Physics of quantum information:
qubits, entanglement and decoherence

Fall 2025

Quantum bits and our ability to control, manipulate, and measure individual quantum systems encoding them are the basic ingredients for the development of quantum technologies. Exploiting intriguing aspects of quantum physics, such as quantum superpositions and entanglement, they allow performing tasks without classical counterparts such as the simulation of quantum many-body systems or the enhancement of the precision of sensors. The general framework describing ensembles of quantum bits lies at the interface between quantum physics and quantum information. Fundamentally, it is also a modern approach to the understanding of the concepts of quantum physics.

This course is an introduction to the physics of quantum information, from concepts to applications in quantum technologies, illustrated by 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 their encoding on physical systems we describe their manipulations and measurement. We then discuss the concept of entanglement and its characterization. As all quantum systems are coupled to an environment, we introduce the mathematical framework used to describe open quantum systems, and show how decoherence emerges from this.

Lecturers

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Lectures Friday 09:00-12:15 AM

Web page of the course

Lecture notes and materials, homeworks and articles will be posted here:
https://atom-tweezers-io.org/teaching/

Tentative outline of the course

12/09 (AB) Introduction to the course. Review of Quantum Physics illustrated on two level-systems (qubit), Bloch sphere, introduction to entanglement. A brief word about circuits, non-cloning theorem.

19/09 (LSP) Physical implementations of qubits and quantum harmonic oscillators.

26/09 (AB) Entanglement 1: Definition. Bell's theorem and its experimental verification. Teleportation.

03/10 (AB) Entanglement 2: Entanglement and density matrix (Statistical approach and quantum information approach), Von Neumann and Renyi entropies: tomography, purity measurement…

10/10 (LSP) Quantum measurements, QND measurements, strong and weak measurements, POVM.

17/10 (LSP) Open quantum systems using the Kraus/Lindblad approach and quantum maps, jumps, real and effective baths.

24/10 (AB) Physical content of the master equation (relaxation towards equilibrium and driven systems, from Jaynes-Cummings to spontaneous emission, Wigner-Weisskopf).

07/11 (AB) Stochastic wave functions. Decoherence.

14/11 (LSP) Recap of the course.

Bibliography and extra material

"Processus d'interaction entre photons et atomes", C. Cohen-Tannoudji, J. Dupont-Roc, G. Grynberg, Editions du CNRS (1998). English translation: Atom-Photon Interactions, basic processes and applications, Wiley (1992). *Some chapters only.*

"Exploring the Quantum", Serge Haroche and Jean Michel Raimond, Oxford (2006)

The following books and lecture notes are more oriented towards quantum information theory. We will point out what is useful for the lectures.

"Quantum Computation and quantum information", M.A. Nielsen and I. Chuang, Cambridge (2010)

Lecture notes from M. Lukin (Harvard):
https://lukin.physics.harvard.edu/files/lukin/files/physics_160_notes.pdf

Lecture notes from J. Preskill (Caltech):
http://theory.caltech.edu/~preskill/ph219/index.html#lecture

Lecture notes from Scott Aaroson:
https://www.scottaaronson.com/qclec.pdf

The Python library Qutip illustrates numerically many notions seen in the course (Bloch sphere, master equation, quantum jumps,…)

For those who have forgotten quantum physics

Mécanique Quantique, J.L. Basdevant, J. Dalibard, M. Joffre, Presse de l'Ecole Polytechnique. Available in English (Springer).