In contrast with the “classical” framework, quantum mechanics provides tools to understand and predict phenomena in the microscopic world. However, adoption of the classical or quantum description seems to not be simply a matter of the size of the system under study. Indeed, there exists an increasing amount of successful experiments demonstrating the quantum nature of macroscopic systems. In this work, we take one step further in this direction and demonstrate the generation of entanglement between a single photon and a macroscopic number of atomic excitations stored in an atomic ensemble embedded in a solid-state crystal host.

The first step in our experiment is to generate a signal-idler polarization-entangled photon pair via spontaneous down-conversion. We refer to this state as a “micro-micro” state. The second step is to displace one polarization mode of the signal photon using a pulsed coherent state, leading to a “micro-macro” state. We then store our displaced single photon into a rare-earth doped crystal using the atomic frequency comb protocol, thereby creating a light-matter micro-macro entangled state. To reveal this micro-macro entanglement, the state re-emitted by the memory is displaced back to the micro domain using a second tailored pulsed coherent state. Our scheme relies of the fact that displacement back to a microscopic scale is a local operation which cannot increase entanglement. Finally, we perform quantum state tomography of the output of the memory together with a Bell test of nonlocality. Our state is shown to violate Bell-CHSH inequalities for micro-macro states containing up to 10 photons per pulse on average before storage, and we show it is entangled for up to 85 photons in the displacement pulse.

Our results provide a new tool to address fundamental questions about entanglement involving large atomic ensembles and macroscopic quantum photonic states, and constitute a first step towards demonstrating nonlocality using macroscopic quantum states of light and matter.