Quantum Systems in External Electromagnetic Fields: Classical Analogies and Quantum Phenomena

Responsible Scientific Assistant: Stavros Athanasiou (stavros.athanasiou@epfl.ch)
Professor: Olivier Martin (olivier.martin@epfl.ch)

Project Type: Bachelor, Semester project (or a combination or all)

Context: Quantum mechanics, developed in the early 20th century, revolutionized our understanding of the microscopic world. It explained the discrete energy levels of atoms, the band structure of solids, and the behavior of molecules, laying the foundation for modern atomic, molecular, and condensed matter physics. These advances have driven technological progress for over a century. External electric and magnetic fields play a key role in shaping the properties of matter, and their effects have been studied since Maxwell's unification of electricity and magnetism revealed light as an electromagnetic wave. With the advent of quantum theory, this classical view was extended to include the quantization of energy and the unique phenomena that arise when matter interacts with fields at the quantum level. Studying these effects not only deepens our understanding of fundamental physics but also connects abstract concepts to real-world applications.

Project overview: In this project, we will use single-particle, non-relativistic quantum mechanics to study systems subjected to external fields [1]. The exploration will span a wide range of phenomena, from simple cases such as free particles and harmonic oscillators in static electric and magnetic fields (Figure 1a,b), to more advanced scenarios involving time-varying fields (Figure 1c) and exotic effects, such as the Aharonov–Bohm (AB) effect [2]. A particular emphasis will be placed on identifying classical analogues for each system and pinpointing where quantum behavior departs from classical expectations. This project is ideal for a student with a basic background in quantum mechanics, preferably with prior exposure through an undergraduate-level course.

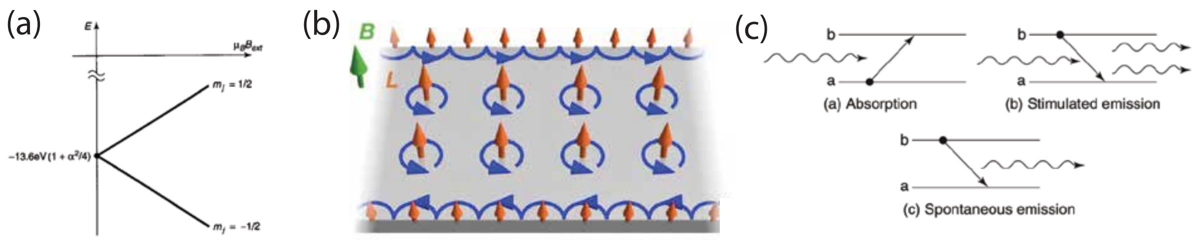

Figure 1. (a) Breaking of energy degeneracy in a magnetic field. (b) Particles in a uniform magnetic field. (c) A two-level system is subjected to an external, time-harmonic electric field.

What the student will do: After a brief review of basic quantum theory, the student will be introduced to a series of physical phenomena involving the interaction of quantum systems with electric and magnetic fields. Each case will be explored using both analytical and numerical methods, allowing the student to reproduce and visualize the phenomena. The results will be compared with classical predictions, making it possible to clearly identify which effects can be explained classically and which arise purely from quantum behavior.

Benefits: This project will combine analytical derivations with hands-on numerical simulations, giving the student the opportunity to both understand the underlying theory and see it come alive through computation. Beyond technical skills, it offers the chance to develop a deeper physical intuition and to explore how abstract quantum concepts connect to tangible physical effects. The work will be carried out in collaboration with a doctoral assistant whose research focuses on light-matter interactions at the nanoscale, ensuring a dynamic and intellectually stimulating environment.

References:

1. Griffiths D., Introduction to Quantum Mechanics, Cambridge University Press (1995)
2. Aharonov and Bohm, Phys. Rev. 115, 485 (1959)