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Time entanglement between a photon and a spin-wave in a multimode solid-state quantum memory

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Abstract

In this presentation we will show our recent results about the direct generation of entanglement in time between a photon and a collective spin excitation in a rare earth ion doped ensemble. The entanglement is analyzed by mapping the atomic excitation onto a photonic qubit and by using time-bin qubits analyzers implemented with another doped crystal using the atomic frequency comb technique. The quality of the entanglement is high enough to enable a violation of a Bell inequality by more than two standard deviations. Our results provide a solid-state source of entangled photons with embedded quantum memory.

Light-matter entanglement is an important resource in quantum information science. It enables complementing the advantages of using photons as flying qubits in quantum communication schemes, with those of matter qubits, which are ideal for quantum storage and processing. A very convenient method to directly generate light-matter entanglement in atomic ensembles is the Duan-Lukin-Cirac-Zoller (DLCZ) protocol [1].

While several experiments have studied the DLCZ scheme in atomic gases [2], the use of atomic ensembles embedded in solid matrices, such as rare earth ion doped (REID) crystals, offers numerous advantages as the coherence times are comparable to those of cold atomic clouds but the natural trapping greatly simplifies the experimental setups. Moreover, the inhomogeneous broadening of the atomic transitions can be used as a resource for quantum information multiplexing. Only recently, the DLCZ scheme has been demonstrated in REID crystals [3, 4] where quantum correlation between single photons and a spin wave have been demonstrated by combining this scheme with the Atomic Frequency Comb technique (AFC).

In the present work, we use the AFC-DLCZ protocol to create entanglement between a single photon (the so-called Stokes photon) and a single collective spin excitation in a rare earth doped crystal, in the photon counting regime. We take advantage of the temporal multimodality of the AFC protocol to demonstrate entanglement in time. This is done by transferring the matter qubit onto a second photon (anti-Stokes photon), and by analyzing the two photons in a Franson like interferometer implemented with another REID crystal. The entanglement is demonstrated by observing high-visibility two-photon correlation in different bases by violating the CHSH Bell inequality with $S = 2.16 \pm 0.07$.

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