# Quantum science based on cavity-assisted atom-photon interactions

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A hybrid system of light and matter qubits might allow to scale quantum communication to large distances using quantum repeaters and to increase the number of qubits in quantum computation. To this end, we have experimentally realized a robust two-qubit gate that allows to link distant computational nodes [1, 2]. The gate mechanism is deterministic, robust and expected to be applicable to almost any matter qubit. It is based on reflecting the photonic qubit from an optical cavity containing a single trapped atom. We characterize the performance of the gate and show that hybrid entangled states can be created from separable input states. The versatility of the interaction mechanism is demonstrated via two further applications: The nondestructive detection of flying optical photons [3] and the heralded storage of a photonic quantum bit in a single atom [4]. Both are of great importance for the rapidly evolving research fields of quantum measurement, quantum computation, quantum communication, and quantum networks.

Our implementation of a robust photon detector is in stark contrast to all existing realizations, because it does not rely on absorption. Instead, the resonant interaction between an impinging photon and the atom-cavity system results in a phase flip of the atomic superposition state. After reflection of a pulse of light, the atomic state is rotated and detected via cavity-enhanced fluorescence [3]. This nondestructive detection facilitates repeated measurements of one and the same photon, which boosts the detection efficiency. It also signals the presence of a photon without affecting its unmeasured degrees of freedom, like its temporal shape or its polarization.

The hybrid quantum gate can also be employed to simultaneously herald the arrival of a photon and to map its quantum state onto the atom [4]. This is essential for many applications in quantum information processing. Photons can be used to distribute quantum information over distances so large that quantum nonlocality becomes a true resource. Nevertheless, they suffer from unavoidable losses. Therefore, in order to realize quantum networks and quantum communication on a global scale, successful transmission needs to be signalled and the information carried by the photon has to be stored in long-lived material particles. We have realized the heralded storage of photonic polarization qubits in a single atom based on the cavity QED interaction mechanism [1]. The protocol is depicted in Fig. 1. After reflection from the cavity, which performs the quantum gate, polarization-sensitive detection of the photon in a suitable bases heralds the state transfer. It is completed by quantum feedback in the form of a conditional state rotation applied to the atom. The reverse process, namely mapping a given atomic state onto the polarization of a photon, is achieved by swapping the roles of atom and photon. Several experiments have teleported the state of a photon into a quantum memory making use of two-photon interference, which is an alternative strategy for a heralded quantum state transfer. We demonstrate that our approach is not only more efficient but also inherently more robust against variations in the arrival time and wave-packet shape of the photon. This makes it ideally suited for the implementation of a long-distance quantum network and quantum repeater protocols under real-world conditions.

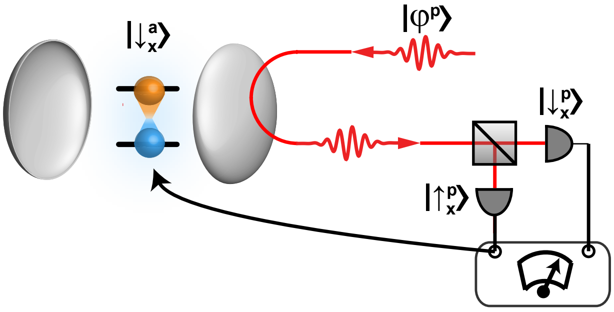

FIG. 1. Heralded storage of the polarization of a photon in a single atom is one of the quantum technologies enabled by cavity quantum electrodynamics. An $^{87}$Rb atom is trapped inside an optical cavity (grey spheres) and prepared in a superposition of two ground states forming the atomic qubit. The photon whose polarization state $|\varphi^p\rangle$ is to be stored is reflected from the atom-cavity system and detected in a polarization-sensitive setup. This signals the successful storage, which is completed by the conditional application of quantum feedback onto the state of the atom.

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