behavior can emerge. These phenomena are universal and largely independent of the underlying physical system. The approaches highlighted are easily extended to study pattern formation in spatio-temporal systems.

There will a strong emphasis on the numerical exploration of complex behavior in nonlinear systems, with theoretical analyses being paralleled by the development of numerical simulations in Python.

Program :

- Geometric description of deterministic dynamical systems : phase space, orbit, flow, fixed points and other invariant sets.
- Linear stability analysis of fixed points.
- Generic bifurcations of fixed points in one-dimensional differential systems: behavior around a structurally unstable situation ; Saddle-node,transcritical and pitchfork bifurcations ; Example of a higher-order bifurcation, cusp catastrophe ; Extension to higher-dimensional systems.
- Self-sustained oscillations : appearance of limit cycles through a Hopf bifurcation ; Stability and bifurcations of periodic orbits
- Quasi-periodic and chaotic behavior : Dynamics on a torus ; Simple examples of chaotic attractors ; Stretching and folding mechanisms as generators of chaos ; Quantification of experimental chaotic attractors.
- Simple examples of pattern formation in spatio-temporal systems.
- Basic Python tools to carry out numerical simulations of nonlinear dynamical systems.

Acquired skills:

Most important skills include the ability to describe dynamical behavior in a state space, to analyse the stability of system, and to grasp which generic behaviors are universally observed in nonlinear systems. Then comes understanding that attractors in state space are probability distributions that can be characterized through concepts largely but not entirely coming from statistical physics. Students will become familiar with an important and defining property of chaotic dynamics, which is the constant instability of individual trajectories, contrasting with the simple rules determining how regions of state space are mapped to other regions of state space.

Students will become familiar with Python tools allowing them to carry out numerical simulations of nonlinear dynamical systems.

Modalités d'évaluation

Evaluation : isolée
CC, CT, rapport, soutenance orale,... + pondérations

MASTER mention PHYSIQUE FONDAMENTALE ET APPLIQUÉE parcours QUANTUM AND PHOTONIC TECHNOLOGIES

S2

CLASSICAL AND QUANTUM COHERENCES

UE : CLASSICAL AND QUANTUM COHERENCES

BCC2 : RÉSOUDRE DES PROBLÈMES COMPLEXES EN QUANTIQUE ET PHOTONIQUE

Enseignement ob
Modalité d'enseignement : présentiel
Langue de l'enseignement : anglais
Responsable : Pierre Suret & Alexandre Feller
Enseignants potentiels : Pierre Suret, Alexandre Feller, Giuseppe Patera, Adam Rançon, Radu Chicireanu ? Clement Hainaut ?

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		24				24

UE(s) prérequise(s) :

Lectures conseillées :

-

Syllabus :

Prerequisite: Linear systems, Light-matter interactions (field quantization)

Objectives:
This course covers classical and quantum coherence of light and matter. Students will study the statistical properties and measurement of coherence in optical fields and photons, as well as coherence in many-body systems (bosonic and fermionic gases, superfluidity, superconductivity). Concepts such as photons, interference, and quantum correlations will be explored through key experiments and examples in condensed matter.

Program :

1. Classical Coherence and Statistical Properties of Light

1.1 Motivation and Context

- What does it mean for a wave to be “coherent”?
- Temporal vs spatial coherence
- Coherence as a measure of predictability and interference potential

1.2 Random Processes and Optical Fields

- Stationary random process
- Autocorrelation functions

- Ensemble averages and ergodicity

1.3 The Wiener–Khinchin Theorem

- Power spectral density vs autocorrelation:
- Physical interpretation in optics / Measurement of coherence

2. Quantum coherences : light and photons

2.1. Photodetection
2.2. First and second quantum coherence of photons
2.3. Measuring coherences

HBT, HOM experiments

2.4 The notion of photon : why do we need it?

2. Quantum coherences : matter

3.1 Quantum coherences in many-body systems

- Bosonic and fermionic gases
- Coherence in superfluids, superconductivity

3.2 Quantum coherences in condensed matter (if we have time)

- Electronic coherences in mesoscopic system

Modalités d'évaluation

Evaluation : isolée
CC, CT, rapport, soutenance orale,... + pondérations

FACULTÉ DES SCIENCES ET TECHNOLOGIES
Université de Lille

MASTER mention PHYSIQUE FONDAMENTALE ET APPLIQUÉE parcours
QUANTUM AND PHOTONIC TECHNOLOGIES

S2

LARGE SCALE RESEARCH INFRASTRUCTURES

UE : LARGE SCALE RESEARCH INFRASTRUCTURES

BCC1 : METTRE EN ŒUVRE DES OUTILS ET DES DÉMARCHES DE PHYSIQUE FONDAMENTALE POUR PRODUIRE DES SAVOIRS HAUTEMENT SPÉCIALISÉS

Enseignement Ob
Modalité d'enseignement : présentiel
Langue de l'enseignement : anglais

Responsable de l'enseignement : *Manuel Goubet* – `manuel.goubet@univ-lille.fr`
Autres enseignants potentiels : Eleonore Roussel eleonore.roussel@univ-lille.fr, Jean-François Brun jfbrun@univ-lille.fr, Suzanne Crumeyrolle suzanne.crumeyrolle@univ-lille.fr, Andre Gomes andre.gomes@univ-lille.fr, Laurent Margulès laurent.margules@univ-lille.fr

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		20	4	3		27

UE(s) prérequise(s) :

Lectures conseillées :

Syllabus :

Objectives
This course aims to introduce students to the principles, functioning, and applications of major large scale research infrastructures (LSRI) used in both fundamental and applied research. It also seeks to develop cross-disciplinary skills such as literature review, critical analysis, and scientific communication.

Course outline
- General Introduction (2h)
  Importance of LSRI, historical perspective, functioning, and scientific challenges
- Examples of scientific advancements thanks to LSRI (4.5h)
  The Higg's boson
  Gravitational waves
  Event horizon of M87 black hole
- Case Study 1: Synchrotron Radiation (4.5h)
  Working principles and applications
  Introduction to coherent light sources (CLS)
- Case Study 2: Neutron Sources (2h)
  Working principles and applications
  Examples of performed researches
- Case Study 3: ACTRIS: Aerosol, Clouds and Trace Gases Research Infrastructure (3h)
  Working principles and applications
  Examples of performed researches
- Case Study 4: Millimeter/Submillimeter Astrophysics (3h)
  Principles and significance of radio telescopes

Overview of major observatories: ALMA, GBT and NOEMA
Role in detecting prebiotic species and understanding the origins of life

- Case Study 5: Large Intensive Computing Equipment (2h)
  Working principles, applications in physics, chemistry, and biology
  Overview of major French facilities: CINES, IDRIS and TGCC
  Examples of performed researches
- Visit of a research infrastructure (3h)
- Bibliographic review of a research article based on LSRI (4h)

Acquired skills

- Understanding the physical concepts underlying modern scientific instrumentation
- Knowledge of how large scale research infrastructures operate
- Ability to identify and analyze fundamental physical phenomena
- Ability to analyze and interpret scientific literature
- Clear and concise written and oral scientific communication

Modalités d'évaluation

Evaluation : isolée
40 % written exam
40 % oral presentation of bibliographic review
20 % written report of laboratory visit

TUTORED TRAININGS

UE : TUTORED TRAININGS

BCC2 : PRODUIRE ET COMMUNIQUER DES SAVOIRS HAUTEMENT SPÉCIALISÉS, Y COMPRIS DANS UN CONTEXTE PROFESSIONNEL

Enseignement Ob
Modalité d’enseignement : présentiel
Langue de l’enseignement : anglais

Responsable de l’enseignement : *Sébastien Merkel* – `sebastien.merkel@univ-lille.fr`

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées						

UE(s) prérequise(s) :

Lectures conseillées :

-

Syllabus :

Discovery of new topics in physics based on the scientific literature and develop your teaching and presentation skills in front of your peers.

Objectives
Promote scientific openness among Physics Masters students. Complement their training in subjects not covered in traditional courses. Develop students' ability to work independently using information from the literature. Develop professional skills (oral presentation, scientific writing, and poster presentation

Course outline
Students choose 1 work topic in pairs. Topics are proposed by department staff, based on scientific articles, books, etc and can cover any field of physics.
The teaching consists in 6 in-person session guided by a main instructor, assistance from tutors, and significant personal work from the students based on information found in the University library and the scientific literature.
In person activities:

- Class 1 (1h30 CTD) Introduction, choice of subject, expectations
- Class 2 (1h30 TD, 1 group): 3 minutes pitch on the topic of study
- Class 3 (1h30 TD, 1 group): Presentation analysis session (based on students reports on the presentations of others, and on their own)
- Class 4 (1h30 CTD) Report preparation
- Class 5 (1h30 CTD) Poster preparation
- Class 6 (3h00 TD) Poster session

Tutor activities

- propose a lead for topic (title, keywords, and references)
- 3 individual meetings with the student pair they supervise

  - First contacts, first publications
  - Assessment of students' individual research and understanding of the topic
  - Detailed plan of report
- Proofreading and evaluation of reports
- Participation in the poster session

Acquired skills
Develop advanced and critical expertise at the edge of knowledge in a sub-field of physics based on documents from the recent scientific literature
Identify, select, and critically analyze specialized resources to document a topic and make a synthesis and exploit their content
Present advanced scientific content in front of your peers

Modalités d'évaluation

Evaluation : isolée
Report (1/3)
Poster (1/3)
Response to questions (1/3)

EXPERIMENTAL PROJECT

UE : EXPERIMENTAL PROJECT

BCC1 : METTRE EN ŒUVRE DES OUTILS ET DES DÉMARCHES DE PHYSIQUE FONDAMENTALE POUR PRODUIRE DES SAVOIRS HAUTEMENT SPÉCIALISÉS

Enseignement Ob
Modalité d'enseignement : présentiel
Langue de l'enseignement : anglais

Responsable de l'enseignement : *Manuel Goubet* – `manuel.goubet@univ-lille.fr`
Autres enseignants potentiels : Suzanne Crumeyrolle suzanne.crumeyrolle@univ-lille.fr, François Anquez francois.anquez@univ-lille.fr, Clément Evain clement.evain@univ-lille.fr

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées				24		24

UE(s) prérequise(s) :

Lectures conseillées :

-

Syllabus :

Objectives
This course aims to develop students' autonomy, scientific rigor, and technical skills through the realization of an experimental project in pairs. It involves applying theoretical knowledge acquired so far to solve a real-world problem.

Course outline
- Design and implementation of an experimental setup or technical study
- Development of measurement protocols
- Use of specialized software
- Use of instruments related to the project
- Critical analysis of results
- Writing of a scientific report and oral presentation of the work

Acquired skills
- Project management in a team setting
- Development of an experimental scientific approach
- Proficiency in digital and instrumental tools
- Critical analysis of experimental data
- Autonomy and initiative
- Bibliographic research and data synthesis
- Professional communication (written and oral)
- Teamwork and collaboration

Modalités d'évaluation
Evaluation : isolée 33% CC (logbook, implication) 33% written report 33% oral presentation

INTERNSHIP

UE : INTERNSHIP

BCC3 : MODÉLISER ET CARACTÉRISER DES SYSTÈMES PHYSIQUES NON LINÉAIRES ET HORS ÉQUILIBRE

Enseignement Ob
Modalité d'enseignement : présentiel
Langue de l'enseignement : anglais
responsable :

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées						

UE(s) prérequise(s) :

Lectures conseillées :

-

Syllabus :

- …

Modalités d'évaluation
Evaluation : isolée *CC, CT, rapport, soutenance orale,... + pondérations*

3 Second year - Semester 3

Semester 3		ECTS
Photonic technologies		6
Quantum and classical information		3
Quantum systems and simulations	aaaaaaaaaaaaaaaaaaaaaaaa	6
Quantum metrology and sensors	aaaaaaaaaaaaaaaaaaaaaaaa	3
Quantum computation	aaaaaaaaaaaaaaaaaaaaaaaa	3
Experimental and numerical tools ?		3
Hot topics?		3
English/Français		3
Semester 4		
Graduate program		3
Internship		27

PHOTONIC TECHNOLOGIES

UE : PHOTONIC TECHNOLOGIES

BCC2 : RÉSOUDRE DES PROBLÈMES COMPLEXES EN QUANTIQUE ET PHOTONIQUE

Enseignement ob
Modalité d’enseignement : présentiel
Langue de l’enseignement : anglais
Responsable de l’enseignement : Christophe Szwaj
Enseignants potentiels : Serge Bielawski, Géraud Bouwmans, Stéphane Randoux, Pierre Suret, Christophe Szwaj, Olivier Vanvincq

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		48				48

UE(s) prérequise(s) :

Lectures conseillées :

-

Syllabus :

Basic foundations in lasers, photonics and non linear optics

I Non-linear Optics

Chapter 1 – Anisotropic Optical Media

- Vectorial nature of light and Maxwell's equations in matter
- Dielectric tensor
- Birefringence, optical axes, index ellipsoid
- Group velocity and walk-off

Chapter 2 – Nonlinear Optics phenomena

- Nonlinear polarization (scalar approach)
- Second order phenomena (SHG, SFG, DFG, Pockels)
- non parametric phenomena (saturable losses, two photon absorption, nonlinear scatterings...)

Chapter 3 – Nonlinear Polarization and Optical Susceptibilities

- Introduction to nonlinear optics

- Electronic Polarization expansion
- Symmetry constraints (centrosymmetry, Kleinman,...)
- Time-domain vs frequency-domain response

Chapter 4 – Wave Equation and Nonlinear Interactions

- Wave equation in nonlinear media
- Second-order processes (exemaple of Second-harmonic generation)
- Phase matching and quasi-phase-matching
- Manley–Rowe relations
- Introduction to Gaussian beam interactions

II Light sources

- Rate equations
- Gaussian beams
- QSwitch
- Modelocked laser
- Generation of THz, VUV, X
- Classification of the sources (coherences, etc)

III Optical waveguides

- Conventional optical fibers (total internal reflexion)
- Intermodal, chromatic and polarization dispersion
- Coupled mode theories, applications to fiber couplers
- Fiber lasers: performance, architecture, challenges, etc.
- Main fiber components

Modalités d'évaluation

Evaluation : isolée
CC

QUANTUM AND CLASSICAL INFORMATION

UE : QUANTUM AND CLASSICAL INFORMATION

BCC2 : RÉSOUDRE DES PROBLÈMES COMPLEXES EN QUANTIQUE ET PHOTONIQUE

Enseignement ob
Modalité d'enseignement : présentiel
Langue de l'enseignement : anglais
Responsable de l'enseignement : Alexandre Feller
Enseignants potentiels : Alexandre Feller, Giuseppe Patera

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		24				24

UE(s) prérequise(s) :

Lectures conseillées :

-

Syllabus :

From Shannon to qubits: understand how information behaves in classical and quantum worlds. Explore entropy, measurement, no-cloning, and quantum communication.

Objectives :

This course provides a unified introduction to classical and quantum information theory. Students will learn how to quantify information, understand key theorems such as the no-cloning and Holevo bounds, and analyze basic protocols like teleportation and superdense coding. They will acquire the tools to reason about the capabilities and limitations of quantum information processing.

Course outline :

Classical Information (4h)

- Rappels proba classique
- Bits and probability
- Shannon entropy and mutual information
- Data compression, channel capacity

Quantum States and Measurements (2h)

- Density matrices (déjà vu), qubit representations
- Projective and POVM measurements, purification

No-go Theorems and Key Results (2-4h)

- No-cloning, no-broadcasting
- Holevo’s bound and accessible information

Foundational Protocols (2-4h)

- Quantum teleportation
- Superdense coding
- Entanglement swapping

Quantum Entropy and Information (10h avec les protocoles et def. Operationelle)

- Von Neumann entropy
- Quantum mutual information
- Relative entropy, fidelity

Acquired skills :

Understand classical vs quantum information representations

- Calculate entropy, mutual information, and related quantities
- Identify and explain key theorems of quantum information
- Analyze simple quantum communication protocols
- Appreciate the impact of decoherence on information transmission

Modalités d'évaluation

Evaluation : isolée
CC, CT, rapport, soutenance orale,... + pondérations

QUANTUM SYSTEMS AND SIMULATION

UE : SPECIALITY I (PICK 1 IN 2)

BCC2 : RÉSOUDRE DES PROBLÈMES COMPLEXES EN QUANTIQUE ET PHOTONIQUE

Enseignement choix
Modalité d'enseignement : présentiel
Langue de l'enseignement : anglais
Responsable : Adam Rançon
Enseignants potentiels : Alexandre Feller, Adam Rançon, Clément Hainaut, Radu Chicireanu, Giuseppe Patera, Alberto Amo

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		48				48

UE(s) prérequise(s) : Advanced Quantum Theory, Light-Matter interaction

Lectures conseillées :

- S.Haroche and J-M. Raimond, *Exploring the Quantum*, Oxford University Press
- Condensed Matter Field Theory, A. Altland and B. Simons, Cambridge Université Press

Syllabus :

Learn how to simulate complex quantum systems using classical and quantum methods. From magnetism and superfluidity, this course explores the power of quantum simulations to solve real-world problems.

Objectives :

This course introduces students to classical and quantum simulation techniques for many-body quantum systems. They will learn how to model systems such as Bose and Fermi gases in optical lattices, simulate their dynamics, and understand quantum phase transitions. Applications to condensed matter and quantum chemistry will be discussed, including electronic structure calculations using quantum algorithms. Students will develop practical skills in implementing and interpreting simulations, and critically assessing their scope and limitations.

Program :

- **Open quantum systems (14h)**
  Decoherence, Lindblad master equation, quantum trajectories; Fokker-Planck; stochastic Langevin; quantum Langevin;
  Examples: spin, Jaynes-Cummings, cavity QED (Haroche), optical cavities, polaritons;
- **Many-body quantum systems (20h)**
  Superfluidity, superconductivity, Bogoliubov, Quantum phase transitions;
  Examples: ultracold atoms, Bose-Hubbard model, Heisenberg spin systems;
- **Condensed Matter: topological aspects (6h)**
  Quantum Hall effect, Berry Phase, Topological invariant, topological insulators

- **Quantum simulations (8h)**
  Platforms and methods of simulation

Acquired skills :

By the end of the course, students will be able to:

- Model complex many-body quantum systems
- Apply and program numerical methods to simulate quantum dynamics
- Understand and utilize analog and digital quantum simulators
- Analyze results from numerical and experimental quantum simulations
- Apply these skills to research problems in quantum physics and quantum technologies

Modalités d'évaluation

Evaluation : *seminar and scientific article analysis*

QUANTUM METROLOGY AND SENSORS

UE : SPECIALITY II (PICK 2 IN 4)

BCC2 : RÉSOUDRE DES PROBLÈMES COMPLEXES EN QUANTIQUE ET PHOTONIQUE

Enseignement choix
Modalité d’enseignement : présentiel
Langue de l’enseignement : anglais
Responsable : Clément Hainaut
Enseignants potentiels : Radu Chicireanu, Clément Hainaut, Giuseppe Patera, Xin Zhou

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		24				24

UE(s) prérequise(s) :

Lectures conseillées :

-

Syllabus :

Learn how quantum technologies are revolutionizing sensing and precision measurements. From ultra-stable clocks to gravitational wave detectors and quantum imaging—discover the future of measurement science.

Objectives :

This course introduces the fundamental concepts and technologies of quantum metrology and sensing. Students will develop a strong understanding of quantum-enhanced measurement strategies and learn to evaluate the performance of quantum sensors in practical settings. Topics include estimation theory, quantum noise, squeezing, entanglement, quantum imaging, optomechanics, and their role in real-world applications such as atomic clocks and gravitational-wave interferometry.

Program :

- Foundations of Quantum Metrology: (4h)
    - Estimation theory, Cramér-Rao bounds
    - Classical vs quantum Fisher information
- Strategies for Enhanced Precision: (4h)
    - Squeezed and entangled states (GHZ, NOON)
    - Heisenberg limit and scaling laws
- Interferometry and Practical Applications: (8h)
    - Mach-Zehnder, Ramsey, and SU(1,1) interferometers

    - Atomic clocks and frequency standards
    - Optical cavities and resonators
    - Quantum-enhanced inertial sensors
- Optomechanics and Gravitational-Wave Interferometry: (8h)
    - Fundamentals of cavity optomechanics
    - Quantum noise in mechanical systems
    - Role of squeezing and back-action evasion
- LIGO/Virgo-type interferometers and quantum enhancement

Acquired skills :

At the end of the course, students will be able to analyze and design quantum-enhanced measurement protocols, compare classical and quantum strategies, and understand key technologies like optical cavities, interferometers, and quantum imaging systems. They will also gain insight into real-world applications including optomechanical sensors and gravitational-wave detectors.

Modalités d'évaluation

Evaluation : isolée
CC, CT, rapport, soutenance orale,... + pondérations

QUANTUM COMPUTATION

UE : SPECIALITY II (PICK 2 IN 4)

BCC2 : RÉSOUDRE DES PROBLÈMES COMPLEXES EN QUANTIQUE ET PHOTONIQUE

Enseignement choix
Modalité d’enseignement : présentiel
Langue de l’enseignement : anglais
Responsable : Giuseppe Patera
Enseignants potentiels : Alexandre Feller, Adam Rançon, Giuseppe Patera, Stephan de Bièvre

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		24				24

UE(s) prérequise(s) :

Lectures conseillées :

-

Syllabus :

Understand how quantum mechanics can revolutionize computing. Learn how qubits, entanglement, and superposition unlock new paradigms through powerful algorithms and scalable architectures.

Objectives :

This course introduces the foundations and challenges of quantum computation. Students will learn how to build and analyze quantum circuits, understand the power of quantum algorithms, and explore quantum error correction and fault tolerance. Emphasis will be placed on both the theoretical underpinnings and experimental realizations of quantum computers.

Program :

Foundations of Quantum Computing:

- Qubits, quantum gates, and measurement
- Quantum circuits: X, H, T, CNOT, Toffoli
- Complexity classes: P, NP, BQP

- Key Quantum Algorithms:
    - Deutsch–Jozsa algorithm
    - Grover’s search algorithm
    - Quantum Fourier transform: Phase estimation, order-finding
    - Shor’s algorithm for factoring

- Quantum Error Correction:
    - Bit-flip and phase-flip repetition codes
    - Shor code and stabilizer formalism
    - Basics of surface codes and fault-tolerant architectures
- Hardware and Enabling Technologies (overview):
    - Physical implementations: superconducting qubits, trapped ions, topological qubits
    - Control, readout, and scalability challenges
    - Quantum compilation and gate decomposition

Acquired skills :

At the end of the course, students will be able to analyze and construct quantum circuits, identify and evaluate the use of major quantum algorithms, and understand the basic principles of quantum error correction. They will gain a broad perspective on the state of current quantum computing hardware and enabling technologies.

Modalités d'évaluation

Evaluation : isolée
CC, CT, rapport, soutenance orale,... + pondérations
CT

COMPLEXITY IN PHOTONICS

UE : SPECIALITY I (PICK 1 IN 2)

BCC2 : RÉSOUDRE DES PROBLÈMES COMPLEXES EN QUANTIQUE ET PHOTONIQUE

Enseignement choix
Modalité d'enseignement : présentiel
Langue de l'enseignement : anglais
Responsable :
Enseignants : Serge Bielawski, Marc Lefranc, Stéphane Randoux, Pierre Suret

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		48				48

UE(s) prérequise(s) :

Lectures conseillées :

-

Syllabus :

I Non-linear dynamics (20 hours)

II Topology (10 hours)

III Nonlinear telecom and solitons (12 hours)

III.1 Integrable systems

- Universal integrable partial differential equations (KdV, 1DNLS…)
- Constant of motions
- Solitons

III.2 Introduction to the Inverse Scattering Transform (IST)

- Nonlinear spectral decomposition
- Lax pair and integrability of NLSE
- Sketch of IST procedure (Direct scattering problem, Evolution of scattering data, Inverse problem)

III.3 Applications in Telecommunications

- Soliton-based communication systems

- Coding signal by using nonlinear spectrum

IV Frequency combs (6hours)

Modalités d'évaluation
Evaluation : isolée *CC, CT, rapport, soutenance orale,... + pondérations*

ULTRAFAST MEASUREMENT, MICROSCOPY

UE : SPECIALITY II (PICK 2 IN 4)

BCC2 : RÉSOUDRE DES PROBLÈMES COMPLEXES EN QUANTIQUE ET PHOTONIQUE

Enseignement choix
Modalité d'enseignement : présentiel
Langue de l'enseignement : anglais
Responsable : Serge Bielawski
Enseignants potentiels : François Anquez, Serge Bielawski, Pierre Suret

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		24				24

UE(s) prérequise(s) :

Lectures conseillées :

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Syllabus :
Advanced characterization and recording methods in the time and space domains Outline 1 Ultrafast Measurement 1.1 Measurement methods for ultrafast laser pulses, including autocorrelation, FROG, SPIDER, terahertz. 1.2 Advanced single-shot and real-time time measurements techniques for recording ultrafast phenomena, including temporal imaging (time lenses) and photonic time-stretch 2 Microscopy 2.1 Fundamentals of Imaging and the Diffraction Limit 2.2 The Modern Microscope and contrast methods 2.3 Advanced Microscopy Methods 2.4 Super-Resolution Microscopy: Beyond the Diffraction Limit 2.5 Optical coherence tomography (OCT)

Modalités d'évaluation
Evaluation : isolée

CC, CT, rapport, soutenance orale,... + pondérations

MASTER mention PHYSIQUE FONDAMENTALE ET APPLIQUÉE parcours
QUANTUM AND PHOTONIC TECHNOLOGIES

S3

ADVANCED PHOTONICS

UE : SPECIALITY II (PICK 2 IN 4)

BCC2 : RÉSOUDRE DES PROBLÈMES COMPLEXES EN QUANTIQUE ET PHOTONIQUE

Enseignement choix
Modalité d’enseignement : présentiel
Langue de l’enseignement : anglais
Responsable : Olivier Vanvincq
Enseignants potententiels : Olivier Vanvincq, Géraud Bouwmans, Yan Pennec

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		24				24

UE(s) prérequise(s) :

Lectures conseillées :

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Syllabus :
• Les différents mécanismes de guidage et leurs propriétés des fibres microstructurées : MTIR, PBG et IC • Les effets non-linéaire dans les fibres optiques : de l’instabilité de modulation à la génération de supercontinnum • Les différentes sources d’atténuation y compris par courbure et fuite • Introduction à la nanophotonique, aux métasurfaces / métamatériaux et à la topologie photonique

Modalités d'évaluation
Evaluation : isolée CC

HOT TOPICS

UE : HOT TOPICS

BCC3 : MODÉLISER ET CARACTÉRISER DES SYSTÈMES PHYSIQUES NON LINÉAIRES ET HORS ÉQUILIBRE

Enseignement ob
Modalité d'enseignement : présentiel
Langue de l'enseignement : anglais
Responsable : François Anquez

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		24				24

UE(s) prérequise(s) :

Lectures conseillées :

Syllabus :

The aim of this module is to introduce students to cutting-edge topics in the field of Quantum and Photonic Technologies. Each student will be mentored by a research expert and will explore the current knowledge based on literature review. Students will also be encouraged to carry out their own experimental investigations, and/or theoretical analyses, and/or numerical simulations.

Objectives:

- Specific topic in quantum physics and/or photonic technologies
- Literature screening
- develop your teaching and presentation skills in front of your peers.

Program:

Students choose 1 work topic in pairs. Topics are proposed by department staff, based on scientific articles, books, etc and can cover any field of physics.

The teaching consists in 6 in-person session guided by a main instructor, assistance from tutors, and significant personal work from the students based on information found in the University library and the scientific literature.

Acquired skills:

Compétences transversales

- Développer une conscience critique des savoirs dans un domaine et/ou à l’interface de plusieurs domaines
- Identifier, sélectionner et analyser avec esprit critique diverses ressources spécialisées pour documenter un sujet et synthétiser ces données en vue de leur exploitation

Compétences spécifiques

- Valoriser et diffuser les résultats des études en sciences physiques (rapports techniques, scientifiques, fiches brevets) au sein de l’entreprise, auprès de la communauté scientifique
- Réaliser une veille scientifique et technique sur la base d’une recherche bibliographique relative aux sciences physiques en analysant des publications récentes en anglais
- Analyser des enjeux techniques environnementaux sociétaux et scientifiques de projets impliquant des phénomènes physiques et proposer des stratégies tenant compte de leurs potentiels d’application

Modalités d'évaluation

Evaluation : isolée
CC, CT, rapport, soutenance orale,... + pondérations

- Report (1/3)
- Oral defense (1/3)
- Response to questions (1/3)

4 Second year - Semester 4

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S4

EXPERIMENTAL AND NUMERICAL TOOLS/METHODS

UE : EXPERIMENTAL AND NUMERICAL TOOLS/METHODS

BCC5 : GÉRER SON PROJET PERSONNEL SCIENTIFIQUE ET/OU TECHNIQUE EN QUANTIQUE ET/OU PHOTONIQUE

Enseignement ob
Modalité d'enseignement : présentiel
Langue de l'enseignement : anglais
Responsable : François Anquez, Christophe Szwaj
Enseignants potentiels : P. Suret, S. Bielawski, C. Hainaut, X. Zhou , R. Chicireanu, F. Anquez, L Bigot

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées		10		20		30

UE(s) prérequise(s) :

Lectures conseillées :

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Syllabus :

Experimental tools :

Choice of several lab experiments among a large number : NV sensors, Signal processing/Noise (sampling, time-frequency analysis,...Qiskit, Modeling the noise, Detection of GW, Spectroscopy, Open lab, Clean room, femtosecond laser. Classical lasers (YAG, He-Ne, Erbium Amplifier). Polarisation, Modulation (acousto-optic & electro-optic).

Numerical tools :

Advanced Python, C++, MPI

Modalités d'évaluation

Evaluation : isolée
CC, CT, rapport, soutenance orale,... + pondérations

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QUANTUM AND PHOTONIC TECHNOLOGIES

S4

INTERNSHIP

UE : INTERNSHIP

BCC5 : GÉRER SON PROJET PERSONNEL SCIENTIFIQUE ET/OU TECHNIQUE EN QUANTIQUE ET/OU PHOTONIQUE

Enseignement ob
Modalité d'enseignement : présentiel
Langue de l'enseignement : Français
Responsable : Christophe Szwaj

volume horaire	CM	C-TD	TD	TP	A distance	Total
Heures d'enseignement encadrées						

UE(s) prérequise(s) :

Lectures conseillées :

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Syllabus :
Internship in research laboratory (minimum 4 months) or in a company

Modalités d'évaluation
Evaluation : isolée *CC, CT, rapport, soutenance orale,... + pondérations* report + oral defense