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Towards a Source of Multi-Photon Entangled States for Linear Optical Quantum Computing

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Abstract

In this work we propose a scheme to generate a stream of entangled and indistinguishable photons based on recent advances in cavity enhanced resonance fluorescence from quantum dots in optical microcavities. Such a source of entangled states is crucial for the development of a linear quantum optical quantum computer. We demonstrate a proof of principle experiment of our proposal by showing that the time bin of a single photon is dependent on the measured state of the spin of the charge trapped in the quantum dot.

1. Introduction

Photons are known to suffer little from decoherence, which makes them good candidates for the transfer of quantum information. At the same time, the weak photon-photon interaction responsible for this robustness towards decoherence means that it is experimentally challenging to implement multi-photon gates needed for information processing. Linear optical quantum computing is an approach proposed to overcome this difficulty, which takes advantage of the Hong-Ou-Mandel (HOM) effect to introduce probabilistic photon-photon interactions [1]. It was shown to be scalable in the seminal publication but requires an infeasible number of optical components. Proposals to reduce the experimental overhead by exploiting entanglement for measurement based quantum computing coupled with advances in integrated photonic circuits bring this closer to an experimental reality [2]. A particularly interesting proposal for the generation of the required entangled states is that of Lindner and Rudolph [3]. Therein they suggest repeatedly exciting a semiconductor quantum dot (QD) containing a single charge resonantly. Under a magnetic field in Faraday geometry, scalable entangled states encoded in polarization can be generated. A recent experiment has demonstrated a similar implementation using a dark exciton instead of a trapped charge, proving the validity of the scheme [4]. Here, we propose a modification of the scheme in Ref. [3] to entangle photons in the time bin basis rather than the polarization basis, making the entangled states more robust and suitable for use with optical fibre and integrated optical circuits.

2. Proposed Scheme

Our proposed scheme works with a QD containing a single charge, embedded in a pillar microcavity. Under a Voigt magnetic field the system takes the form of a double lambda system, as presented in Fig. 1, where one of the vertical transitions is selectively enhanced by the cavity. The Zeeman-split hole (trion) states are denoted by $|h\rangle$ and $|\bar{h}\rangle$ ($|T\rangle$ and $|\bar{T}\rangle$). The desired state is build up by repeated excitation of this system. The microcavity provides a high collection efficiency, as well as allowing fast spin preparation.

Two laser fields are used to control the state. A laser resonant with the enhanced transition is used to initialize the hole spin state in $|h\rangle$, to generate single photons by means of resonance fluorescence, and to read out the final spin state. Pulses from a red-detuned Ti:Sapphire laser

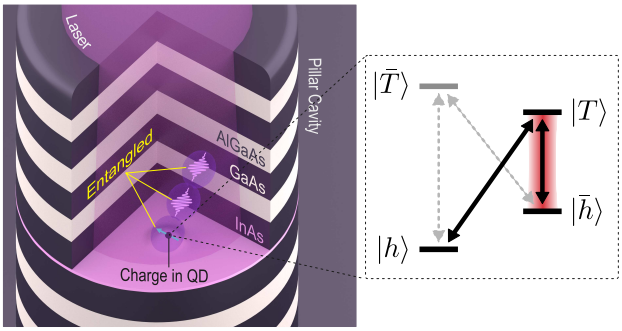

FIG. 1. Artist impression of the investigated system. A semiconductor quantum dot charged with a single hole in a Voigt magnetic field is driven resonantly with a laser. With the appropriate pulse sequence a stream of entangled single photons could be generated. The inset shows the energy levels for this singly-charged dot. All transitions are allowed but the vertical transition $|T\rangle \rightarrow |\bar{h}\rangle$ is enhanced by the cavity.

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are used to rotate the spin state [5]. After initialization, a $\pi/2$ spin rotation pulse creates a superposition of the spin state. Subsequently applying a short resonant pulse generates a photon in the first time bin conditional on the spin being in the $|\bar{h}\rangle$ state, yielding the total state

$$(|h\rangle\,|0_{\tau=1}\rangle + |\bar{h}\rangle\,|1_{\tau=1}\rangle)/\sqrt{2}. \tag{1}$$

A π pulse is then used to flip the spin, and a second resonant pulse generates the photon in the second time bin, giving

$$(|\bar{h}\rangle\,|1_{\tau=2}0_{\tau=1}\rangle - |h\rangle\,|0_{\tau=2}1_{\tau=1}\rangle)/\sqrt{2}. \tag{2}$$

This last sequence of pulses can be repeated to add more time bins. After two repetitions the state becomes

$$\begin{aligned}(\,&|h\rangle\,|1_{\tau=6}0_{\tau=5}1_{\tau=4}0_{\tau=3}1_{\tau=2}0_{\tau=1}\rangle + \\ &|\bar{h}\rangle\,|0_{\tau=6}1_{\tau=5}0_{\tau=4}1_{\tau=3}0_{\tau=2}1_{\tau=1}\rangle)/\sqrt{2}.\end{aligned} \tag{3}$$

After the sequence is complete a final $\pi/2$ spin rotation and resonant driving are used to perform a measurement in the $|\pm\rangle = \frac{1}{\sqrt{2}}(|h\rangle + |\bar{h}\rangle)$ basis. Assuming the spin is measured to be in the $|+\rangle$ state, the photonic state is $(|1_{\tau=6}0_{\tau=5}1_{\tau=4}0_{\tau=3}1_{\tau=2}0_{\tau=1}\rangle + |0_{\tau=6}1_{\tau=5}0_{\tau=4}1_{\tau=3}0_{\tau=2}1_{\tau=1}\rangle)/\sqrt{2}$. Rewriting this state using a photon in an odd numbered time bin to be a logical 1 and a photon in an even numbered time bin as a logical 0 yields $(|111\rangle + |000\rangle)/\sqrt{2}$ - a 3 photon GHZ state. The same principle can be used to produce a cluster state by introducing additional spin rotations [3].

3. Proof of Principle Experiment

We perform experiments following the outlined procedure, demonstrating spin rotations and high fidelity spin initialization within 5 ns. Fig. 2a shows the employed laser pulse sequence. It is worth noting that we use a third laser in order to probabilistically introduce a charge in the dot, as the sample is undoped. The pulse sequence is repeated at 80 MHz for an hour and each photon detection is time-tagged. Fig. 2b presents the extracted correlations between the windows marked in Fig. 2a. The degree of correlation is defined as the number of coincidences between these time windows within the same sequence repetition, normalized by the amount of coincidences between the same windows on different repetitions. This data clearly shows that the time bin of the photon is determined by the spin state. For sequence A, where the system is measured in the $|\bar{h}\rangle$ state, there is a probability of $g^{(2)}_{2,R}(0)\,[(g^{(2)}_{1,R}(0) + g^{(2)}_{2,R}(0)]^{-1} \approx 0.77$ that the photon (if measured) will be in the second time bin. However, the situation is reversed for pulse sequence B, where an additional π spin rotation means the measurement is performed in the $|h\rangle$ state and the probability that the photon is measured in the first time bin is ≈ 0.68.

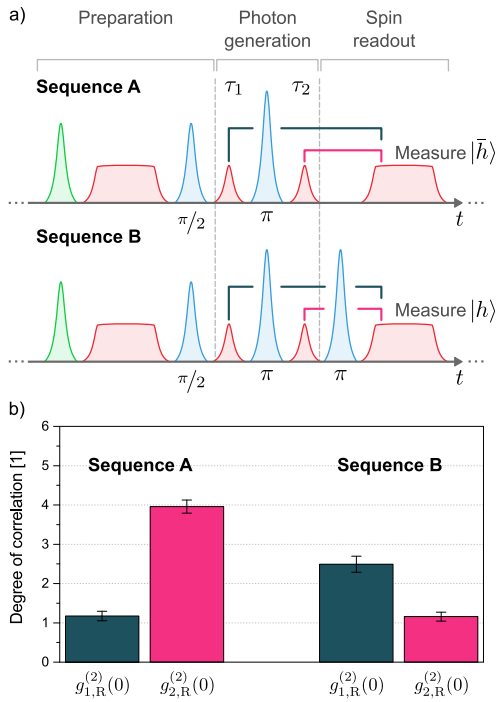

FIG. 2. **a)** Pulse sequences for the generation of a time-bin encoded photon entangled with the hole spin. Green: non-resonant laser, red: resonant laser, blue: spin rotation laser. **b)** Measured degree of correlation between photon generation pulses and readout pulses for each of the sequences in a).

4. Conclusions

We have presented a new scheme for generating entangled, time-bin encoded multi-photon states. Experimentally, we have demonstrated complete coherent control of a trapped hole spin via multi-pulse sequences and shown that the time bin of the generated photons is dependent on the measured state of the spin. From previous experiments we expect these photons to be highly indistinguishable and thus suitable for HOM based operations. Modifications to the setup are required to quantify entanglement fidelity but this paves the way towards generating chains of indistinguishable entangled photons.

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