

Internship proposal

Title: Single-Photon-Mediated Electron–Electron Interactions

Keywords: Light-matter interaction, quantum optics, electron microscopy, ultrafast optics

Context:

Quantum optics is the domain of natural science lying at the intersection between optics and quantum mechanics, encompassing all the situations where the electromagnetic field exhibits non-classical statistics, including discrete-variable (e.g. single photons) or continuous-variable (e.g. squeezed light) states. Over the last sixty years, this field played a pivotal role in the development of the foundations of quantum mechanics, thanks to key experimental breakthroughs such as the measurement of the violation of Bell's inequalities or the observation of the decoherence of a Schrödinger's "cat state".

In 2015, quantum optics entered a seemingly unrelated field of research: ultrafast transmission electron microscopy (UTEM). A paradigm-shifting experiment evidenced that when a narrow (nanometric) fast beam of free electrons was illuminated by a strong laser pulse, Rabi oscillations could be triggered, leaving the electrons in a quantum superposition of momentum states [1]. Subsequent theoretical studies showed that the electron-light interaction occurring in UTEM could be described by a Hamiltonian corresponding to a realization of the celebrated Jaynes-Cummings model [2], one of the most important models of cavity quantum electrodynamics. This striking analogy was the act of birth of a new domain in 2020: quantum optics with free electrons (QUOFE).

Since then, QUOFE has reproduced with electrons many of the historical successes of its photonic counterpart, including Ramsey interferometry [3], quantum state tomography [4], quantum state heralding [5] and electron-photon entanglement [6]. However, in all these experiments, the electron beam is produced by photo-emission and consists of regularly spaced ultrashort single-electron pulses. As a consequence, the fermionic nature of electrons plays no role. This has deprived QUOFE from many rich features of fermion statistics and has consequently circumscribed QUOFE to mimicking light quantum optics.

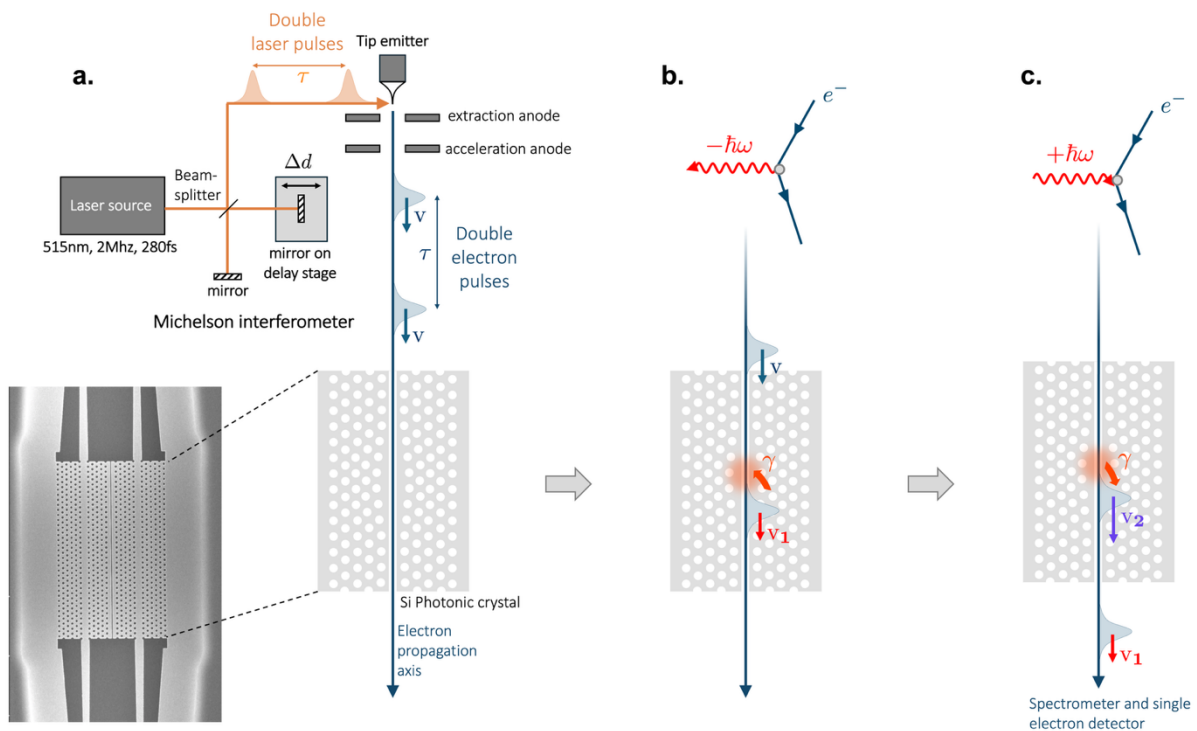
The goal of the QUORUM project is to break this limit by generating beams made of pairs of correlated electrons. Switching from single electrons to multiple-electron pulses will strongly modify their interaction with light, making it sensitive to their Coulomb correlation, temporal statistics or entanglement [7,8]. This opens the path towards the observation of a new class of effects in QUOFE which go beyond the conventional description of single-electron–light interactions.

Internship objective:

The objective of this internship is to **experimentally investigate the interaction between a pair of electrons and a non-classical optical field**. In particular, the first electron will interact

with a high-Q photonic crystal (see figure a) and generate a single quantum of excitation in its optical near-field (see figure b). The second electron will subsequently interact with this field and will therefore experience a single photon state (see figure c).

When the coupling between the electrons and the photonic mode is sufficiently strong, there is a non-zero probability that the second electron picks up the photon generated by the first electron. Strong non-classical effects have been predicted in such a regime but have never been observed so far [9]. The internship will aim at experimentally demonstrating this interaction using a high-Q photonic crystal, which was designed and fabricated by Xavier Checoury at C2N Orsay [10].



The experimental work will be carried out in collaboration between **CEMES and the Laboratoire de Physique des Solides (LPS) in Orsay**. At LPS, monochromated electron energy-loss spectroscopy (EELS) will be used to characterize the photonic crystal and determine its optical properties and electron-photon coupling [10]. At CEMES, the student will implement the double-electron experiment on the ultrafast transmission electron microscope, using time-tagged electron detection to measure the energy of the two electrons individually and investigate their correlations.

The experimental results will be complemented by theoretical modelling using the QuTiP Python framework. The simulations will describe the interaction between the two electrons and the photonic mode and will provide a quantitative framework for interpreting the experimental energy spectra and identifying the signatures of the interaction with the single-photon Fock state.



Profile: solid background in quantum mechanics and optics, strong taste for experimental and fundamental physics.

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Location: CNRS-CEMES (Toulouse) and/or LPS (Orsay)

PhD: a funded PhD position is available

Bibliography

- [1] A. Feist et al., "*Quantum coherent optical phase modulation in an ultrafast transmission electron microscope*", *Nature* **521**, 200–203 (2015)
- [2] O. Kfir, "*Entanglements of Electrons and Cavity Photons in the Strong-Coupling Regime*", *Physical Review Letters* **123**, 103602 (2019)
- [3] J. Gaida et al., "*Attosecond electron microscopy by free-electron homodyne detection*", *Nature Photonics* **18**, 509–515 (2024)
- [4] K. Priebe et al., "*Attosecond electron pulse trains and quantum state reconstruction in ultrafast transmission electron microscopy*", *Nature Photonics* **11**, 793–797 (2017)
- [5] G. Arend et al., "*Electrons herald non-classical light*", *Nature Physics* **21**, 1855–1862 (2025)
- [6] J-W Henke et al., "*Observation of quantum entanglement between free electrons and photons*", *arXiv:2504.13047* (2026)
- [7] R. Haindl et al., "*Coulomb-correlated electron number states in a transmission electron microscope beam*", *Nature Physics* **19**, 1410–1417 (2023)
- [8] R. Haindl et al., "*Femtosecond and Attosecond Phase-Space Correlations in Few-Particle Photoelectron Pulses*", *Physical Review Letters* **135**, 165002 (2025)
- [9] S. Kumar et al., "*Strongly correlated multielectron bunches from interaction with quantum light*", *Science Advance* **10** (2024)
- [10] M. Bézard et al., "*High-Efficiency Coupling of Free Electrons to Sub- λ^3 Modal Volume, High-Q Photonic Cavities*", *ACS Nano* **18** (15): 10417–10426 (2024)