Quantum Network with Neutral atoms array in an optical cavity

Matthias Seubert[1], Lukas Hartung[1], Stephan Welte[1,2], Gerhard Rempe[1] and Emanuele Distante[1,3]

1. Max-Planck-Institute of Quantum Optics, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany

2. Institute for Quantum Electronics, ETH Zürich, Otto-Stern-Weg 1, 8093 Zürich, Switzerland

3. ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Barcelona, Spain

Abstract: We present a neutral atoms qubit register coupled to an optical cavity formed by reconfigurable optical tweezers. A single-atom addressing beam enables photon emission from each atom, demonstrating multiplexed atom-photon entanglement with 90% efficiency.

Quantum networks [1] offer vast potential for numerous applications, including secure communication, distributed quantum computing, precision sensing, and clock synchronisation. The envisioned architecture comprises network nodes with stationary qubits for storing and processing quantum information, connected via optical fibres for the exchange of photonic qubits. Elementary quantum network protocols require only one or two qubits per node. However, this simple architecture faces substantial challenges in practical applications. Intrinsic optical losses and seemingly unavoidable errors make quantum information exchange across the network slow and unreliable. A solution is using a larger qubit register per node. Multiple qubits can then be employed in a multiplexed way to facilitate information exchange between the nodes, thereby boosting communication rates beyond the limit set by the optical losses and the lengths of the communication channels. Furthermore, the redundancy provided by large qubit registers enables correcting for errors through protocols such as entanglement distillation or quantum error correction.

The challenge consists of creating a scalable register of individually controllable qubits, each coupled to a photonic channel for network connectivity. This requires coupling the qubits strongly to an optical cavity that serves as an efficient light-matter quantum interface. In principle, several different platforms can be considered for this purpose [2], but so far, none of them have achieved the required scalability. Only recently, new possibilities emerged with the progress made in the optical tweezer technology. Optical tweezers are tightly focused laser beams that one can manoeuvre at will to move a trapped atom to an arbitrary position in the region of interest. Nowadays, large arrays of such tweezers can realise registers containing hundreds of atomic qubits, with quantum logic enabled via Rydberg blockade [3,4]. However, none of these experiments has been performed in the desired network setting, mainly because the cavity structure restricts the optical access required for the tweezers. In fact, despite long-standing efforts, only a few examples of cavity-coupled atoms trapped in arrays of tweezers have been reported. Nevertheless, all of them lack individual control over the quantum states of the atoms, a necessary requirement for the envisioned applications in a quantum network.

Here [5,6], we bring arrays of optical tweezers into a microscopic optical cavity and combine this with individual control over the atomic qubits, thereby demonstrating the potential of the platform for scalable quantum networks. We create one- and two-dimensional registers of up to 6 atoms and address each atom individually to generate atom-photon entanglement (APE) using vacuum Stimulated Raman Adiabatic Passages (vSTIRAP). Scalability comes from the observation that the APE fidelity remains constant as the number of qubits in the register increases parallel and perpendicular to the cavity axis. By implementing a multiplexing scheme, we generate APE with a source-to-detection probability of up to ~90% per attempt, an important step towards the deterministic distribution of entanglement across networks. All this is achieved by exploiting the advantages of a Fabry-Pérot cavity that allows for optical access in a thin sheet perpendicular to the symmetry axis.

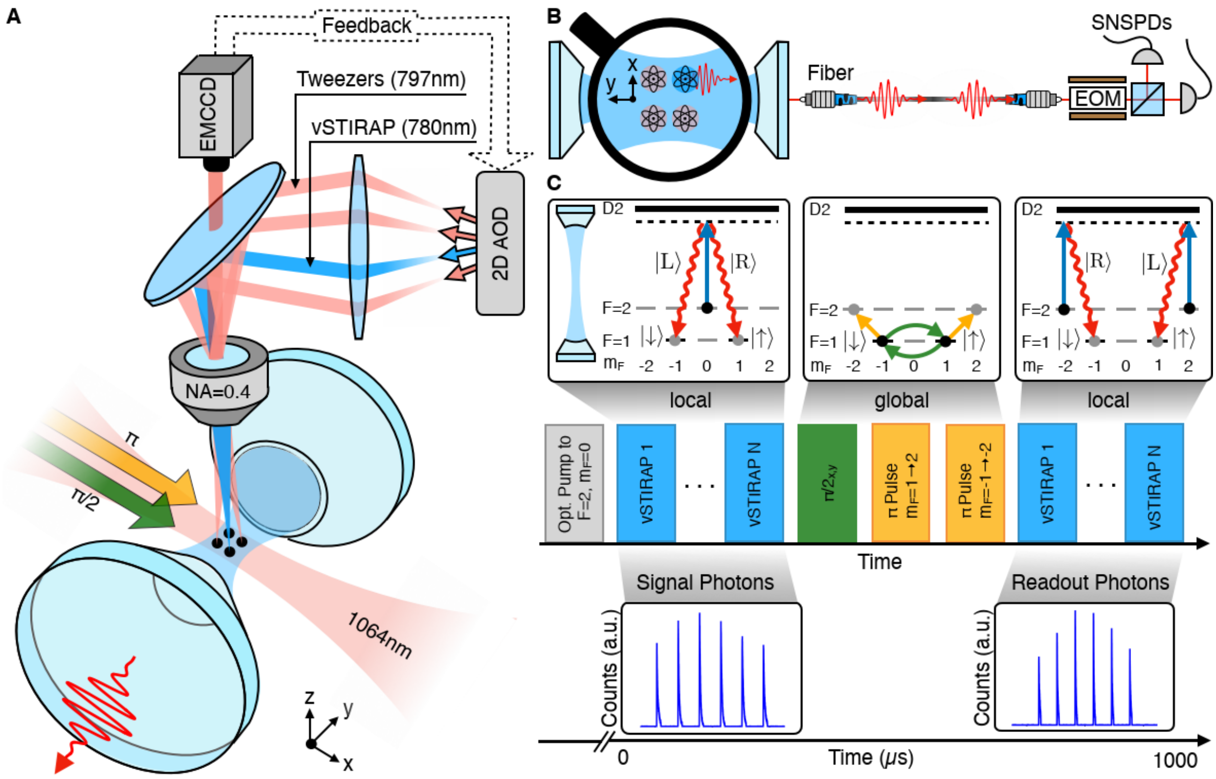

Fig. 1 Setup and Experimental Sequence Overview: (A) Tweezers and vSTIRAP lasers are directed onto individual atoms at the centre of the cavity using 2D-AODs to create and manage two-dimensional arrays of atoms. Atom positions are captured via an EMCCD camera. A feedback signal is sent to the 2D-AODs based on these images to arrange the atoms orderly. Following preparation, atoms are transferred to a 2D lattice created by a 1064-nanometer standing wave trap and a 770-nanometer intra-cavity standing wave trap. Transitions between the hyperfine ground states are driven by a global pair of Raman lasers. (B) Photons emitted into the cavity mode primarily exit through the outcoupling mirror and pass through an optical fibre and an electro-optical modulator (EOM), enabling the switching of the detection basis of the photons. The photons are then detected using highly efficient superconducting nanowire detectors. (C) Protocol for Atom-Photon Entanglement (APE) Generation: After optical pumping to |F=2, mF=0⟩, we sequentially apply N local vSTIRAP pulses to generate photons (signal photons). Global π/2 and π pulses establish the detection basis for the atom readout. Finally, N vSTIRAP pulses produce N readout photons

Example References

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