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D2.3 Report: Multi-photon entanglement from a quantum dot

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1. Abstract

One-way all-photonic quantum repeaters offer a potentially advantageous route to long distance quantum communication with high rates of communication without the use of quantum memories [1]. In such schemes, the quantum state is encoded in a large cluster state of entangled photons which acts as an error correction code for photon loss. The crucial component for this approach is an on-demand source of entangled photons with high fidelity, photon indistinguishability and low optical loss. Here, we report on theoretical and experimental progress towards exploiting a single solid-state quantum dot (QD) as a source of multi-photon entanglement. First, we summarize the pursued time-bin entanglement protocol. Then we describe the experimental setup and summarize the obtained experimental results including the verification of spin-photon entanglement. The main experimental results have been submitted for publication and can be viewed in the pre-print arXiv:2111.12523

2. Keyword list

Quantum dot, single emitter, multi-photon entanglement

3. Acronyms & Abbreviations

DoA	Description of Action
EC	European Commission
WP	Work Package
QD	Quantum dot
PCW	Photonic crystal waveguide
GHZ	Greenberger–Horne–Zeilinger

4. Introduction

This report concerns the development of a scalable source of spin multi-photon entanglement for quantum repeaters (Task 2.3). To achieve a scalable source we have employed QDs embedded into nanophotonic structures such as photonic crystal waveguides (PCWs). QDs offer state-of-the-art single-photon emission in terms of single-photon purity, indistinguishability and emission rate, and the nanostructures further enhance the light-matter coupling and internal collection efficiency. Furthermore, QDs can be charged with a single spin-possessing charge carrier, which acts as a stationary matter qubit and can be controlled to ensure entanglement of the emitted photons.

An overarching goal has been to study how entanglement generation may be efficiently scaled to a large number of entangled photons. We have considered several entanglement protocols and encoding schemes and have settled on a time-bin entanglement protocol to best overcome the intrinsic limitations present in QD (such as short spin dephasing time). As a proof-of-principle, we have implemented the first step of the protocol experimentally and showed genuine spin-photon entanglement. This experiment can readily be scaled to a high number of photons given realistic improvements to photon collection efficiency and spin control fidelity.

5. Results

5.1. Protocol

Our chosen entanglement protocol uses a dual-rail encoding where each photon is emitted in one of two temporal modes separated by (in the case of our experiment) 12 ns. By applying a sequence of optical π-pulses and Raman spin rotation pulses, the photon emission time is maximally entangled with the quantum state of the optically active spin. By repeating this sequence *N* times, one can generated states containing one spin and *N* photons entangled as a one-dimensional cluster state or a Greenberger–Horne–Zeilinger (GHZ) states. We have theoretically studied the protocol extensively and quantified the relevant errors as described in our publications [2,3]. In particular, we show that the protocol offers immunity to the strong inhomogeneous spin dephasing which has limited previous QD experiments. An additional novelty of our approach is the use of the photonic crystal waveguide (PCW) to enhance the optical cyclicity of the QD while retaining all-optical spin initialization, control and readout. This approach has been successfully demonstrated experimentally [4].

5.2. Setup and regime

All experiments are done using the same QD and the same experimental setup. The QD is held at T = 4K in a closed-cycle cryostat and a 2 T magnetic field is applied perpendicular to the QD growth direction. The QD emits photons at a 950 nm wavelength with 0.4 ns lifetime. Light is coupled from the waveguide into a single-mode fiber using a shallow etch grating coupler. We currently achieve an estimated 1% source to fiber coupling, which we expect to improve significantly based on results achieved on similar PCW structures. The single-photons are detected using superconducting nanowire single-photon detectors.

5.3. Entanglement visibility

We run the time-bin entanglement once to create a maximally entangled spin-photon Bell state where the photon is time-bin encoded. We measure the spin-photon Bell state in the ZZ, XX and YY basis to evaluate the fidelity. Data is post-selected on measuring the photon and spin. Running the experiment at a 1.65 MHz repetition rate yields a 124 Hz spin-photon coincidence rate. The time-bin photon is measured using a double-pass Franson interferometer. The spin state is measured using a combination of Raman pulses and resonance fluorescence readout. Performing this experiment yields a (67.8 **±** 0.4)% fidelity of the generate maximally entangled state. This fidelity is largely limited by the optical Raman pulses (~89% π-pulse fidelity) used for spin control. In our current sample, Raman pulses result in rapid spin-flips between the two spin ground states which limit the control fidelity. Significantly better spin control has been achieved in the literature (99% in [5]) and we consider this obstacle to be resolvable. The detrimental role of spin-flips has been further confirmed by Monte Carlo simulations, which closely replicate the experimental detection patterns.

5.4. Spin coherence

To further characterize the setup we measure the coherence properties of the spin. We charge the QD with a single hole spin which results in reduced hyperfine-interactions compared to the electron spin and prolongs the spin dephasing time T2*. Using a spin echo sequence, we estimate a spin dephasing time $T_2^* = (23 \pm 1.3)ns$ and a spin coherence time $T_2 = (448 \pm 37)\ ns$. Prolonged dephasing times can be increased using higher magnetic fields [5] or nuclear spin cooling [6]. However, spin coherence does not currently limit the entanglement generation owing to the protocol's built-in spin echo.

5.5. Single-photon properties

Finally we investigate the coherence properties of the emitted photons. We measure the single-photon purity and indistinguishability under the exact same conditions as the entanglement generation and measure a $g^{(2)}(0) = (4.7 \pm 0.6)\%$ intensity-autocorrelation and a raw $V_{HOM} = (86.5 \pm 0.6)\ \%$ Hong-Ou-Mandel visibility. These values are mainly limited by multi-photon emission during the optical excitation pulses. Applying a higher magnetic field should permit faster excitation pulses and a reduced $g^2(0)$. When correcting for $g^2(0)$ and imperfections of the experimental setup, we estimate a corrected Hong-Ou-Mandel visibility of $V_{HOM}^{corr} = (95.7 \pm 0.8)\%$, which is compatible with the QD state of the art and conducive to the fusion of smaller cluster states for the generation of more advanced entangled states.

6. Conclusion

In conclusion, we have achieved the first experimental demonstration of spin-photon time-bin entanglement using QDs. This follows a significant theoretical analysis of the entanglement protocol and experimental progress on the spin-photon interface. The entanglement protocol can be scaled to emit many photons in a 1d-cluster state or a GHZ state. To reach a higher number of entangled photons, significant improvements of the spin control pulses and the photon collection efficiency are required. Given such improvements and realistic waveguide parameters, our theoretical calculations predict that it should be possible to reach an error rate of 2.1 % per emitted photon [3].

7. References

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