Content and topics of lectures of the Master Quantum Engineering – M2

Quantum mechanics (2ECTS)
Kris Van Houcke

1. Review of the basics of quantum mechanics, postulates of quantum mechanics, Schrodinger/Heisenberg/interaction pictures, two-level systems and the Bloch sphere

2. Relation between quantum and classical mechanics, the Feynman path-integral representation

3. Many-body systems, second quantization, path-integral representation for many-particle systems, quantum Monte Carlo and the fermionic sign problem

4. Bogoliubov theory of weakly interacting bosons

5. Pure states versus mixed states, density operator, reduced density operator, entanglement, (maybe: EPR paradox and Bell's theorem)

6. Open quantum systems, operator-sum representation, quantum measurements, Lindblad representation, Born-Markov master equation

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Introduction to quantum information theory (2ECTS)
Alain Sarlette, Harold Ollivier

1. States: Density matrices, Inner product, Norms, Fidelity, TVD, State decomposition (Schmidt, Pauli)

2. Operators (1): Unitary representation, CPTP Maps, Other representations (larger unitary / Kraus / Choi)

3. Operators (2): Pauli operators, Channels acting on operator algebra, Recovering subsystems from commutation relations, Clifford Hierarchy, Classes of restricted operations (LOCC, LO1WCC)

4. Measurements: Projective Measurements, Update rule, POVM, Non-commuting / joint measurability

5. Entanglement: Measures of entanglement, Entanglement monotones, Distillation of entanglement, Using entanglement (Teleportation, Swaping, Gate teleportation, Relation with Choi, Super dense coding)

6. State discrimination: Hypothesis testing, Entropies, Holevo, Conditional entropy / mutual information / strong subadditivity, Data processing inequality, Relative Entropy, Pinsker

7. State estimation: Tomography, Efficiency of tomography, Shadow Estimation

8. Some applications of quantum communication: QKD, Fingerprinting, Uncloneable encryption, Self-testing

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Control of quantum systems (3ECTS)
Pierre Rouchon

Lecture 1: Recap of time-dependent perturbation theory, Using Fermi's Golden Rule to calculate transition rates for a system under constant or monochromatic perturbations.

Lecture 2: System coupled to an environment. The case of a qubit or a simple harmonic oscillator. Simple derivation of the Lindblad master equation for a qubit. Understanding the energy relaxation and dephasing times of a qubit, working with Bloch's equations. Theoretical concept: an elementary derivation of Born-Markov master equations, frequently used to model dissipation.

Lecture 3: Adiabatic elimination. From derivation all the way to concrete examples, such as driven dissipative stabilization of bosonic cat codes.

Lecture 4: The Jaynes-Cummings Hamiltonian of a spin coupled to a photon, as a first model of circuit quantum electrodynamics. Introducing the dispersive approximation using a Schrieffer-Wolff approach, and a first take on dispersive qubit readout in circuit QED. Theoretical principles: systematic approaches to the rotating-wave approximation

Lecture 5: One new topic (maybe adiabatic theorem and Berry's phase), or more in-depth examples.

Lecture 6: The Haroche photon box (micromaser): ideal model with wave function for dispersive/resonant interaction, Quantum Non-Demolition (QND) measurement of photon, realistic model with density operator and Kraus operators including measurement imperfection and decoherence, open-loop Monte-Carlo simulations.

Lecture 7: Feedback stabilisation of the Haroche photon Box: stabilisation of photon-number state either via measurement-based feedback (classical controller) or via decoherence engineering and autonomous feedback (quantum controller), convergence and robustness based on closed-loop Monte-Carlo simulations.

Lecture 8: Measurement and decoherence models for quantum harmonic oscillator: counting measurements, damping and thermal environment, corresponding stochastic master equation driven by Poisson processes, Lindblad master equation, Wigner function, numerical simulations.

Lecture 9: Measurement and decoherence models for a two-level system: homodyne/heterodyne measurements of a super-conduction qubit, T1 and T2 of a qubit, corresponding stochastic master equation driven Wiener processes, numerical simulations.

Lecture 10: One new topic (maybe parameter estimation and quantum filtering), or more in-depth examples.

Quantum sensing (2ECTS)
Alexey Tiranov, Philippe Goldner

1. Platforms
   a) Solid-state spin ensembles
      - (NMR ensembles, NV center ensembles …)
   b) Single solid-state spins
      - Defects in crystalline materials (diamond, silica, silicon carbide …)
      - Single organic molecules, single quantum dots
   c) Superconducting circuits:
      - SQUIDs, superconducting qubits
   d) Quantum optomechanics
      optomechanics, electromechanics and hybrid circuits

2. Quantum sensing
   a) Protocols
      - Quantum sensor Hamiltonian, Examples of Ramsey and Rabi sequences
   b) Sensitivity
      - Quantum noise, decoherence, single shot readout, averaged readout
      - Slope and variance detection, Allan variance
   c) Sensing ac Signals
      - Multipulse sequences, dynamical decoupling
   d) Noise Spectroscopy
      - Decoherence, dynamical decoupling and filter functions, relaxometry (T1, T2, T2*)

3. Applications:
   a) Biomedical applications (brain imaging, single-cell spectroscopy), quantum optimal control and machine learning

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Quantum computing (2ECTS)
Francesco Arzani, Ulysse Chabaud

1. Quantum Computing Models and Applications
    - Universal models (MBQC, Gate, CV in its own module, Adiabatic)
    - Subuniversal models I: qubit sampling
    - sampling problems: introduction, complexity, the example of IQP (in the gate and MBQC models)
    - random circuit sampling (and the whole controversy about whether Google achieved quantum supremacy)
    - Sub-universal models II: boson sampling
    - Boson sampling (introduction, ideas)
    - Boson sampling (proof sketch?)
    - Other flavours of Boson sampling (Gaussian, scattershot, …)
    - NISQ models (I-II)
    - Quantum Approximate Optimization Algorithm (and the importance of polynomial speedup for NP-hard problems, finding ground states, graph optimization problems, …)
    - Quantum machine learning (intended as e.g. quantum variational circuits – aka quantum neural networks)

    For all models there will be a mention about status of current experiments

2. Error correction and mitigation
    - Intro on error correction: channels and the Knill-Laflamme conditions
    - Stabilizer formalism I: Pauli strings, stabilizer states, proof of the dimension of stabilized subspace wrt number of independent stabilizers
    - Stabilizer formalism II: symplectic formalism, efficient simulation of Clifford circuits on stabilizer states, the need for T-gates
    - Stabilizers III: introduction to the surface code: stabilizers, logical operators.
    - Notions of topological error correction and computation, notions of anyons, ideas of LDPC codes and going beyond surface code(s).
    - From error correction to fault tolerance, the threshold theorem, transversal gates, the Eastin-Knill theorem and other approaches to fault-tolerance (magic state distillation)
    - Introduction to bosonic quantum error correction: cat codes, GKP codes
    - Error mitigation (randomized compiling – ZNE, etc.)

3. Continuous variables quantum computing
    - Math toolbox
    - CV formalism (phase-space)
    - Gaussian Boson Sampling from A to Z

Quantum programming (3ECTS)
Francesco Arzani, Ulysse Chabaud, Harold Ollivier

- Starting with Qiskit
- Using linear optics simulation framework (Perceval)
- Tutorial (Small surface code, MBQC, etc)
- TPs in sync with QC and QIT courses

Advanced Atomic physics (3ECTS)
Tarik Yefsah, Bess Fang, Franck Pereira

1. A deeper look into quantum sensors
    - Atomic clocks
    - Cold atom interferometers
    - Other sensors
2. Quantum Simulators and computers
    - Simulating Hamiltonians in optical lattices
    - Controllable simulators in optical tweezers
    - Trapped ion-based quantum computers
3. Hybrid systems and atomtronics
    - Introduction to cavity QED Atom light interfaces (cavity QED, EIT …)
    - Quantum memories with atoms
    - Hybrid mechanical-atomic systems
    - Hybrid superconductors-atomic systems
    - Atomtronics

Options: One joint course with the ICFP Quantum Master to choose between:
1) Light-matter interaction and
2) Electronic transport & Superconductivity (6ECTS)

1 Light-matter interaction

The main goal of this course is to cover the physics of light-matter interaction in the context of quantum devices, and materials at the nanoscale. This UE features both theoretical aspects in lectures and tutorials - possibly based on the analysis and discussion of recent research papers - and experimental projects (12h) on research grade experiments at the end of the semester. Typical experimental projects comprise (i) a nanofabrication stage in one of the clean rooms of the Paris centre cluster (including a general introduction to nanofabrication techniques) and (ii) optical measurements guided by a researcher in one of the associated labs.
The lectures will cover a general introduction on the basics of light-matter interaction in the semi-classical and quantum approach. The body of the lectures will consist of three main parts:
I Properties arising from free electrons in both the bulk and quantum confined regimes, including plasmonics and its applications for photo-detection and optical information processing, photonic quantum devices, cooperative enhancement of the light-matter interaction.
II Properties arising from interband transitions in natural and artificial nanostructures of semi-conductors: excitons, correlations effects, light absorption, light emission, introduction to spectroscopic techniques; strategies to enhance light-matter interaction at the single quantum particle level. Applications.
III Ultrafast phenomena in nanostructures: introduction to nonlinear optics and ultrafast spectroscopy (femto/picosecond): pump-probe, four-wave-mixing, photon-echo experiments.

2. Electronic Transport and Superconductivity

The main goal of this course is to present the different regimes of electronic transport in conductors and how quantum mechanical effects affect their resistance or conductance. The first part of the course will present the quasi-classical regime and it corrections related to electronic interferences in diffusive conductors as well as the quantization of the conductance of low dimensional ballistic conductors. Topological materials, where the quantization of the conductance can become insensitive to the local properties of the conductor will also be discussed. The second part of the course is devoted to superconductivity. After a brief introduction on superconductors, the microscopic BCS theory will be presented, and the electrodynamics properties of superconductors studied. Special attention will be devoted to quantum phase coherence aspects, such as the Josephson effect. In particular, transport properties through Andreev states in normal conductors coupled to superconductors will be explained in the spirit of the first part of the lecture. Topological superconductors and their specificities will be also discussed.

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 realisation 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 knowledge of M1 students.

Quantum lab works/Laboratory projects (3ECTS)

Innovation and entrepreneurship in quantum technologies (1ECTS)