On-Demand Generation of Entangled Multiphoton States

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Abstract: We demonstrate gigahertz rate, deterministic generation of long strings of polarization-enetangled photons and photonic cluster states. We use repeated timed excitation of a semiconductor quantum dot-confined dark exciton, which entangles the sequentially emitted photons.

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We present the first experimental realization of a prototype device capable of on-demand generation of entangled multi-photon states. Our practical realization is based on an ideal protocol originally proposed in [1]. In that proposal, the quantum dot (QD)-confined electron is repeatedly excited optically in synchronization with the electron precession in an externally applied magnetic field. The polarization state of the sequentially emitted photons resulting from the optical excitations are entangled with the precessing electron spin and, as a result, entangled also with the polarization states of the photons which were previously emitted. In our practical realization, we replaced the electron by a QD-confined dark exciton (DE) [2–4], and thereby did not have to apply an external magnetic field.

We begin by describing an idealized form of the protocol, which is summarized in Fig. 1(a). First, the DE is deterministically generated in a spin eigenstate by a short π-area picosecond pulse [4]. The initialization pulse, represented in Fig. 1(a) by an upwards green arrow, prepares the DE in an eigenstate $|\Psi_{\mathrm{DE}}^{\mathrm{init}}\rangle = (|+2\rangle - |-2\rangle)/\sqrt{2}$ where $|+2\rangle$ and $|-2\rangle$ are the DE spin projections on the symmetry axis of the QD (Fig. 1(b)). In the circuit diagram of Fig. 1(c), this preparation is represented as a Hadamard gate (H). Immediately after the initialization, the cycle for sequentially generating the photonic cluster state begins. One cycle of this protocol contains three elements: 1) a converting laser pulse that coherently converts the DE population to a biexcitonic population (teal upward arrow), 2) subsequent radiative recombination of this biexciton, resulting in emission of a photon (magenta downward arrow) and an entangled DE which remains in the QD, and 3) timed precession of the DE spin. This cycle can be applied multiple times to generate a multiphoton cluster state. One cycle is indicated in the circuit diagram in Fig. 1(c) by a dashed rectangle.

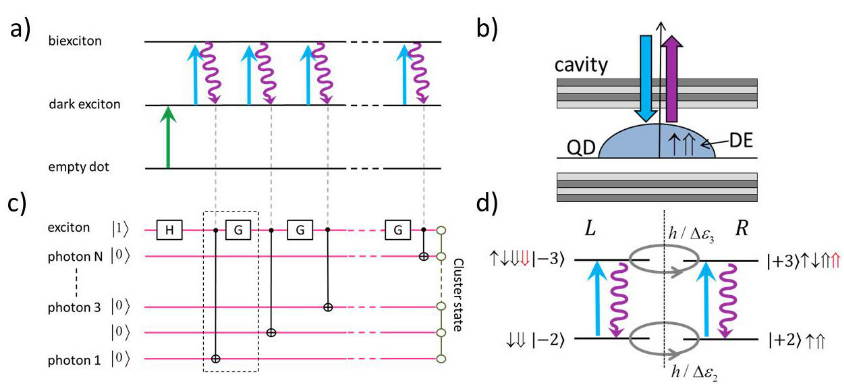

Fig. 1. (a) The experimental scheme. (b) A dark exciton (DE) in a quantum dot (QD). (c) The equivalent quantum circuit diagram. (d) The selection rules between the DE states ($|\pm 2\rangle$) and the biexciton states ($|\pm 3\rangle$). Excitation is indicated by upwards arrows, emission by downards arrows, and precession by grey circular arrows.

A horizontally polarized π-area pulse, resonantly tuned to the DE-biexciton optical transition, “converts” the DE coherent state into a coherent biexciton state: $|\Psi\rangle_{\mathrm{BiE}} = (|+3\rangle - |-3\rangle)/\sqrt{2}$. Radiative recombination of this biexciton results in an entangled state of the emitted photon polarization and the dark exciton spin [3], $|\Psi\rangle_{\mathrm{DE-Ph_1}} = (|R_1\rangle|+2\rangle - |L_1\rangle|-2\rangle)/\sqrt{2}$, where $|R_1\rangle$ ($|L_1\rangle$) is the first photon right (left) hand circular polarization state. The excitation and subsequent photon emission, are represented in Fig. 1(c) by a vertical line or a CNOT gate between the DE and the emitted photon. The DE spin state then continues to precess (around the "x axis" in terms of the states $|\pm 2\rangle$) for three quarters of a precession period. The precession is represented by the single qubit gate G in Fig. 1(c). The sequential application of the CNOT and G gates form one full cycle in our protocol. In the beginning of the next cycle, the DE is re-excited [2,3] to the biexciton state. The recombination of the second biexciton then results in emission of a second photon, whose polarization state is entangled with that of the first photon and the spin of the remaining DE, yielding the state

$$|\psi\rangle_{\mathrm{DE-Ph_1-Ph_2}} = \left[|R_1\rangle|R_2\rangle|+2\rangle - |L_1\rangle|L_2\rangle|-2\rangle - i|L_1\rangle|R_2\rangle|+2\rangle + i|R_1\rangle|L_2\rangle|-2\rangle\right]/2, \quad (1)$$

which is followed by precession of the DE. The re-excitation-emission and subsequent precession cycle can, in principle, be repeated indefinitely, generating a one dimensional string of polarization-entangled photons, as shown in the equivalent circuit diagram of Fig. 1(c). To demonstrate that our device deterministically generates entangled photons, we perform three photon intensity correlation measurements. We perform tomography on two photons emitted from two cycles of the cluster state generation protocol, together with a projective measurement of the DE spin on the $|+2\rangle$ state. Assuming the idealized form of the protocol and following Eq. (1), projecting the DE on the $|+2\rangle$ state yields the following two photon state

$$|\psi\rangle_{\mathrm{Ph_1-Ph_2}} = \tfrac{1}{2}\left[|R_1\rangle(|R_2\rangle - |L_2\rangle) - i|L_1\rangle(|L_2\rangle + |R_2\rangle)\right) = \tfrac{-i}{\sqrt{2}}\left(|R_1\rangle|V_2\rangle + |L_1\rangle|H_2\rangle\right) \quad (2)$$

which is a maximally entangled state of two photons. In Fig. 2(a), the measured polarization density matrix of the first two emitted photons, conditioned on the projective DE measurement, is presented. The density matrix has a negativity of 0.26 ± 0.07, clearly indicating entanglement. Comparison of this two-photon density matrix to the pure state appearing in Eq. (2) yields a fidelity of 0.74. In conclusion, we provide experimental demonstration of a prototype

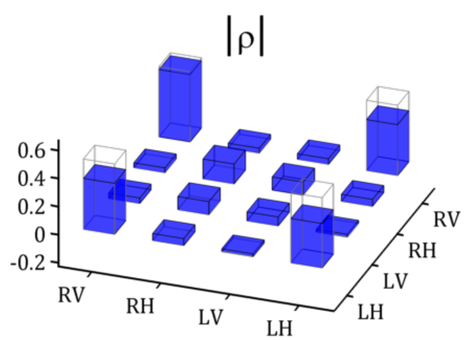

Fig. 2. Two-photon density matrix showing the quantum state in Eq. (2) and demonstrating the cluster state generation protocol from [1].

device for generating a deterministic, scalable, one-dimensional photonic cluster state [1]. The device is based on a semiconductor quantum dot and utilizes the spin of the dark exciton as an entangler.

References

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