# Experimental Demonstration of Quantum Wrenching Orbital Angular Momentum Memory

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**Abstract:** The complex interactions between orbital angular momentum (OAM) light and atoms are particularly intriguing in the areas of quantum optics and quantum information science, allowing us to construct OAM-based applications, including quantum memory, quantum cryptography, quantum sensing and etc. In the previous works, it is difficult to achieve asymmetric OAM quantum interface between photon and memory, thus restricting the breakthrough of extending OAM applications in the quantum information field. Here, we experimentally demonstrate a quantum wrench, a method of freely generating asymmetric quantum interface between a photon and a memory in OAM space. With twisted fields of pumping, the correlated OAM distribution between emitted photon and the spin wave can be encoded versatilely, and stretched in radial direction. By this method, the quantum interface can be multiplexed and can work in high-quanta scenario with capability of $|l|$=30, and we demonstrate the entanglement within 2-D subspace with a fidelity of 80.5±4.8%. Such state-of-the-art technology to wrench OAM memory in quantum regime is very helpful to construct high-dimensional quantum networks and provides a benchmark in the field of actively developing methods to engineer OAM single photon from matters.

## 1. Introduction

The interaction between orbital angular momentum (OAM) of structured light and the matters has many intriguing applications [1], including trapping of particles [2, 3] and measuring rotation angular [4, 5] and OAM-based imaging [6]. In the quantum information field, photon carried with OAM can be coherently mapped into atomic ensemble, thus resulting in OAM-based quantum memory [7]. In this area, some progresses on OAM-based quantum memory are recently reported, for example, building a 3-dimensional OAM entanglement between atom and single photon [8], quantum storing OAM qubit [9, 10], 3-dimensional (3-D) OAM entanglement [11] or 2-D [12] and high-D OAM entangled quantum memories [13, 14]. Exploring a versatile OAM quantum interface between photon and memory would attract many people in this field for a long time.

Constructing a versatile OAM quantum interface would be significantly helpful to build an OAM-based quantum network based on Duan-Lukin-Cirac-Zoller (DLCZ) protocol [15] where probabilistically generated atom-photon OAM entanglement is stored in the DLCZ-type memory, or based on directly quantum storage schemes [16, 17]. Usually, the quantum interface between photon and the memory is achieved in symmetric photonic path [18-21], polarization (H/V polarization) [22, 23]. However, the adjacent nodes in quantum networks may be different, for example, one is encoded in $\pm l$ OAM spaces and the other one is in $\pm(l+m)$ OAM spaces; or one is encoded in polarization while the other one is in OAM space [24], thus needing a technology of quantum wrench (given in Fig. 1(a)) to make the quantum interface asymmetric and then connect them [25]. For different degrees of freedom, like polarization and OAM, it is promising to build hyper-entanglement and hybrid-entanglement [14, 24] to connect different quantum nodes encoded in polarization and OAM spaces respectively. However, in high-D OAM space, there are no reports about how to create an asymmetric quantum interface that can conveniently match the quantum nodes encoded in different OAM modes [11-12, 26-28]. The mismatch between quantum interfaces of photon and atom could be resolved by a quantum wrench which can change the properties of quantum system toward what we want, such as the spiral bandwidth, correlated eigenmode of photons and so on. Here, we demonstrate a quantum wrench that can freely tune the spiral bandwidth of the interface of single photon and atom, in which the OAM spectrum of the quantum interface is broadened, and the high-quanta OAM interface could be accessible.

We use a write-laser beam carrying OAM mode to excite atoms through spontaneous Raman scattering (SRS), and have generated the photon-atom entanglement and stored it in DLCZ memory. After a programmable storage time, we open the read-laser beam carrying OAM to retrieve the atomic spin-wave to Signal photon and check the entanglement between two Signal photons. The measurements of the OAM writing and reading processes are non-intuitively dependent on the post-selected quanta of OAM, showing an asymmetrical entanglement distribution, although the angular momentum conservation condition is satisfied completely. In addition, the spiral bandwidth of prepared OAM quantum interface is broadened. Based on that, firstly, we have achieved a 4-dimensional entanglement with *l* up to 16 and checked the entanglement by dimensionality witness method, with a violation of 3 standard deviations. Then, we increase the quanta of OAM of write-laser beam and store a high-quanta OAM entanglement with *l* up to 30. Finally, we check the entanglement by quantum state tomography with fidelity of 80.5±4.8% and violation of Clauser-Horne-Shimony-Holt (CHSH) inequality by the value *S* of 2.22±0.07, which certificates that we have successfully stored a high-quanta OAM entangled state in our memory. By achieving the quantum memory of high-quanta OAM entanglement, it can be useful for realizing higher-dimensional quantum memory and increasing the capacity of quantum communication, and is a benchmark of searching ways to explore the versatile quantum interface.

## 2. Basic theory

In this section, in order to demonstrate quantum wrenching effect of quantum interface in DLCZ memory, we input the write-laser with OAM quanta of $l_W$. Due to the fact that SRS process conserves angular momentum, we have created OAM entanglement between Signal 1 and atomic spin wave, which can be specified by the formula

$$\left|\psi\right\rangle_{photon-atom}^{l_W} = \sum_{l=-\infty}^{l=\infty} c_l \left|l\right\rangle_{S1} \otimes \left|l_W - l\right\rangle_a \tag{1}$$

Here, $\left|c_l\right|^2$ represents excitation probability, $\left|l\right\rangle_{S1}$ represents the OAM eigenmode of Signal 1, with quanta of l. $\left|l_W - l\right\rangle_a$ is the OAM eigenmode of atomic spin wave, with quanta of $l_W - l$. Through this method, the atomic spin wave could carry the arbitrary OAM topological charge with the term of $l_W - l$, the resulting in an asymmetric quantum interface.

After a period of storage, we check photon-atom entanglement by inputting read-laser with OAM quanta of $l_R$, and checking the entanglement between Signal 1 and Signal 2. The entanglement between Signal 1 and Signal 2 can be written as

$$\left|\psi\right\rangle_{photon-photon}^{l_W, l_R} = \sum_{l=-\infty}^{l=\infty} c_l \left|l\right\rangle_{S1} \otimes \left|l_W + l_R - l\right\rangle_{S2} \tag{2}$$

At first, we set $l_W$=2 and $l_R$=0, it means using OAM quanta of 2 and 0 to write and read respectively. Thus, the photonic entangled state is a sum of $\left|l\right\rangle_{S1} \otimes \left|2-l\right\rangle_{S2}$ with different l, this is a modulated asymmetric OAM entangled state. Here, we only post-select the OAM mode of entangled state into two-dimensional subspace $\left|0\right\rangle_{S1}\left|2\right\rangle_{S2}$ and $\left|2\right\rangle_{S1}\left|0\right\rangle_{S2}$, that is

$$\left|\psi\right\rangle_{photon-photon}^{2,0} = 1/\sqrt{2}\left(\left|0\right\rangle_{S1}\left|2\right\rangle_{S2} + \left|2\right\rangle_{S1}\left|0\right\rangle_{S2}\right). \tag{3}$$

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