A Source of Indistinguishable Time-Bin Entangled Photons from a Waveguide-Embedded Quantum Dot

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Deterministic sources of multi-photon entanglement are highly attractive for quantum information processing but are challenging to realize experimentally. In this paper, we demonstrate a route towards a scalable source of time-bin encoded Greenberger-Horne-Zeilinger and linear cluster states from a solid-state quantum dot embedded in a nanophotonic crystal waveguide. By utilizing a self-stabilizing double-pass interferometer, we measure a spin-photon Bell state with (67.8±0.4)% fidelity and devise steps for significant further improvements. By employing strict resonant excitation, we demonstrate a protocol capable of generating multi-photon GHZ and linear cluster states. The protocol is analyzed in Refs. [12, 13] and the first experimental steps were implemented with a micropillar QD source [15] while spin-photon Bell-state generation was realized with nitrogen-vacancy centers [16, 17]. Contrary to the Lindner–Rudolph protocol, we apply strong magnetic fields which permit the use of spin-echo pulses and render the protocol insensitive to spin-dephasing [12]. Additionally, a single optical transition is excited resonantly and emits highly indistinguishable photons into a single-mode photonic crystal waveguide (PCW) with near-unity internal collection efficiency [18, 19]. Here, we focus on measuring spin-photon Bell states using a novel double-pass interferometer and determine a raw (corrected) fidelity of 65.7%(67.8%). This fidelity is predominantly limited by the quality of the spin rotations, which can be substantially improved in future experiments [20].

The entanglement protocol builds upon our recent work on uniting optical cycling transitions with optical spin control [21], as summarised in FIG. 1a. A positively charged InAs QD in an in-plane (Voigt geometry) magnetic field \( B_y = 2 \text{T} \) gives rise to a pair of Zeeman-split heavy-hole ground states \(|\uparrow\rangle\) and \(|\downarrow\rangle\), which are used as a spin qubit [22], and a pair of Zeeman-split triexcitons \(|\uparrow\uparrow\downarrow\rangle\) and \(|\downarrow\uparrow\downarrow\rangle\) enabling photon generation. The four linear dipoles are driven by a red-detuned Raman laser to rotate the spin qubit [20] while the PCW (FIG. 1b) selectively enhances the optical transitions resulting in the optical cyclicity \( C = \gamma_y/\gamma_x = 14.7 \pm 0.2 \) [21], which is otherwise unity in a bulk environment. Spin-photon entanglement is then generated according to the protocol in FIG. 1c. Optical pumping initializes \(|\downarrow\rangle\) and a \( R_y(\pi/2) \) rotation around the y-axis prepares the superposition state \((|\downarrow\rangle + |\uparrow\rangle)/\sqrt{2}\). The QD is
then subjected to a y-polarised optical π-pulse resonant with |⇑⟩ ↔ |↑⇑⇓⟩. As the other y-polarised transition is detuned by $\Delta_0 = 2\pi \times 17\,\text{GHz}$, trion excitation and thus photon emission is conditioned on |⇑⟩. The enhanced cyclicity ensures photon emission via the spin-preserving $|\uparrow\uparrow\downarrow\rangle \rightarrow |\uparrow\rangle$ transition with probability $C/(C + 1) \approx 94\%$. Thus, an early excitation entangles |⇑⟩ with an early photon |⇑⟩. The spin states are then swapped by a π-rotation before applying a late excitation pulse resulting in the emission of a late photon |⇑⟩. The resulting state is the spin-photon Bell state

$$|\psi_{\text{Bell}}\rangle = (e^{i\phi_e} |\uparrow\rangle, l - |\downarrow\rangle, e)/\sqrt{2},$$

(1)

where the emission time of the single photon is maximally entangled with the hole spin and $\phi_e$ is the phase difference between the two excitation pulses. Note that the spin does not undergo precession as we work in the rotating frame of the Raman laser. The spin thus only rotates when we actively apply a Raman pulse in contrast to Refs. [6, 11].

The entangled state is analyzed using the setup in FIG. 1d. The QD is held at 4 K in a closed cycle cryostat and pump pulse (red squares), rotation pulses (purple squares) and fast optical π-pulses (red pulses). The spin-photon state is indicated on top with |⇑⟩ ↔ |⇑⟩ denoting an early(late) photon. (d) Experimental setup. The PCW embedded QD is subjected to lasers propagating from free space. A double-pass TBI defines the excitation pulses (dashed red line) and interferes the emitted photons (solid orange line) resulting in mutual phase stability. A polariser with angle $\theta_{\text{pol}}$ determines the photonic readout basis. $\lambda/2(\lambda/4)$ denotes half(quarter)-waveplates. (e) Fluorescence histogram resulting from Bell state generation summed over both detectors including a 50 ns spin readout detection window (shaded area). The inset shows a magnified view of the early(e), middle(m) and late(l) detection windows (2 ns each) which herald the measurement basis of the photonic qubit. The peaks at 120 ns are optical reflections inside the TBI.

gives an equal probability of transmission and reflection. This passive routing leads to three detection windows (see FIG. 1c) which herald the photonic measurement basis. An early(late) detection corresponds to an early(late) photon propagating through the short(long) interferometer arm and thus constitutes a Z-basis measurement. By contrast, the middle window represents the time-bin encoded photon interfering with itself on BS₁. A photon click on detector D₁ or D₂ thus projects the photon onto $|\phi = (|e\rangle \pm e^{i\phi_\text{pol}} |l\rangle)/\sqrt{2}$ where $\phi_\text{pol}$ is the interferometer phase. Rather than stabilizing the TBI [16, 24] or monitoring its phase [17] we utilize a second pass through the TBI (dashed line in FIG. 1d) which derives the early and late excitation pulses from a single input pulse [25]. As a result, the phases $\phi_\text{pol}$ and $\phi_e$ experience the same drift and are thus mutually stable resulting in a stable detection pattern. The long arm delay $T_{\text{inf}} = 11.8\,\text{ns}$ defines the time-bin separation and is sufficient for performing photon emission (400 ps lifetime) and π-rotations (7 ns) between the early and late excitations. The TBI also includes two 3 GHz FWHM etalon filters which reject the Raman laser scatter and the QD phonon sideband [26].

We now proceed to quantify the spin-photon entanglement using the approach of Ref. [27] in which the fidelity of an N-qubit GHZ state may be exactly determined with only $N + 1$ measurement settings. Adapting
the technique to a Bell state gives
\[ F_{\text{Bell}} = \frac{\langle P_+ \rangle - \langle M_y \rangle}{\frac{1}{2} + \frac{\langle M_y \rangle - \langle M_z \rangle}{4}}, \]
using the operators \( \hat{P}_+ = |\psi, l\rangle\langle \psi, l| + |\psi, e\rangle\langle \psi, e| \), \( \hat{M}_y = \hat{\sigma}^y_\psi \otimes \hat{\sigma}^y_\phi \) and \( \hat{M}_z = \hat{\sigma}^z_\psi \otimes \hat{\sigma}^z_\phi \), where \( \hat{\sigma} \) denotes single qubit pauli matrices, s(p) superscripts denote spin(photonic) qubit, and we designate the logical qubits \( |0\rangle = |\psi\rangle, |l\rangle \) and \( |1\rangle = |\psi\rangle, |e\rangle \). We post-select on measuring photons in both the photonic and spin readout windows and achieve a 124 Hz coincidence rate when repeating the experiment at a 1.65 MHz repetition rate.

As the spin readout can only detect \( |\psi\rangle \) we apply a \( \hat{R}_i \) rotation prior to readout (FIG. 1c) fulfilling \( \hat{R}_i |s\rangle = |\psi\rangle \) to realize the desired spin projector \( \hat{S}|s\rangle\langle s| \). FIG. 2a shows the results of a ZZ-basis measurement. Projection on \( |e\rangle \) and \( |l\rangle \) is given by the photon detection time (both detectors are treated equally) and the \( \hat{R}_i \) pulse is toggled between a 0 and a \( \pi \) rotation to realize projections onto \( |\psi\rangle \) and \( |e\rangle \), respectively.

In order to measure time-bin encoded photons in the equatorial plane of the Bloch sphere, we add a controllable phase difference between the early and late excitation pulses. These pulses are orthogonally polarized upon encountering PBS(1) (FIG. 1d) but are projected onto the transmission axis of a rotatable polarizer, which adds \( 2\theta_{\text{pol}} \) to the phase \( \phi_e \). FIG. 2b shows the TBI detection pattern when the classical excitation pulses are reinjected into the detection pass and reveals a near-perfect visibility. The angle \( \theta_{\text{pol}} = \theta_0 \) corresponds to the condition \( \phi_d = \phi_e \) and depends on the precise TBI alignment but is stable on a week timescale. We then run the entanglement protocol, project the QD spin onto \( |\pm X\rangle_s = (|\psi\rangle \pm |\phi\rangle)\sqrt{2} \) (for \( \hat{R}_i = \hat{R}_{\psi}(\pm \pi/2) \)) and measure the spin state dependent contrast, see FIG. 2b. Crucially, the two fringes are perfectly in-phase and out-of-phase with the classical TBI response. In summary, measuring the photon in the X-basis corresponds to setting \( \theta_{\text{pol}} = \theta_0 \) and assigning the photon states \( |\pm X\rangle_p \) to a middle window detection on D1 and D2, respectively. FIG. 2c shows the outcomes of an XX-basis measurement. The outcomes are normalized as before and the probability difference between the positive and negative eigenstates of \( M_x \) results in \( \langle M_x \rangle = (-42.3 \pm 1.1)\% \). The \( \hat{M}_y \) measurement is similarly realized by setting \( \theta_{\text{pol}} = \theta_0 + \pi/4 \) and \( \hat{R}_i = \hat{R}_{\psi}(\pm \pi/2) \) leading to \( \langle M_y \rangle = (42.1 \pm 1.1)\% \). By applying Eq. (2) we arrive at the final estimate
\[ F_{\text{Bell}}^{\text{raw}} = (65.7 \pm 0.4)\% \]
which exceeds the classical threshold of 50\% by 39 standard deviations using only 6 minutes of acquisition and no corrections. We note that some of the recorded spin-photon coincidences are due to uncorrelated laser leakage. However, this contribution is minor and correcting for the background (as in Ref. [17]) leads to a corrected fidelity of \( F_{\text{Bell}}^{\text{corr}} = (67.8 \pm 0.4)\% \).

NV centers [16, 17] have produced similar quality Bell states but with greater reliance on background subtraction.

FIG. 2. (color online) Entanglement verification. (a) Spin-photon Bell state measured in ZZ-basis. Magenta bars denote the measured spin-photon coincidences during a 120 s acquisition. The right y-axis indicates raw counts and the left y-axis shows the probability normalized across all four outcomes. The yellow and blue bars represent the ideal and simulated detection patterns, respectively. (b) Determination of the photonic readout basis. The y-axis indicates the normalized intensity difference between the two TBI detectors in the middle window. The gray dots show the TBI response to a classical input while the blue and orange curves denote spin-photon coincidences when projecting the spin on \( |\pm X\rangle_s \) (legend). The fits follow \( V = 49.4(9)\% \). Errorbars are within the datapoints. (c) Spin-photon measurements in the XX-basis (top row) and YY-basis (bottom row). The s and p subscripts denote spin and photonic qubit, respectively. Axes and legends follow (a).
We now highlight two of the errors limiting $F_{\text{Bell}}$. Our dominant error is the quality of our Raman pulses which is characterized in the Supplemental materials and Ref. [21]. By measuring the dampening of Rabi oscillations between $|\uparrow\rangle$ and $|\downarrow\rangle$ we extract a $\pi$-pulse fidelity of $F_{\pi} = 88.5\%$ which is predominantly limited by incoherent spin-flips between the two spin states. Naturally, the time-bin protocol relies on highly coherent spin control, and $F_{\pi} = 88.5\%$ alone limits the Bell state fidelity to 77% according to Monte Carlo simulations. Thus, we may attribute $\sim 70\%$ of the measured infidelity to this mechanism. Fortunately, a recent scheme using electron spins and nuclear spin cooling [20] demonstrated $F_{\pi} = 98.8\%$ and could readily be implemented in the experimental protocol. This would increase the achievable fidelity to $F_{\text{Bell}} = 97.3\%$ (neglecting other errors).

A second relevant error is the single-photon purity and indistinguishability of the emitted photons. This error is particularly relevant for combining multiple smaller cluster states through entanglement fusion [2]. To accurately characterize the time-bin encoded photon, we retain the magnetic field and minimally modify the pulse sequence to emit two separable single photons (FIG. 3a). By using the TBI, we simultaneously measure the $g^{(2)}$ intensity autocorrelation and Hong–Ou–Mandel (HOM) visibility by letting the detection time herald the experiment. FIG. 3b shows the delays between photons recorded in either the early or late detection windows and constitutes two sets of $g^{(2)}$ measurements. A slight bunching is observed for short delays owing to non-deterministic initialization of the hole charge state and the minor proclivity for coincidences in the early data set is a consequence of the finite cyclicity. Normalizing $g^{(2)}$ at long delays and averaging over early and late gives $g^{(2)}(0) = (4.7 \pm 0.6)\%$ from which 1.1% may be attributed to excitation laser scatter. The remaining contribution is likely a result of multi-photon emission owing to the fast, Purcell enhanced decay rate $\gamma_0 = (\gamma_x + \gamma_y) = 2.54\text{ns}^{-1}$ and the FWHM duration of the $\pi$-pulse $T_{\text{opt}} = 35\text{ps}$. $T_{\text{opt}}$ represents a trade-off [12, 13] between multi-photon emission (minimized for $T_{\text{opt}} \ll \gamma_0^{-1}$) and unwanted excitation of $|\uparrow\rangle \leftrightarrow |\uparrow\uparrow\rangle$ (minimized for $T_{\text{opt}} \gg \Delta_0^{-1}$). A larger magnetic field will increase $\Delta_0$ and permit a shorter $T_{\text{opt}}$ and thus reduced $g^{(2)}(0)$. FIG. 3c shows the delay between two photons recorded within the same experimental repetition when at least one photon was measured in the middle window. Following Ref. [28], this estimates a raw indistinguishability of $\mathcal{V}^{\text{raw}} = 1 - 2N_2/(N_1 + N_3) = (86.5 \pm 0.6)\%$ (integration windows given in FIG. 3c). $\mathcal{V}^{\text{raw}}$ is primarily limited by the finite $g^{(2)}(0)$ according to $\mathcal{V}^{\text{raw}} \approx \mathcal{V}/(1 + 2g^{(2)}(0))$, which assumes the multi-photon contribution to consist of distinguishable photons [28, 29]. Correcting for $g^{(2)}(0)$ and the slight imperfection of the TBI yields a corrected HOM visibility of $\mathcal{V} = (95.7 \pm 0.8)\%$ which is compatible with the QD state of the art [30–32].

In summary, we have used a PCW embedded QD to implement a scalable protocol for the generation of time-bin entangled photonic states. This is facilitated by the PCW platform which offers a compelling marriage of spin control and photonic enhancement. Operating at high magnetic fields allows spin initialization without projective measurements and the photon indistinguishability is independent of the magnetic field strength as a single optical transition is used for emission. Our insights from theory and simulation show a clear path towards improving the fidelity with the quality of spin rotations requiring the most attention. Indeed, given realistic PCW parameters and greatly enhanced Raman pulses we expect to reach an error level of 2.1% per emitted photon [13]. The generalization to more photons is straightforward and only requires additional rotation and excitation pulses to create a multi-photon GHZ or 1D-cluster state with photonic qubits emitted.
every 28 ns. We have attempted a three-qubit GHZ state (Supplemental materials) but only measured a $F_{GHZ} = (42.3 \pm 1.4\%$) fidelity due to the imperfect Raman pulses.

Another promising aspect of our approach is the entanglement generation rate. Our 124 Hz Bell-state detection rate is already favourable against similar protocols based on NV centers (7 mHz in Ref. [17]) despite our limited and non-optimized total detection efficiency $\eta_{total} = 0.3\%$. Indeed, a QD-to-fiber collection efficiency of $\eta = 7\%$ was recently demonstrated in a similar PCW structure and further realistic improvements may facilitate collection efficiencies as high as $\eta = 78\%$ [32]. Finally, we note that the high magnetic field regime can give access to nuclear magnon modes [33], which may be used as a long-lived quantum memory for repeater applications or as an ancillary qubit for use in photonic graph state generation [34, 35].

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