CONTRATS DOCTORAUX 2026
PROJET QUANTEDU

Sujet de thèse – Laboratoire de Physique des Lasers

Title: **Quantum near-field sensing of THz metamaterials with Rydberg atoms**
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Quantum sensing is one of the most rapidly advancing branches of quantum technologies and is now approaching the stage of commercialization. This progress has been largely driven by the development of atomic vapor platforms, whose simplicity and robustness enable compact and transportable devices. Atomic vapor cells have proven particularly powerful as ultra-sensitive magnetometres, while electric field sensing at frequencies extending up to the GHz range has been demonstarted by the use of Rydberg atom vapors [1]. More recently, THz sensing has been achieved by converting absorbed THz radiation to visible fluorescence (via Rydberg atoms), thereby enabling optical detection in a challenging frequency range [2].

Despite these advances, quantum sensing has so far been predominantly exploited in the far-field regime, where external fields are measured at distances far from solid-state interfaces. Extending these capabilities to the near-field represents a major step forward. By using atoms as local probes of electric fields generated by surface features such as patch potentials, charges, or impurities, one can envision a quantum analogue of electrostatic force microscopy or Kelvin probe force microscopy, in which classical cantilever probes are replaced by non-invasive quantum sensors. Beyond static fields, near-field quantum sensing paves the way for mapping infrared and THz electromagnetic fields in the vicinity of structured materials such as planar metamaterials. In this context, atoms can directly probe locally enhanced electromagnetic fields with minimal perturbation, providing a quantum counterpart to scanning near-field optical microscopy (SNOM).

The proposed project has the following pioneering goals:

1) Interface Rydberg atoms with metamaterials:
Fabricating vapor cells that integrate metallic nanofabricated resonators, submerged into an atomic gas.

2) Perform near-field characterization of the metamaterials using Rydberg probes:
When excited by an external THZ source, the resonators generate an intense electromagnetic response in the near-field. This field will induce dipole transitions on the surrounding vapor of Rydberg atoms transferring population to adjacent energy levels from which they will decay by fluorescing visible photons. Visible light can be detected by ultra-sensitive cameras providing a mapping of the electric field in the vicinity of the resonators with a resolution that beats the diffraction limit by 3 orders of magnitude. This will constitute a quantum technique for performing near-field optical microscopy.

3) Probe the Casimir-Polder interaction between Rydbergs and metamaterials:
Beyond quantum optical microscopy, interfacing THz resonators and Rydberg atoms can allow us to study the fundamental Casimir-Polder interaction between atoms and metamaterials. THz resonators modify the local density of states of the electromagnetic field, suggesting that a resonant coupling between Rydberg atoms and THz metamaterials could be used to tune Casimir-Polder interactions. To probe Rydberg-metamaterial interactions, we will use selective reflection spectroscopy, developed by the SAI group to probe atoms [3], at nanometric distances (typically ~100nm) above the active region of the resonator.

Perspectives:
Rydberg-metamaterial coupling and THz to visible conversion offers fascinating possibilities for performing quantum optics experiments in the THz regime and testing dynamical Casimir effects.

The SAI group of the LPL are specialists in Casimir-Polder spectroscopy of atoms and molecules close to interfaces. This project is in collaboration with the C2N group of J-M Manceau specialists in THz metamaterials and the group of S. Scheel's in the University of Rostock (Germany) specialists in QED theory.

We are looking for a PhD student with good background in quantum and atomic physics to work on both experimental and theoretical aspects of this project and participate in the collaborations of the SAI group.

References

1. J. A. Sedlacek, A. Schwettmann, H. Kübler, R. Löw, T. Pfau, et J. P. Shaffer, 'Microwave electrometry with Rydberg atoms in a vapour cell using bright atomic resonances', Nat. Phys., 8, p. 819-824, (2012).
2. 2Downes, L. A. et al. Full-Field Terahertz Imaging at Kilohertz Frame Rates Using Atomic Vapor. Phys. Rev. X 10, 011027 (2020).
3. A. Laliotis et al., 'Atom-surface physics: A review', AVS Quantum Science 3, 043501 (2021).