Content and topics of lectures of the Master Quantum Engineering - M1

<u>Quantum Optics (3 ECTS)</u>
Jérôme Lodewyck

Part I: Interaction between the quantum atom and the classical electromagnetic field
- Parametrization of the two-level system (Bloch sphere)
- Electric dipole interaction and Hamiltonian
- Solution of the Schrödinger equation in the rotation frame
- Equivalent rotation on the Bloch sphere

Tutorials (TD1): Ramsey fringes
- Evolution of the density matrix
- Optical Bloch equation
- Ad hoc introduction of damping in the optical Bloch equation
- Approximation in the case of fast damping coherence and derivation of the stimulated emission. Application to lasers.
- Approximation in the case of a dilute gas (opening for the cold atoms course)

Part II: Quantization of the electromagnetic field
- Historical introduction

Tutorials (TD2): Einstein models (1905 and 1916)
- Decomposition of the field in spatial and frequency modes
- Mode decomposition of the classical Hamiltonian of the field
- Quantization of the Hamiltonian: $\hat{a}$ and $\hat{a}^+$ operators
- Photon number basis and vacuum state
- Change of mode decomposition
- Momentum operator
- Quadrature operators, commutation relations.
- Wave function of photon number states
- Displacement operator
- Coherent states, notion of shot noise

Tutorials (TD3): Properties of coherent states
- Definition and basic properties of the Wigner function
- Examples of Wigner functions for various quantum states
- Thermal state
- Squeezing operator. Effect on the quadratures and on the Wigner function. Squeezing of coherent states

Part III: Experiments in quantum optics
- Quantum model of the beam splitter, examples of various states interfering

Tutorials (TD4): Example of a multimode quantum state: the EPR pair

- Shot noise and the beam-splitter; Squeezing and the beam splitter: the attenuation

process in quantum optics
- Phase independent amplification
- Photo detection process: an interferometric point of view

Tutorials (TD5): Quantum optics in gravitational wave detectors
- Homodyne detector
- Heterodyne detector
- Casimir effect

Part IV: Interaction of a quantum atom with the quantum field
- Electric dipole interaction. Role of the vacuum
- Spontaneous emission: Fermi golden rule and non-perturbative approach

Tutorials (TD6): Spontaneous emission revisited
- Interaction with a single mode: Jaynes-Cummings Hamiltonian, eigenstates, adiabatic passage
- Evolution of a coherent state

<u>Quantum Mechanics (3 ECTS)</u>

Yanko Todorov

1. Basic Quantum Mechanical Concepts
   - Wavefunction and probabilistic interpretation, interference, position and momentum measurement and representation.
   - Stability of the atom, wavefunctions and energy levels in hard wall potentials (through standing wave condition)
   -Introduction to Hilbert space; measurement as projection; introduction to Schrodinger equation

2. Dirac formalism

   Observables, Hilbert space, Probability amplitude (bra, ket product), position & momentum operators, Hamiltonian, Commutator and Heisenberg uncertainty relation, The postulates of quantum mechanics, Evolution operator, Time evolution of variables, Schrödinger and Heisenberg picture, Tensor product of Hilbert spaces, The Einstein-Podolsky-Rosen “paradox”.

3. Some 1D problems in Quantum Mechanics
   - Conservation law for probability current, Transmission, Three “classic” 1D problems in Quantum Mechanics (step, barrier, well), Numerical resolution of 1D Schrödinger equation
   - The Quantum Harmonic Oscillator: Hamiltonian, spectrum, ladder operators, eigenstates, coherent states, Translation operator

4. Spin and Two-level systems
    - Stern and Gerlach experiment, Pauli matrices & their properties, Spin in an arbitrary direction, Spin and 3D rotation, Coherent control of a spin, Spin as a Q-bit: single bit quantum gates, Two Q-bits quantum gates, Intro: Spatial rotations and angular momentum operator

5. Open systems and density matrix
    - Case study: quantum well coupled to a continuum, Wigner-Weisskopf approach & derivations of the Fermi's golden rule,
    - Density matrix operator: Definition, properties, examples, application, elementary introduction to Lindblad equation

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<u>Quantum communications (3 ECTS)</u>
Diana Serrano and Philippe Goldner

In this lecture, we will review the principles of quantum communications. In the first part, we will look at the use of quantum physics to drastically increase security in communications, which is the field of quantum cryptography. After a general introduction, we will discuss single-photon quantum key distribution (QKD), followed by protocols involving entangled states. In the second part, we will study interferences with single photons and quantum teleportation. We will then consider quantum networks and the building blocks of long-distance quantum communications. Throughout the lecture, concepts and calculations will be illustrated by research papers and experimental implementations will also be presented.

1. Introduction
    - Classical cryptography
    - Quantum approach
    - Non-cloning theorem
    - Polarization states

2. QKD with single photons
    - BB84 protocol
    - Experimental implementations
    - B91 protocol
    - Attacks

3. QKD with entangled states
    - Bell states and Bell inequalities
    - Eckert91 protocol
    - Experimental implementations

4. Quantum teleportation
- Interferences with single photons
- Multi-photon entangled states
- Teleportation protocols
- Experimental implementations

5. Quantum networks
- Building blocks
- Long-distance quantum communication
- Experimental implementations

Atomic Physics (3 ECTS)
Bess Fang and Franck Pereira dos Santos

1 Introduction: a historical perspective
- 1.1 Spectrum of atomic Hydrogen
- 1.2 Bohr's theory
- 1.3 Relativistic effects
- 1.4 Other observations

2 The Hydrogen atom
- 2.1 Some useful concepts from Quantum Mechanics
- 2.2 The Coulomb potential
- 2.3 Transitions
- 2.4 Fine structure
- 2.5 Hyperfine structure

3 Many-electron atoms and spectroscopy
- 3.1 The shell model and the periodic table
- 3.2 Alkali atoms
- 3.3 The Helium atom
- 3.4 Atoms with 2 valence electrons
- 3.5 The Stark effect
- 3.6 The Zeeman effect

4 Laser cooling and trapping
- 4.1 Radiative forces
- 4.2 Doppler cooling
- 4.3 Magneto-otpical trap

5 Introduction to quantum sensors

- 5.1 Noise and its characterization
- 5.2 Atomic clocks and realization of time scale
- 5.3 Cold-atom inertial sensors
- 5.4 Other sensors
- 5.5 Fundamental physics and applications

<u>Introduction to quantum computing (2 ECTS)</u>

Antoine Tilloy, Alain Sarlette

1. Detailed presentation of Deutsch-Jozsa algorithm, with an in-depth discussion on the meaning of "quantum algorithm", and how to rule the game.

2. Elements of complexity theory, starting with the classical (universal Turing machine, P, NP, BPP and BQP, oracles)

3. General elements on quantum circuits, basic gates, and the beginning of universality

4. Universality and the Solovay-Kitaev theorem

5. Introduction to quantum platforms (photonics, ions, supra) and computational alternatives (measurement-based, Ising machines, adiabatic computation)

6. Quantum algorithms:
   - a) Deutsch-Jozsa "le retour", Bernstein-Vazirani, Simon
   - b) Period finding and Shor
   - c) Grover and quantum simulation

7. Introduction to error correction:
   - a) classical and quantum repetition codes, Shor code
   - b) back to noise sources (quantum channels = Kraus maps), noise discretization theorem, heuristic approach on the meaning of *fault-tolerance of logic gates*.

Mathematical methods for quantum Engineering (2 ECTS)
Alexandru Petrescu, Pierre Rouchon

1. Basic concepts of linear algebra leading to a rigorous formulation of the postulates of quantum mechanics

2. Schrödinger, Heisenberg and Dirac pictures

3. Introduction to the density operator and the von Neumann equation

4. Simple systems such as the spin 1/2, the harmonic oscillator, and the Jaynes-Cummings model;

5. Time-independent and time-dependent perturbation theory

6. Introduction to three specific mathematical methods illustrated on physical examples encountered in classical/quantum engineering:
    i) Single frequency averaging and rotating wave approximation (phase-looked loop, resonant control of a qubit, Kapitsa pendulum and Paul traps)
    ii) Euler/Lagrange and Hamilton equations with the classical/quantum correspondence (1D/2D pendulum, LC and Josephson electrical circuits)
    iii) Stability of dynamical systems and feedback (damped pendulum, Lyapunov function, transfer functions of first/second-order systems, PID-regulator/cascade, slow/fast systems)

Quantum Theory of Materials (3 ECTS)
Nicolas Bergeal, Arthur Marguerite

1. Specific heat of solids
    - Classical specific heat, Dulong and Petit law, Boltzmann explanation
    - Einstein's model of the specific heat, canonical partition function, quantum harmonic oscillator
    - Debye's model of the specific heat, collective vibration of atoms, towards phonon modes

2. Cristal structure of solids
    - Lattices and unit cells, Bravais lattices
    - Reciprocal lattice, Brillouin zone

3. Phonons in solids
    - Vibration of the 1D mono atomic chains, comparison with Debye model
    - 1D diatomic chain, optical and acoustic modes
    - Phonons

4. Free electrons and quantum transport
   - Drude model, Hall effect, thermal transport
   - Sommerfeld model, Fermi-Dirac statistics, electrons heat capacity
   - Quantum transport, mesoscopic scales, coherent transport, ballistic transport

5. Electrons in solids
   - Nearly free electrons models, perturbative approach, band representation, energy gap
   - Bloch’s theorem, electron wave function in a solid
   - Tight-binding model, 1D chain, band structure, Graphene band structure (TD)

6. Semiconductors and devices
   - Band structure, electrons and holes
   - statistical mechanics of semiconductors, intrinsic and extrinsic doping, law of action mass
   - semiconductor devices, p-n junction, solar cell

Entrepreneurship (1 ECTS)
Etienne Krieger

1. Growth Options for Startups
   - Innovation, strategy and finance: prospects and dilemmas
   - How to allocate equity to founders?
   - Testimonial of a deep tech entrepreneur: Dr. Christophe Bureau

2. Business Planning and Financial Modelling
   - Main financial requirements.
   - Business Planning and financial modelling
   - Financial resources for new ventures

3. Sources of Financing and financial engineering
   - Notions of financial engineering
   - Testimonial of a deep tech entrepreneur: Dr. Niccolo Somaschi
   - Concluding comments

Case studies (3 ECTS)

A case study is a lecture on three hours only aiming is to tell the complete "story" of a quantum device or a quantum effect from the discovery or realsation to today's impact on the scientific community and even to society. The challenge is to be exhaustive within the time limit, i.e. to give the theoretical basis, describe the quantum nature of the effect and explain how it is possible to measure it.

A few examples to give you an idea of what it is about are: Superconducting Quantum Interference Device (SQUID), single-photon detection, a concrete example of light trapping (atoms, dielectric spheres, etc.), the Aharonov-Bohm effect, quantum cascade lasers,…

The aim is to illustrate a concrete case that demonstrates the quantum effect and makes it visible, bearing in mind that the lecture has to be adapted for the knowelefge of M1 students.

Quantum physics, practical work (7 ECTS)

Gerbold Ménard, Arthur Marguerite

The purpose of this class is to bring the students to apply practically their knowledge of quantum mechanics through two different subjects. The two subjects that will be studied are the Zeeman effect and optical pumping. In this class the student will be able to witness and basic quantum mechanics effects directly. In particular, they will study the absorption and emission of light by an atom and study the properties of this light in order to understand the electronic structure of atoms in a magnetic field.

In the case of the Zeeman effect, students will focus on using an Fabry-Pérot interferometer in order to study the splitting of spectral lines of Cadmium atoms. By using an optical system comprising polarizers, filters and quarter-wave plates the students will be able to discriminate between the various types of light emitted by the relaxation of an electron and study the effect of the magnetic field. Using this experimental setup, the students will experimentally measure the value of the Bohr magneton.

In the case of the optical pumping experiment, students will focus on the dynamical filling and emptying of the electronic levels of Rubidium atoms in static and oscillating magnetic field. They will study the fine and hyper-fine structure of 2 isotopes of Rubidium and explore one and many-photon processes. At the end of the practical the students will observe Rabi oscillations. Experimentally, the students will learn how to use an oscilloscope and send different types of RF signal modulation.

The class will span 8 half-days (4 half-days per subject) and will conclude with the redaction of two experimental reports. The grade will be decided by looking at the level of engagement of the students during the class, the quality of the experimental work, the quality of the report and the scientific rigor applied to the analysis of the data.