Photonic sources for entanglement-based quantum network

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1/ Scientific Objectives : a quantum-connected SU campus

In the broad context of quantum communications, one stream of research aims at eventually creating a so-called Quantum Internet. Among other applications, ranging from extending the baseline of telescopes to clock synchronization and sensor networks, the creation of a Quantum Internet would enable long-distance unconditionally-secured information transfer. Central to this endeavor is the concept of quantum repeater. It consists in dividing a communication channel between two end nodes into various shorter segments over which entanglement can be faithfully distributed. Adjacent segments are then connected by entanglement swapping operations. To be scalable, this approach requires quantum memories, which enable quantum states to be stored at each intermediate node. It also requires the development of very **specific photonic sources** enabling to connect such atom-based memories to **telecom infrastructures**.

In this context, this project will target the realization of frequency non-degenerate photon pairs, compatible with cold-atom memory and telecom network. This **quantum light source** will be integrated into the **Sorbonne Université dedicated quantum testbed**, which will also be tested and characterized along the project.

2/ State-of-the-art and Methodology

Significant advances have been made for quantum networks in the last decade, including very first rudimentary capabilities for quantum repeater architectures. However, most of these seminal demonstrations were plagued with limited efficiency and scalability. In the more recent years, optical memories have been largely improved due to the rapid progress in implementing elongated ensembles of cold neutral atoms with ultra-high optical depths, which a strong prerequisite for large efficiency. Using a large cold atomic ensemble based on an elongated magneto-optical trap (3-cm long), in 2018, the LKB team demonstrated qubit storage with an overall efficiency close to 70%, a value that doubled the usual performances at that time. In 2020, the team pushed this value even higher and reached the 90% mark for entanglement storage. This is the state-of-the-art in term of storage-and-retrieval efficiency for a quantum memory, regardless of the physical platform considered.

Given this capability, the project will aim at demonstrating an entangled link between the cold-atom memory located at LKB and the LIP6 lab. A telecom network is currently being installed between the two labs and connected to other Paris region hubs in the framework of the ParisRegionQCI project.

The thesis project will require to test the telecom infrastructures, and the required phase stabilization. It will also focus on the development of a photon-pair source based on type-II phase-matched optical parametric oscillators (crystal in cavity) running in a frequency non-degenerate configuration: signal and idler will be at the cold-atom wavelength and a telecom wavelength, either in C- or L-band. **A final step will be then to demonstrate light-matter entanglement generation between the LKB lab where the memory is located and the LIP6 lab where characterization and subsequent use for remote state preparation will be realized**.

3/ Synergies and Interactions in QICS

The present research activity will strengthen the already established collaboration between the LIP6 and LKB labs and will enable to take a first step **towards a SU 'quantum-connected' campus by demonstrating entanglement between the two remote labs**, with storage capacity. The project outcomes will eventually provide a **key component that is required for the envisioned mid-term project of a quantum communication infrastructure in the Ile-de-France region** towards the first repeater segments for quantum information distribution on deployed fibers on long distance. More generally, this is part of the ambitious EuroQCI project, which aims at deploying such testbeds in several major cities in Europe for unlocking the full potential of quantum communication technologies.

This project can only be based on a synergetic effort between the two labs. LKB is providing the memory capability while the LIP6 team has an extended expertise on the design, analysis and implementation of quantum network protocols that can be used as blueprints for the future Quantum Internet. The photonic source will enable the connection between the labs and will provide a **crucial testbed for benchmarking protocols that belong to the so-called quantum memory stage of quantum networks**, hence placing our University in the forefront of advances in this field.

4/ Recent publications related to the research context:

LKB:

- M. Cao *et al.*, Efficient reversible entanglement transfer between light and quantum memories, Optica 7, 1440 (2020).
- P. Vernaz-Gris *et al.*, Highly-efficient quantum memory for polarization qubits in a spatially-multiplexed cold atomic ensemble, Nature Commun. 9, 363 (2018)
- V. Parigi *et al.*, Storage and retrieval of vector beams of light in a multiple-degree-of-freedom quantum memory, Nature Commun. 6, 7706 (2015).

LIP6:

- R. Yehia *et al.*, Quantum city: simulation of a practical near-term metropolitan quantum network, arXiv:2211.01190
- A. Unnikrishnan *et al.*, Anonymity in practical quantum networks, Phys. Rev. Lett. 122, 240501 (2019).
- M. Bozzio *et al.*, Experimental investigation of practical unforgeable quantum money, npj Quantum Information 4, 5 (2018).

The dynamic and highly-motivated PhD candidate should have an initial training on experimental quantum photonics, light-matter interactions or quantum information technologies.