Centre de Nanosciences & de Nanotechnologies

Proposition de sujet de thèse 2025 – COFUND 'Light in Paris'

Nuclear spin cooling for the generation of long photon cluster states by a III-V semiconductor quantum dot

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Keywords : quantum dots, photonic cluster states, spin coherence, hyperfine interaction

General context: The thesis proposal addresses the field of quantum information with non-classical light states produced by solid-state devices, and involves knowledge and know-how at the frontiers of quantum optics, semiconductor physics and nuclear magnetism.

Main objectives: Implementing experimental protocols for "cooling" nuclear spins in III-V semiconductor quantum dots to increase the electron spin coherence time in the weak magnetic field regime, such that these protocols are compatible with the generation of photon cluster state using the spin-photon entanglement provided by a quantum dot. Demonstration of long cluster state (>10 entangled photons).

Subject proposal: In the context of photonic quantum technologies, self-assembled III-V semiconductor quantum dots are today one of the most promising platforms for implementing quantum computing protocols or serving as quantum memory within a quantum network. When integrated into photonic devices such as pillar-shaped cavities, they become excellent single-photon sources. It is also possible to load them with an electron or a hole (an electron vacancy) and use the spin 1/2 of this charge as an additional quantum resource. The spin-orbit interaction leads indeed to optical selection rules that allow spin to be entangled with the polarization of an emitted photon. Numerous demonstrations have already demonstrated the full potential of this system, notably for the generation of photon cluster states (a succession of multi-entangled photons), which are essential resource states for efficiently implementing optical quantum computing protocols. However, these quantum dots have the serious drawback of presenting a spin coherence time greatly reduced to a few ns, due to the hyperfine interaction with the disordered set of nuclear spins inherent in the III-V elements of quantum dots. To date, this is the main limitation for the size and quality of photon cluster states. Very recently, optical techniques exploiting Zeeman splitting of nuclear spins in a magnetic field of several Teslas have made it possible to reduce the entropy of nuclear spins in quantum dots, and have demonstrated their effectiveness in increasing the spin coherence time by at least two orders of magnitude. The aim of the doctoral project is to implement this type of nuclear spin 'cooling' for the micropillar cavity quantum dots being fabricated and studied at C2N in collaboration with Quandela, and to extend it to the low magnetic field regime (ideally <100mT) to make it compatible with the cluster state generation protocol.

References:

Enhanced Electron-Spin Coherence in a GaAs Quantum Emitter, G. N. Nguyen, et al Phys. Rev. Lett. 131, 210805 (2023)

Quantum sensing of a coherent single spin excitation in a nuclear ensemble, D. M. Jackson, et aL;, Nat. Phys. 17, 585 (2021).

High-rate entanglement between a semiconductor spin and indistinguishable photons, Coste, N., et al. Nat. Photon. 17, 582–587 (2023).

Tuning the coherent interaction of an electron qubit and a nuclear magnon, Noah Shofer et al., arXiv:2404.19679 (2024)

Research team, thesis supervision and outcomes: The PhD student is integrated into a research team at C2N comprising 5 permanent staff and around twenty PhD students, postdocs and interns. The supervisor will carefully follow the advancements of the work, with an involvement of at least 20% of his working time. The co-supervisor is Stephen Wein, an expert theoretician in quantum optics, light matter interaction and quantum information. The PhD student will also work on a weekly basis with Dr. Noah Shofer, highly experimented in techniques of nuclear spin cooling/control in quantum dots, and working at Quandela since July 2024 as an experimental quantum optics scientist. The doctoral project is part of the research program of the joint laboratory 'QDlight' started in 2024 between C2N and the startup Quandela. As such, the PhD student will benefit from regular interactions with Quandela's research teams, while the joint laboratory framework with a private partner fulfills the '3i' dimension of the COFUND call 'Light in Paris'.

All the material conditions are in place to take over this project in October 2025. Several projects contracted in 2023 and 2024 guarantee financial support for the purchase of missing equipment and for operating requirements.

The research results will be published in peer-reviewed scientific journals. The patentability of developments will be carefully considered, still without being a priority.

Applicant profile :

We welcome excellent students with solid training in quantum physics, ideally including good background in condensed matter physics and quantum optics. The applicant should also have a real taste for experimental studies, demonstrated by internships during his/her master studies, ideally in classical/quantum optics and/or semiconductor physics.