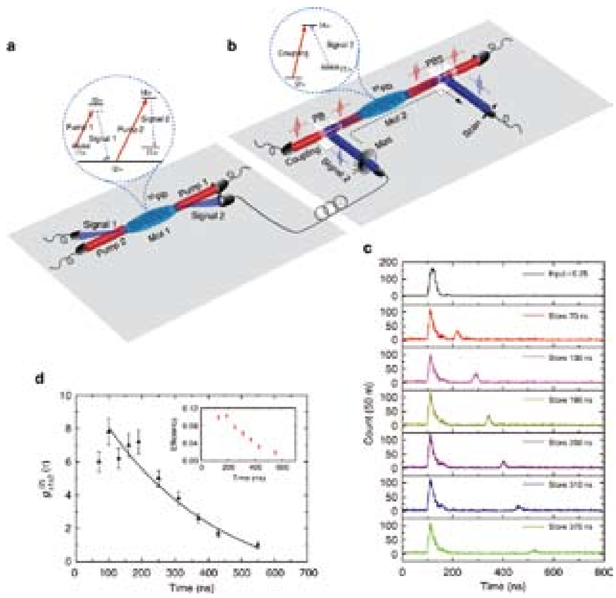
USTC Develops the First Quantum Memory that Records Orbital Angular Momentum of a Single Photon

Scientists from the CAS Key Laboratory of Quantum Information based at the University of Science and Technology of China (USTC) in Hefei have achieved significant progresses in developing high-dimensional quantum memory. Under the leadership of Prof. GUO Guangcan and Prof. SHI Baosen, they achieved the storage and release of a single photon with a spatial structure, which carried the orbital angular momentum (OAM) in a cold atomic ensemble for the first time. It demonstrated the possibility of high-dimensional quantum memories, and marked the first step towards long-distance quantum communication with large information-carrying capability based on high-dimensional quantum repeaters.

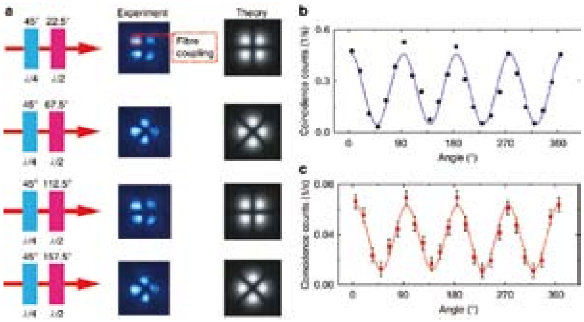
Usually, quantum information is encoded in a two-dimensional space spanned, for instance, by orthogonal polarizations of a photon. Each photon can carry 1 bit information. However, if the photon could live in a higher dimensional space, say one spanned by the inherently infinite-dimensional OAM, then the information it carries would increase significantly (from 1 bit to $\log_2 d$ bits). Moreover, compared with a two-dimensional state, high-dimensional states show many interesting properties, including more efficient quantum-information processing and more secure flux of information in quantum key distribution.

Quantum repeaters are indispensable for extending transmission distance and improving the efficiency of quantum information processing, and quantum memory is a key component of quantum repeaters. If scientists can realize the reversible transfer of a high-dimensional quantum state between a true single photon and a matter used as a quantum memory with high fidelity and reliability, they may find a final solution to reduce transmission losses and enhance channel capacity. The construction of such a quantum memory is a hot topic and big challenge in the world. Before this study, there had been no work reported on the storage of a photon encoded in a high-dimensional space in any physical system.



A heralded single photon is generated through the spontaneous four-wave mixing in Mot 1 (a). Then this single photon, which imprint a special structure and carry OAM by a spiral phase plate, is stored through electromagnetically induced transparency in Mot 2 (b). (c) is the image the photon carries. Scientists experimentally measure the image carried by the photon before storage and after that along the transverse position, and the results are shown in (d) and (e) respectively, exhibiting strong similarity. The solid lines are theoretical fits. *(Image by SHI Baosen's Group)*

Prof. SHI Baosen and his coworkers have been working on the storage of a photon carrying a spatial structure for quite a while (see *PRA*, 87, 013835, 013845, 053830, (2013)). Recently, they scored a major progress by making the first experimental realization of a true single-photon-carrying OAM stored via electromagnetically induced transparency (EIT) in a cold atomic ensemble. In the experiment, they prepared two cold atomic clouds by laser cooling and trapping techniques in two magnetic-optical traps. They used one atomic cloud as a nonlinear media to prepare a heralded single photon. Then this single photon, which imprinted a special structure and carried



Storage of a superposition of OAM. (a) Rotated interference patterns at different angle settings of the half-wave plate. The left column represents the experimental angle settings of the half-wave and the quarter-wave plates. The middle column is the experimental results and the right column is the theoretical simulations; (b) interference pattern of the input signal photon as a function of plate angle; (c) interference of retrieved signal with plate angle. Blue and red lines are fits of sinusoid *sin(4θ)*. *(Imaged by SHi Baosen's Group.)*

OAM by a spiral phase plate, was stored through EIT in the second atomic cloud and retrieved after a programmed storage time. It turned out that the single photon with OAM was stored with high fidelity, when with the help of a well-designed Sagnac interferometer and quantum tomography technique, the superposition state of OAMs carried by the photon was also well preserved during the storage.

These results were firstly published on the academic website of arXiv (arxiv: 1305: 2675) and immediately attracted world's attention. The famous *MIT Technology Review* declared that "the world's first quantum memory that stores the shape and structure of single photons has been built in a Chinese lab". Reviewers of *Nature Communications* hailed the study as an "extremely impressive work", "establishing a very high standard in the rapidly growing field of quantum memories". "In fact, the authors could have probably split the results into two papers. But taken together, this demonstration of the ability to generate, store, and read out on-demand, arbitrary OAM qubits encoded onto true single photons, represents an exciting watershed in the development of quantum-enabled technologies. The results will have a large impact within the quantum information and quantum atom optics communities, and should be of general interest to a wider physics audience," a reviewer wrote, "and I look forward to the future results from this research group."

The results were published in *Nature Communications* online on October 2, 2013.

Members of Prof. SHI's group (from right): PAN Jiansong, ZHOU Zhiyuan, ZHANG Wei, Prof. SHI Baosen, LI Yan, ZHOU Zhonghao, SHI Shuai and DING Dongsheng.