Course code:	**Light Matter interaction**	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	David Clément and Jean-Sébastien Lauret	
Volume: Period:	27 Hours	**3 ects**
Assessment:		
Language of tuition:	English	

Course Objectives: The interaction between light and matter holds a central place in experimental physics, to manipulate and to probe properties of light and/or matter. This ranges from the early spectroscopic studies of solids to the emergence of quantum technologies and the manipulation of individual quantum systems.

This course provides a comprehensive introduction to the interaction between light and matter, from a modern and transversal view. Starting from the structure of matter (atoms, solids) and classical models (Lorentz, Einstein), a semi-classical description of light-matter interaction is introduced. Both systems with discrete levels of energy (atoms, molecules, defect centers, quantum dots, ...) and with band structures (solids, excitons, …) are considered, and their similarities and differences are illustrated. The role of quantum coherences and of the dissipation are discussed, with descriptions based on rate equations and Optical Bloch equations. The course covers the manifestations of light-matter interaction in modern research and quantum technologies.
(Non-linear optics and ultrafast dynamics with short light pulses are treated in dedicated, separate courses).

Course prerequisites: Atomic Physics (M1); Solid State physics (M1); Quantum mechanics

Syllabus

Introduction
Atomic structure (H atom, atoms with several electrons); Electronic structure of solids (Bloch functions, band structure, electron-hole pairs)
Lorentz and Einstein models; illustration of coherent manipulation (Lorentz) and of rate equations (Einstein)
Semi-classical description of light-matter interaction; Rabi oscillations, coherent manipulation of discrete systems; out of resonance Rabi, passage to a continuum, Fermi golden rule, semi-classical dielectric constant in solids
Excitonic transitions / Dimensionality
Dissipation in discrete systems; Optical Bloch Equations; Coupling to a continuum and rate equations
Manipulation of three level systems; optical pumping, superpositions of coherent states and two photons transitions
Impulsion exchange between light and matter; optical trapping of particles et laser cooling force
Mollow triplet (examples in atomics physics, quantum dots); field confinement (Jaynes-Cummings); molecules/colored centers; illustrations with quantum technologies

On completion of the course students should be able to: The students will have acquired a broad knowledge of the light-matter interaction, both in dilute and condensed matter systems. Following this course, students can specialize by choosing appropriate elective courses focused on excitonic or atomic physics. This course opens the way to a PhD in the broad domain of light-matter interaction (cold atoms, solid state quantum optics, single molecule quantum optics, polariton physics, optical properties of new semiconductor materials etc.…)

Textbooks/bibliography:

- "Optical properties of solids" M. Fox
- "Fundamental of semiconductors" PY Yu & M. Cardona
- "Optical processes in Solids" Y. Toyozawa
- "Introduction to Quantum Optics: From the Semi-classical Approach to Quantized Light", G. Grynberg, A. Aspect, C. Fabre – Cambridge Univ. Press, 2010 (in particular the first chapters describe the semi-classical approach and the Optical Bloch Equations)
- "Optical Resonance and Two-Level Atoms", L. Allen, J. H. Eberly, Dover 1975.
- "The quantum theory of light", L. Loudon, 3rd Ed. Oxford Press, 1997.
- Online lectures of C. Cohen-Tannoudji at Collège de France on Laser cooling and manipulation of atoms - years 1981, 1982 and 1983.
- Online lectures of J. Dalibard at Collège de France on Laser cooling of atoms - year 2014/2015.

Course code:	**Introduction to 2^{nd} Quantization**	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	Nicolas Pavloff, Christoph Westbrook	
Volume: Period:	27 Hours	**3 ects**
Assessment:	Written exam	
Language of tuition:	English	

Course Objectives: We Introduce the formalism and first applications. Starting from the quantization of the electromagnetic field, we discuss the emergence of quantum states without classical counterparts and two-photon correlation effects. The formalism is then extended to the quantization of matter for both Bose and Fermi systems. Some widely used approximation methods are discussed as well as their applications to superfluidity and superconductivity. The notions of quasi-particles and collective modes are introduced and some universal aspects resulting from the mapping between Bose, Fermi, and spin systems are discussed. Students will be asked to read and analyse some landmark papers in the field.

Course prerequisites:
Elementary quantum mechanics
Statistical physics

Syllabus

1. **Quantization of electromagnetic field.** Quantum harmonic oscillator, Coulomb gauge. Fock states, Coherent states, Thermal states. Means and and variances of observables in these states
2. **Interaction with a bound electron in the dipole approximation.** Time dependent perturbation theory. Stimulated emission and absorption, spontaneous emission. Connection to Einstein's treatment of BLackbody radiation. Inhibition of Spontaneous emission, Porcell factors.
3. **Single photon detection.** Photo electric effect, for a classical and a quantum field. Action of a beam splitter in terms of the fields
4. **Two photon detection.** Anticorrelation at beam splitter, antibunching. Hong Ou Mandel effect
5. **Second quantization of massive particles.** Bosons and fermions, two-particle case, Fock states and annihilation / creation operators, field operator, correlators and Green's function, Wick's theorem.
6. **Bose fluids.** Bose-Einstein condensation, the effect of interactions, Bogoliubov approximation for bosons. Introduction to phonons.
7. **Fermi fluids and pairing.** Fermi gases. Paired state and BCS wave-function, gap equation
8. **Quantum magnetism.** Spin models, spin-wave theory, Jordan-Wigner transform, quantum phase transitions.

There will be 4 or 5 homework problems to be worked at home.

On completion of the course students should be able to: read some of the basic literature and advanced textbooks in the field.

Textbooks/bibliography:

"Introductory Quantum Optics", C.C. Gerry and P.L. Knight, Cambridge Univ. Press (2005)

"Introduction aux lasers et à l'Optique Quantique", G. Grynberg, A. Aspect, C. Fabre, Ellipses, English version (september 2010) significantly updated "Introduction to Quantum Optics: From the Semi-classical Approach to Quantized Light"

"Quantum Mechanics, Volume 3: Fermions, Bosons, Photons, Correlations, and Entanglement", Cohen-Tannoudji, B. Diu, F. Laloë, Wiley
"Many-body problems and quantum field theory", Ph.A. Martin, F. Rothen, Springer

"Many-body quantum theory in condensed matter physics", H. Bruus, K. Flensberg, Oxford Press

"An introduction to quantum spin systems", J.B. Parkinson, D.J.J. Farnell, Springer

Course code:	**Physics of Quantum Information: qubits, entanglement and decoherence**	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	Antoine Browaeys and Laurent Sanchez-Palencia	
Volume: Period:	27 Hours	**3 ects**
Assessment:	Final exam + 4-5 problem sets and/or quizzes during the course that will be graded	
Language of tuition:	English	

Course Objectives:

Qubits and our ability to control, manipulate, and measure them are the basic ingredients for the development of the emerging quantum technologies. Exploiting the most intriguing aspects of quantum physics, such as quantum superpositions and entanglement, they will allow us to perform tasks without classical counterparts such as the simulation of many-body systems or an unprecedented enhancement of the precision of sensors. The general framework to understand the potential of ensembles of quantum bits to perform such tasks lies at the crossroads of quantum physics and quantum information.

This course is an introduction to the physics of quantum information, from concepts to applications in quantum technologies, illustrated by the most recent experiments. These concepts are the common language of the four pillars of quantum technologies (communication, sensing, simulation, computation). Starting from the notion of qubit and its control using logical gates and quantum measurements, we show how to exploit it to perform elementary tasks. We then discuss the notion of entanglement and decoherence effects within an extended introduction to open quantum systems.

Course prerequisites:

A course in quantum physics at the level of, for example, the book “Mécanique Quantique”, J.L. Basdevant, J. Dalibard, and M. Joffre, Presse de l’Ecole Polytechnique. Available in English (Springer).

Although the course is independent from other ones, the concepts discussed in the lectures are related to the ones taught in the courses: “Quantum optics and second quantization” and “Light-matter interaction”.

Syllabus

- Notion of qubit, Bloch sphere, 1 and 2 qubit gates, non-cloning theorem.
- Implementations of qubits on physical systems.
- Quantum measurement theory, QND measurements, strong and weak measurements.
- Entanglement and density matrix. Application to teleportation.
- Von Neumann and Renyi entropies: Tomography, purity measurement.
- Introduction to open quantum systems within the Krauss/Lindblad formalism, quantum jumps.
- Physical content of the Lindblad equation: Relaxation towards equilibrium and driven systems, from Jaynes-Cummings to spontaneous emission, Wigner-Weisskopf approach.
- Stochastic wave functions.
- Decoherence and its control

We will use illustrate the concepts with the python environment QuTip (http://qutip.org).

On completion of the course students should be able to:

- Understand quantum physics from a modern perspective, using the language of quantum information.
- Have on overview of quantum information theory within the rapidly evolving field of quantum technologies.
- Read the more specialized literature related to recent experiments in the field.

Textbooks/bibliography: Notes provided by the lecturers.

Course code:	**Non-Equilibrium Statistical Physics and Phase Transitions**	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	David Clément Denis Grebenkov	
Volume: Period:	27 Hours	**3 ects**
Assessment:	Written examination	
Language of tuition:	English	

Course Objectives:

Introductory courses on statistical physics deal with non-interacting particles in equilibrium. The first part of this course deals with nonequilibrium. The second part deals with interacting particles. Several approaches to non-equilibrium statistical physics will be presented: linear response theory, Langevin model, Boltzmann equation and irreversible thermodynamics. The role of inter-particle interactions and resulting collective phenomena such as phase transitions will be discussed.

Course prerequisites:

Basic quantum mechanics, introduction to statistical physics

Syllabus

Linear response theory
Fluctuation-dissipation theorem
Brownian motion: Langevin model
Introduction to transport phenomena
Boltzmann equation
Introduction to irreversible thermodynamics
Inter-particles interactions, Ising model
Mean field approximation, critical behavior
Order parameter, symmetry breaking
Examples of phase transitions

On completion of the course students should be able to:

deal with nonequilibrium systems and systems of interacting particles. They should be able to extract information from correlations, master the key concepts of transport phenomena and phase transition.

Textbooks/bibliography:

R. Balian, From microphysics to Macrophysics Vol.1 Springe-Verlag, Berlin, 1982
R. Balian, From microphysics to Macrophysics Vol.2 Springe-Verlag, Berlin, 1991
R. Kubo, M. Toda, N. Hashitsume, Staistical Physics II, Springer Verlag, Berlin, 1985

Course code:	**Laser Physics**	Semester 1
Contributes to:	M2 QLMN – Track "Light and Matter"	

Course director: Course teachers :	Fabien Bretenaker (LAC) Marc Hanna (LCF), Frédéric Druon (LCF), Thierry Ruchon (CEA)	
Volume: Period:	30 Hours (exam included)	**3 ects**
Assessment:	Final exam / midterm exam	
Language of tuition:	English	

Course Objectives:
The course starts with a semi-classical description of light-matter interaction, and establishes Maxwell-Bloch equations. The rate equation approximation is used to provide operational principles of the single frequency laser. Starting from this description, transition broadening mechanisms, dynamical regimes, and noise properties of lasers are described. The spatial aspects are then examined, using paraxial transfer matrices to describe cavity stability and beam propagation. Finally, ultrafast lasers using mode-locking are studied along with related subjects such as the propagation and characterization of femtosecond pulses and attosecond pulse generation.

Course prerequisites: Undergraduate knowledge of electromagnetism and quantum mechanics. A first course in lasers helps, but is not required.

Syllabus

- Matter-light interaction; Equations of the single-frequency laser
- Single frequency laser in steady-state regime
- Inhomogeneous line broadening
- Transient and Q-switched operation
- Noise properties of lasers
- Mode-locking and ultrashort pulses
- Optical resonators: ray matrices, Gaussian beams, cavity stability
- Advanced topics in ultrafast optics : carrier-envelope phase and attosecond pule generation

On completion of the course students should be able to: understand and be able to describe the physical principles underlying laser operation in a wide variety of regimes.

Textbooks/bibliography: Lecture notes written by Fabien Bretenaker

Course code:	**Non-Linear Electromagnetism**	Semester 1
Contributes to:	M2 QLMN – Track "Light and Matter"	

Course director: Course teachers :	François Hache (LOB) Nicolas Fabre (TPT), Marie-Claire Schanne-Klein (LOB)	
Volume: Period:	27 Hours Semester 1	**3 ects**
Assessment:	Final exam + Homework midterm exam	
Language of tuition:	English	

Course Objectives:
Since the laser has been invented, optics opened a new dimension entering the nonlinear world with already numerous applications to light sources and optical processing of information. This course will introduce the students to this domain and enable them to fully master its innovative aspects. It describes the physics of the nonlinear interaction between light and matter from a perturbation approach and shows its consequences on the propagation of optical waves. Its describes in detail the second and third order non linear effects rich in applications.

Course prerequisites: Undergraduate knowledge of electromagnetism (linear regime, optical properties of anisotropic media…). A first course in nonlinear optics helps, but is not required.

Syllabus
I - INTRODUCTION TO NONLINEAR OPTICS
Basics of nonlinear optics
Physical origins of the optical nonlinearities

II - NONLINEAR WAVE EQUATIONS
Derivation of Maxwell's equations – Constitutive relations
Linear wave equation : pulse response and linear susceptibility – anisotropic medium – transfer of energy – group velocity
Nonlinear susceptibilities : nonlinear pulse response and susceptibilities – properties of the nonlinear susceptibilities tensors
Nonlinear wave equations

III - 2nd ORDER NONLINEARITIES
Manley-Rowe relations
2nd Harmonic Generation : weak conversion, phase matching, strong conversion : SHG with pump depletion, phase matching in uniaxial crystal.
Quasi-phase matching in materials
Frequency Mixing, Optical parametric amplification and oscillation
Spontaneous parametric down conversion
Sources of entangled photons based on SPDC

IV - MICROSCOPIC THEORY of the NONLINEAR OPTICAL RESPONSE
Notion of polarizability and local field factor
Liouville equation: perturbation approach with the density matrix formalism
Calculation of the linear susceptibility
Calculation of X(2)
Calculation of the third-order nonlinear response function for resonant configurations
Introduction to the 2D spectroscopy

V - 3rd ORDER NONLINEARITIES
Four-wave Mixing
Optical Kerr effect : n2(I), optical bistability, self-focusing effect, self-phase modulation and solitons
Raman Scattering : spontaneous and stimulated Raman scattering, Raman amplification, Raman Laser
2 photons Absorption

On completion of the course students should be able to: understand and be able to describe the physical principles underlying various nonlinear interactions.

Textbooks/bibliography:
F. Hache, Optique non linéaire, CNRS-EDPSciences, Savoirs actuels, 2016.
Lecture notes available at http://paristech.iota.u-psud.fr/site.php?id=84
Robert W. Boyd, Nonlinear Optics, 4th Edition, Elsevier Ed
Butcher, P N. / Cotter, D., The Elements of Nonlinear Optics , Cambridge University Press.1993.
F. Sanchez, Optique non linéaire, Ellipses, 1999.

Course code:	**Ultracold atoms and quantum simulators**	Semester 1
Contributes to:	M2 QLMN – Track "Light and Matter"	

Course directors:	Marc Cheneau and Igor Ferrier-Barbut	
Volume:	CM: 27 Hours	**3 ects**
Assessment:	Weekly exercises, written exam (~3 hours, with documents)	
Language of tuition:	English	

Course Objectives:

This set of lectures is an introduction to the modern many-body physics of ultracold atoms and to the notion of quantum simulators with neutral atoms.

The lectures will review the basic physics of non-interacting bosons and fermions, before diving in the description of interacting quantum many-body physics. The emergent collective phenomena of Bose-Einstein condensation and superfluidity will be described. We will study the different interactions that take place between cold atoms, that are needed to derive their many-body Hamiltonian. Then an example of a quantum phase transition and its observation in experiments will be presented through the superfluid-insulator transition in an optical lattice. Next, we will focus on examples of how quantum simulations of magnetism problems can be implemented experimentally. Finally, we will present numerical methods to predict the result of a quantum simulation experiment (in collaboration with the quantum simulation startup pasqal.io), and showcase the state-of-the art experimental methods in modern setups.

Course prerequisites:

- Introduction to second quantization
- Physics of quantum information
- Light-matter interaction

Syllabus:

- Statistical quantum physics: Bosons and fermions, Bose-Einstein condensation (BEC) of the ideal gas.
- Mean-field level description of a BEC: Phase coherence and excitations.
- BEC beyond the mean-field level: Bogoluybov transformation and quasi-particles.
- Superfluidity: Vortices, Landau criterion.
- Interactions in atomic systems: Effective contact interaction, long-range interactions.
- Simulation of a quantum phase transition: Bose Hubbard model, superfluid - Mott insulator transition
- Quantum magnetism in optical lattices: Spin exchange interaction, perturbation theory
- Numerical simulation of quantum many-body systems
- Step-by-step description of a quantum simulation experiment

On completion of the course students should be able to:

Read the more specialized literature related to recent experiments in the field.

Have a comprehensive understanding of the field of many-body physics with neutral atoms, and of the rapidly developing quantum simulation platforms.

Textbooks/bibliography:

L.P. Pitaevskii and S. Stringari, *Bose-Einstein Condensation and superfluidity* (Oxford Science Publication, 2016).

Course code:	**Manipulation de systèmes quantiques simples**	Semester 1
Contributes to:	M2 QLMN – Track "Light and Matter"	

Enseignants:	Rosa Tualle-Brouri (Institut d'Optique Graduate School) Nina H. Amini (L2S, CentraleSupelec)	
Volume horaire:	27h	**3 ects**
Modalités d'évaluation:	En plus de l'examen final (écrit), une petite partie du contrôle des connaissances porte sur des compte-rendus et des TDs.	
Langue:	English or French	

Objectifs du cours:

• 1ère partie : Rosa Tualle-Brouri : *Manipulation d'états quantiques de la lumière:*
Les objectifs sont d'étudier l'optique quantique et ses applications. Seront abordés : la nature du photon; l'amplitude et la phase au niveau quantique ; l'intrication ; la propagation du champ quantique dans les milieux matériels ; des notions d'information quantique ; ainsi que les techniques expérimentales associées.

• 2ème partie : Nina H. Amini : Stabilisation de systèmes quantiques ouverts par *feedback quantique*
Nous allons considérer des systèmes quantiques ouverts soumis à des mesures non-destructives. Nous présentons des méthodes de Lyapunov stochastiques afin de stabiliser des états quantiques pures qui sont des états propres des operateurs de mesures.

Pré-requis:
Des pré-requis de base en mécanique quantique sont nécessaires comme par exemple décrits dans le livre Mécanique quantique (Cohen-Tannoudji, Diu, Laloë).

Contenu du cours

I – Quantification du champ électromagnétique (Rosa Tualle-Brouri, 3 heures)
- Nature du photon – espace de Fock - Etats cohérents
- Action d'une séparatrice – coalescence de photons
- Quadratures - tomographie quantique - fonction de Wigner
- Problèmes multimodes – interférences à 1 photon

II – Propagation du champ quantique dans les milieux matériels (Rosa Tualle-Brouri ~ 7,5 heures)
- Etude de l'amplification paramétrique optique
- Génération de vide comprimé – paires EPR
- Génération conditionnelle d'états quantiques
- Applications à l'optique quantique: intrication, inégalités de Bell, téléportation, opérations fondamentales du calcul quantique, finalité du calcul quantique.
- Etude du problème multimode, modélisation en temps continu. Application au cas d'une source de photons uniques.

III - Système ouvert soumis à des mesures non-destructives (Nina H. Amini ~ 3 heures)
- Systèmes ouverts
- Mesures quantiques non-destructives
- Trajectoires quantiques
- Cavité QED: Exemple de système ouvert soumis à des mesures QND en temps-discret

IV – Stabilisation d'états « nombre de photon » pour une cavité QED (Nina H. Amini ~3 heures)
- Cavité QED soumise à des mesures non-destructives imparfaites
- Comportement asymptotique en boucle ouverte (sans contrôle)
- Feedback basé sur la mesure
- Stabilisation par des méthodes de Lyapunov

V – Stabilisation de systèmes de moments angulaires quantiques soumis à des mesures QND (Nina H. Amini ~3 heures)
- Systèmes quantiques ouverts en temps continu
- Mesure non-destructive Homodyne
- Exemple : Systèmes de moments angulaires quantiques soumis à des mesures QND en temps continu
- Comportement asymptotique sans contrôle
- Feedback basé sur la mesure
- Stabilisation par des méthodes Lyapunov stochastiques

Compétences attendues à la fin de l'UE:
A la fin du cours un étudiant doit pouvoir lire et expliquer les articles récents dans le domaine du contrôle quantique, particulièrement pour ce qui concerne les travaux en relation avec l'optique quantique.

Bibliographie:
Des notes de cours seront distribuées.
-J-M. Raimond and S. Haroche. Exploring the quantum : atoms, cavities, and photons. Oxford University Press, 82 :86, 2006.
-H. M. Wiseman and G. J. Milburn. Quantum measurement and control. Cambridge university press, 2009.

Course code:	**Quantum communication**	Semester 1
Contributes to:	M2 QLMN – Track "Light and Matter"	

Course directors: **Co-teachers :**	Nicolas Fabre (Télécom ParisTech, LTCI)	
Volume:	CM 14h - TD 7h	**3 ects**
Assessment:	Multiple Choice Questions test, oral presentation of a research paper	
Language of tuition:	English	

Course Objectives:
In this course, we will explore quantum communications protocols, focusing primarily on quantum key distribution (QKD) protocols. Quantum communication harnesses the principles of quantum mechanics to provide secure and efficient ways of transmitting information.

Course prerequisites:
Basics electromagnetism, quantum physics, quantum optics (field quantization)

Syllabus

The plan of the course will be divided as follows:
- Introduction in quantum communications
- Sources of quantum states and detectors
- Quantum networks
- Discrete variables quantum key distribution
- Generation of random quantum numbers
- Continuous variables quantum key distribution.
- Quantum memory and quantum repeater
- Exam (Quiz, and presentation of articles).

On completion of the course students should be able to:

explain how fundamental principles of quantum physics can be used to guarantee the security of communications
- list the requirements of a quantum network (ressources, performance)
- assess the performance of the major components used in quantum communications: sources, detectors, memories
- assess the performance of a communication protocol
- identify some major flaws in a quantum communication system design

Textbooks/bibliography:

Course code:	**Technologies quantiques : communication, calcul et capteurs**	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	B. Valiron / T. Antoni	
Volume: Period:	27 Hours	**3 ects**
Assessment:	Différente suivant chacune des études de cas, elle seront annoncée par les intervenant lors de chacune de leurs premières séances.	
Language of tuition:		

Course Objectives:

Le but de ce module est de présenter trois axes principaux identifiés à la fois comme critiques et prometteurs par la Commission Européennes dans le cadre de la seconde révolution quantique. Actuellement en train de sortir des laboratoires les retombées grand public sont attendues à 5-15 ans. l'enseignement se fera sous forme d'une étude de cas en partant des concepts physiques mis à jeu pour aboutir au dimensionnement d'un système permettant d'adresser un enjeu concret.

Course prerequisites:

Syllabus

Cours sous forme d'étude de cas quantiques :

3. Communication et cryptographie
4. Ordinateur et calcul
5. Capteurs

On completion of the course students should be able to:

Connaissance des principales technologies quantiques actuelles et de leurs applications, ainsi que des rudiments de recherche et développement.
(C1.2) Identifier, formuler et analyser un problème dans ses dimensions scientifiques, économiques et humaines.
(C1.3) Utiliser et développer les modèles adaptés, choisir la bonne échelle de modélisation et les hypothèses simplificatrices pertinentes pour traiter le problème.
(C1.4) Résoudre le problème avec une pratique de l'approximation, de la simulation et de l'expérimentation.
(C1.5) Spécifier, concevoir, réaliser et valider tout ou partie d'un système complexe.
(C2.2) Maîtriser les compétences d'un des métiers de base de l'ingénieur (au niveau junior).

Textbooks/bibliography:

Course code:	**Ultracold Molecules and Rydberg atoms: Interaction, Dynamics and Control**	Semester 1
Contributes to:	M2 QLMN – Track “Light and Matter”	

Course teachers:	Goulven Quéméner, Patrick Cheinet (Laboratoire Aimé Cotton, CNRS, Université Paris-Saclay)	
Volume: Period:	27 Hours December - February	**3 ects**
Assessment:	bibliographic project + oral presentation	
Language of tuition:	English (or French, depending on the audience)	

Course Objectives:
- Multipolar expansion in Cartesian and spherical coordinates; application of quantum perturbation theory to calculate long-range interactions; examples of their importance for modern research in ultracold gases
- Theory of ultracold collisions (partial waves). Control of interactions and dynamics with magnetic and electric fields and electromagnetic waves
- Applications to ultracold molecules and Rydberg atoms

Course prerequisites:
Quantum mechanics, basics in atomic and molecular physics.

Syllabus

1. An overview on ultracold molecules and Rydberg atoms (3h) (Goulven Quéméner, Patrick Cheinet)

2. Long-range interactions between atoms and molecules (6h) (Patrick Cheinet)
2.1 Reminder: atomic and molecular quantum numbers
2.2 Calculation of electrostatic energy between two charge distributions
2.3 Long-range interactions in ultracold matter

3. Ultracold molecules collisions with control by fields and waves (12h) (Goulven Quéméner)
3.1 Collisions of two molecules: Time-independent Schrödinger equation and generalities
3.2 Collisions of two molecules: Partial wave expansion and coupled equations
3.3 Collisions of two molecules: Cross sections and rate coefficients
3.4 Simple collisional models
3.5 Magnetic field control of ultracold matter
3.6 Formation of molecules with electromagnetic waves
3.7 Electric field control of ultracold matter

4. Rydberg atoms and their interactions (6h) (Patrick Cheinet)
4.1 Recalling basic properties
4.2 Long distance interactions between Rydberg atoms
4.3 Circular Rydberg atoms
4.4 Divalent atoms
4.5 Towards various applications: quantum simulation, electromagnetic field sensors

On completion of the course students should be able to:
- understand how interactions between ultracold molecules or Rydbergs atoms are described
- get a knowledge on the collisional formalism between ultracold molecules
- understand how one can form and control ultracold molecules with fields and electromagnetic waves
- compute various Rydberg atoms properties (AC-DC Stark effect, interactions…)
- get an overview of the field of ultracold molecules and Rydberg atoms, and their applications

Textbooks/bibliography:

- M. Lepers, O. Dulieu, "Long-range interactions between ultracold atoms and molecules", in Cold chemistry: Molecular scattering and reactivity near absolute zero, edited by A. Osterwalder, O. Dulieu, The Royal Society of Chemistry (2018), https://arxiv.org/abs/1703.02833
- G. Quéméner, "Ultracold collisions of molecules", in Cold chemistry: Molecular scattering and reactivity near absolute zero, edited by A. Osterwalder, O. Dulieu, The Royal Society of Chemistry (2018), https://arxiv.org/abs/1703.09174
- G. Quéméner, P. S. Julienne, "Ultracold molecules under control!", Chem. Rev. 112, 4949 (2012)
- T. F. Gallagher, “Rydberg atoms” (Cambridge University Press 1994)
- H. A. Bethe and E. E. Salpeter, “Quantum mechanics of one- and two-electron atoms”, Springer 1957
- D. A. Varshalovitch, A. N. Moskalev and V. K. Khersonskii, “Quantum theory of angular momentum”, World Scientific, 1988