Micro-macro entanglement between light and matter

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Quantum mechanics is undeniably a successful theory on all fronts. In contrast with the «classical» framework, it provides tools to understand and predict phenomena in the microscopic world. Adoption of the classical or quantum framework is not, however, a simple question of the size of the system under study. Additionally, there is no consensus on the meaning of macroscopicity, especially when entanglement is involved. Quantum optics is one of the main vehicles in the development of quantum information science and offer tools to study fundamental questions in quantum mechanics.

We experimentally demonstrate the presence of entanglement in the system involving «macroscopic» photonic states after storage in the solid-state quantum memory. The possibility to distinguish between two macroscopic components of the state makes it analogous to Schrödinger's cat state [1]. While the coupling to the atomic ensemble leads to the absolutely new physical quantum systems involving large number of the atoms and the photons at the same time which are entangled with microscopic object.

To generate entanglement involving two macroscopically distinguishable components the displacement operation in the phase space can be applied [2, 3]. For this a photon pair entangled in polarization was generated from spontaneous parametric downconversion

$$\frac{1}{\sqrt{2}}\left(\left|1_H,0_V\right\rangle_s\left|1_H,0_V\right\rangle_i+e^{i\theta}\left|0_H,1_V\right\rangle_s\left|0_H,1_V\right\rangle_i\right), \quad (1)$$

where s and i are two modes corresponding to the generated signal and idler photon, respectively. To amplify one of the polarization modes the signal photon is combined on the high transmission non-polarizing beam splitter with the local oscillator. In the limit of high transmittance this corresponds to the unitary displacement operation $\mathcal{D}_s(\alpha_H)$ in the phase space, where H is the polarization state of the local oscillator and s is the spatial mode of the signal photon. The displaced polarization entangled state can be written

$$\frac{1}{\sqrt{2}}\Big(\mathcal{D}_s(\alpha_H)\left|1_H,0_V\right\rangle_s\left|1_H,0_V\right\rangle_i+ \\ +e^{i\theta}\left|\alpha_H,1_V\right\rangle_s\left|0_H,1_V\right\rangle_i\Big). \quad (2)$$

The displacement operation $\mathcal{D}_s(\alpha_H)$ is based on the interference effect, which means that the state (2) contains the displaced single photon state $\mathcal{D}_s(\alpha_H)\left|1_H,0_V\right\rangle$ and the coherent state combined with the single photon with perpendicular polarizations $\mathcal{D}_s(\alpha_H)\left|0_H,1_V\right\rangle$. In the limit of high α these two states could be distinguished by the detectors resolving just large photon number differences [1]. It is possible because displaced single photon state is a non-Gaussian state and is characterized by a photon number distribution with a mean photon number $|\alpha|^2+1$ and a variance $3|\alpha|^2$. In the limit of large $|\alpha|$ probability to distinguish their photon number distributions reaches 74% [1].

To store this state the Atomic Frequency Comb (AFC) quantum memory protocol was used. Thanks to the periodic profile of the AFC in frequency space, the atoms absorbed input photonic state then collectively interfere after a specific time, which can lead to re-emission of the state into the same spatial mode it was absorbed in. We implement the AFC quantum memory protocol using rare-earth ion doped Nd^{3+}:Y_2SiO_5 crystals [4].

The presence of entanglement after storage is done after displacing macroscopic state 2 back to the micro domain. Then it was proven by performing Clauser-Horne-Shimony-Holt inequality violation and quantum state tomography. Entanglement between two components involving up to ≈ 100 photons in average was generated and stored inside a quantum memory. This could be seen the presence of entanglement ≈ 40 atomic excitations inside the crystals right after the absorption which are entangled with the idler photon.

Due to the high phase noise sensitivity such states could be very useful to probe decoherence mechanisms of the quantum systems including quantum memories. As the first experimental demonstration of the macroscopic quantum state storage using atomic ensemble inside the crystals, our work paves the way to experimentally explore quantum entanglement involving large number of atoms and macroscopic quantum photonic states.

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[1] P. Sekatski, N. Sangouard, M. Stobińska, F. Bussières, M. Afzelius, and N. Gisin, Phys. Rev. A **86**, 060301 (2012)
[2] N. Bruno, A. Martin, P. Sekatski, N. Sangouard, R. T. Thew, and N. Gisin, Nat. Phys. **9**, 545 (2013).
[3] A. I. Lvovsky, R. Ghobadi, A. Chandra, A. S. Prasad, and C. Simon, Nat. Phys. **9**, 541544 (2013).
[4] F. Bussières, C. Clausen, A. Tiranov, B. Korzh, V. B. Verma, S. W. Nam, F. Marsili, A. Ferrier, P. Goldner, H. Herrmann, C. Silberhorn, W. Sohler, M. Afzelius, and N. Gisin, Nat. Photon. **8**, 775 (2014).