

## Entangled photon pairs from radiative cascades in semiconductor quantum dots

N. Akopian<sup>1</sup>, N. H. Lindner<sup>1</sup>, E. Poem<sup>1</sup>, Y. Berlatzky<sup>1</sup>, J. Avron<sup>1</sup>, D. Gershoni<sup>\*1</sup>,  
B. D. Gerardot<sup>2</sup>, and P. M. Petroff<sup>2</sup>

<sup>1</sup> Department of Physics, Technion – Israel Institute of Technology, Haifa 32000, Israel

<sup>2</sup> Materials Department, University of California, Santa Barbara, CA 93106, USA

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Entangled photon pairs are emitted from a biexciton decay cascade of single quantum dots when spectral filtering is applied. We show this by experimentally measuring the density matrix of the polarization state of the photon pair emitted from a continuously pumped quantum dot. The matrix clearly satisfies the Peres criterion for entanglement. By applying in addition a temporal window, the quantum dot becomes an entangled light source.

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### 1 Introduction

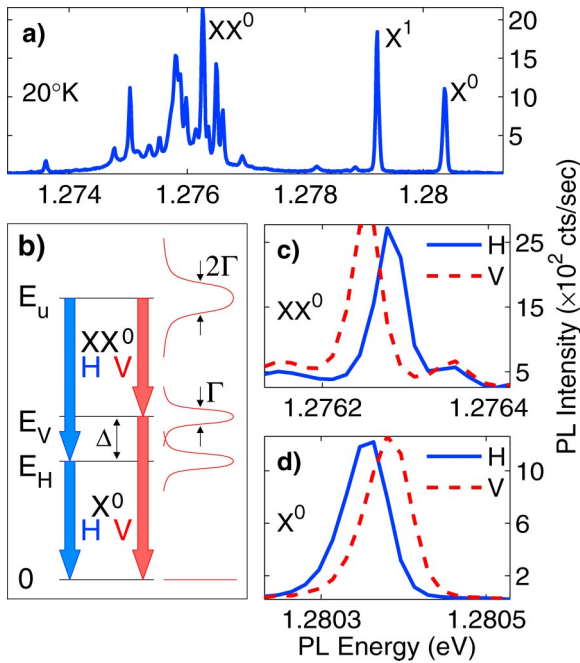
Entanglement, the intriguing correlations of quantum systems [1, 2], is an essential resource of quantum information and communication [3, 4]. Entangled photons are particularly attractive for applications due to their non interacting nature and the ease by which they can be manipulated. Polarization entangled photons are routinely produced by nonlinear optical effects [5]. Such sources have, however, a large random component, whereas applications require non-random entangled photons.

Semiconductor quantum dots (QDs) provide optically and electrically driven sources of single photons on demand [6–8]. Compatibility with modern electronics makes them potential building blocks for quantum information processing [9] and sources for “event-ready” entangled photons [10, 11].

In a recent Letter [12] we demonstrated for the first time that the polarization state of pairs of photons emitted from a biexciton decay cascade becomes entangled when spectral filtering is applied. It is well known that the efficiency of correlation measurements is proportional to the square of the events rate. Therefore, for our demonstration, we chose to use continuous wave (cw) optical pumping, rather than triggered one [7, 8], since this way one maximizes the emission rate from a spontaneously decaying source of photons. Here we show that by adding a temporal filter, a single QD undergoing a cw excitation becomes a physical source of entangled light.

A QD biexciton decays radiatively through two intermediate optically active exciton states [13, 14]. Entanglement requires two decay paths with different polarizations, but indistinguishable otherwise. This is the case if the intermediate exciton states are energetically degenerate and if, the final state of the QD is independent of the decay path. The first requirement is difficult to fulfil since the intermediate exciton states are split by the anisotropic electron–hole exchange interaction [15]. The two decay paths, which we denote horizontal (H) and vertical (V), have corresponding photon polarizations relative to the asymmetry axis of the QD (see Fig. 1b). Since the paths are spectrally distinguishable the polarization

\* Corresponding author: e-mail: dg@physics.technion.ac.il, Phone: +972 4 829 3630, Fax: +972 4 823 5107



**Fig. 1** (online colour at: [www.pss-b.com](http://www.pss-b.com)) (a) Photoluminescence (PL) spectrum of a single QD [12]. (b) Schematic description of the biexciton radiative cascade in natural QDs with its two co-linearly polarized photons (either H or V) and energetically distinguishable paths. (c), (d) High resolution polarization sensitive PL spectra of the biexciton  $XX^0$  (exciton  $X^0$ ) lines. Due to spectral diffusion (see text), the measured line widths are larger than the radiative widths, shown schematically in (b).

state of the photons cannot be entangled [16]. We overcome this requirement by using spectral filtering [12]. The requirement that the QD final state does not depend on the decay path, has been recently shown experimentally [12].

## 2 Experiment

For the measurements we used planar microcavity (MC) embedded QDs samples. The samples were grown by molecular beam epitaxy on a (100) oriented GaAs substrate. One layer of strain-induced InAs QDs was deposited in the center of a one wavelength GaAs microcavity formed by two unequal stacks of alternating quarter wavelength layers of AlAs and GaAs, respectively. The height and composition of the QDs were controlled by partially covering the InAs QDs with a 3 nm layer of GaAs and subsequent growth interruption. To improve photon collection efficiency, the microcavity was designed to have a cavity mode, which matches the QD emission due to ground state e–h pair recombinations. Unlike previous studies of radiative cascades in QDs [17], our sample was not masked or patterned laterally to prevent obscuration of the emitted photon polarizations.

We used a diffraction limited low temperature confocal optical microscope for the photoluminescence (PL) studies of the single MCQDs [14]. Temporal correlations between emitted photon pairs were measured using a wavelength and polarization selective Hanbury–Brown–Twiss (HBT) arrangement [14]. We used a 1 meter monochromator in each arm of the HBT setup to obtain spectral resolution of  $\sim 15 \mu\text{eV}$ . The polarization state of the emitted light was monitored by the use of liquid crystal variable retarders (LCVRs) and high quality polarizers.

In Fig. 1a we present PL spectrum of a single, resonant MCQD. The MCQD was excited by a continuous-wave HeNe laser. The spectrum is composed of sharp lines with linewidths of roughly  $50 \mu\text{eV}$  due to the spectral diffusion. We identified most of the observed spectral lines using power and energy dependence polarization sensitive magneto spectroscopy. Here, we are only interested in the neutral single exciton line ( $X^0$ ) and the neutral biexciton line ( $XX^0$ ). In Fig. 1c and d we present high resolution polarization sensitive PL spectra of the lines  $X^0$  and  $XX^0$ . Figure 1 demonstrates that the neutral spectral

lines  $XX^0$  and  $X^0$  are composed of two cross linearly polarized split doublets with detuning of  $\Delta = 27 \pm 3 \mu\text{eV}$ .

We used the HBT setup to measure polarization sensitive temporal intensity correlations between photons emitted from all the observed spectral lines. The auto-correlation measurements of the lines (not shown), show a deep anti-bunching notch at coinciding times ( $t = 0$ ), demonstrating that each line is a spectral source of single photons [6–8]. The intensity cross correlation measurements between the neutral exciton  $X^0$  and the neutral biexciton  $XX^0$  lines are presented in Fig. 2 for 16 different combinations of the polarizers in front of the two detectors. For these measurements, the excitation intensity was tuned such that both lines were essentially equal in strength. Spectral filtering was implemented by the two monochromators' slits, which were closed to obtain spectral width of roughly  $25 \mu\text{eV}$ . Under these conditions, we detect around 5000 photons/sec from each line. This amounts to about 10% of the open slits counts.

From the temporal correlation measurements we obtain the radiative lifetime of the exciton [14]  $T_{X^0} = 0.8 \pm 0.2 \text{ ns}$ , or  $\Gamma = 1.6 \pm 0.4 \mu\text{eV}$  for its radiative width.

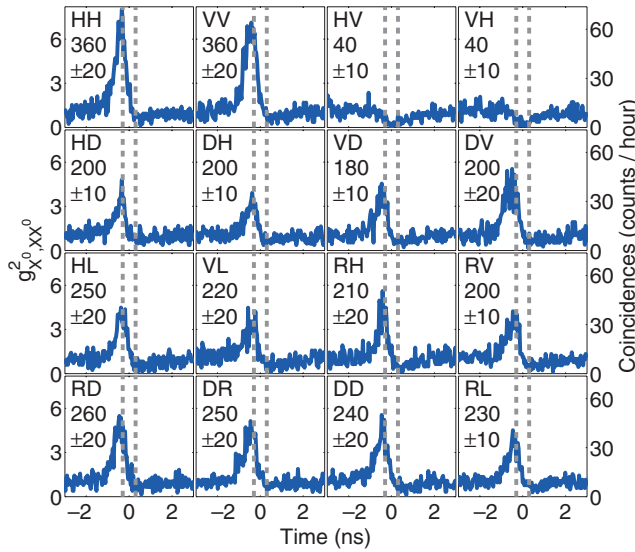
Spectral diffusion, due to changes in the QD environment, causes the energy levels of the QD to fluctuate slowly relative to the radiative time. This leads to inhomogeneous broadening of the spectral lines (see Fig. 1c, d). One may worry that the “which path” information in the decay path will not be erased if the spectral filters are narrower than the linewidth. This is not the case, since in a given radiative cascade both photons are shifted equally relative to the energy of their fixed spectral filters. Therefore, large fluctuations result in a rapid decrease in the probability of detecting both photons [12].

### 3 Results and discussions

By inspecting Fig. 2, we note that when the two polarizers are co-linearly oriented along the major QD axes (HH or VV) an asymmetric trace is obtained in which the positive temporal part shows an anti-bunching notch, while the negative part shows a strong, enhanced bunching peak. This asymmetrical shape, an experimental signature of an optical cascade, reveals the temporal sequence of these events. While emission of a horizontally (vertically) polarized  $XX^0$  photon is followed by emission of a horizontally (vertically) polarized  $X^0$  photon, the opposite never happens [10, 11]. When the polarizers are cross linearly polarized (HV or VH) the bunching trace at negative times, is replaced by a deep (down to zero within the experimental uncertainty) anti-bunching-like trace. This is exactly as anticipated by the considerations of Fig. 1b. The linear polarization states of the two photons emitted during the same biexciton-exciton radiative cascade are completely correlated, both are collinearly polarized and the state of the photons emitted in the same radiative cascade does not contain a cross polarized component. The positive trace however, in which the exciton-photon is detected prior to the biexciton-photon are due to pairs of photons which do not occur in the same radiative cascade. The trace here is the same in both the cross and co-polarized measurements. It therefore follows that all the measured coincidences in the HV and VH cascades are due to photon pairs from two distinct radiative cascades. The polarizations of such photons are completely uncorrelated, as can be easily verified by inspecting the correlation traces at positive time. Hence, by subtracting the cross-polarized measurements, one obtains the net “same-cascade” correlation functions, which include only photon pairs emitted in the same radiative cascade [12]. We showed in [12] that pairs from the same cascade are entangled, significantly violating Bell's inequality.

When the QDs are excited continuously, it is impossible to distinguish, however, between a pair of photons from same radiative cascade and a pair of photons from distinct ones. Therefore, in order to use a continuously excited QD as an entangled light source, the raw measurements should be considered. Clearly, the events in a wide temporal window will be dominated by distinct cascades with uncorrelated polarizations. In a sufficiently narrow time window, however, events originating from the same cascade will dominate, and the two photon state should be entangled.

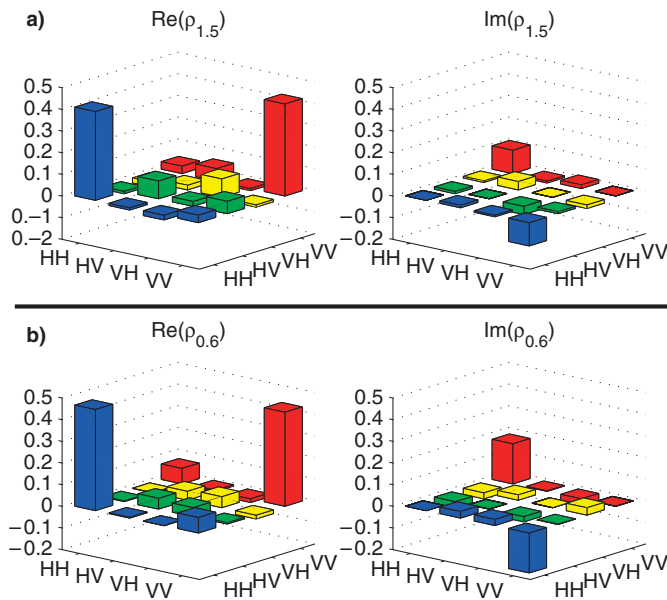
We apply temporal window of 1.5 ns, in which merely all the same cascade pairs were included, and a window of 0.6 ns, centered around the antibunching notch of the raw, spectrally filtered, corre-



**Fig. 2** (online colour at: [www.pss-b.com](http://www.pss-b.com)) Tomographical measurements of the temporal intensity cross-correlation functions of the exciton  $X^0$  and the biexciton  $XX^0$  spectral lines with spectral resolution of  $25 \mu\text{eV}$ .  $D$  stands for linear polarizer at  $45^\circ$  relative to the  $H$  direction and  $R$  ( $L$ ) stands for right (left) hand circular polarizer. The integrated numbers of coincidences with a temporal window (dashed lines) of  $0.6 \text{ ns}$ , centered around the antibunching notch in each measurement are indicated.

lation measurements. The number of coincidences from these polarization tomography measurements [5], within each temporal window, were then used to generate the H-V base density matrix of the emitted photon-pairs.

In Fig. 3 we present the density matrices obtained from these measurements. For the wide temporal window (Fig. 3 a), the events from distinct cascades are still dominant and the partial transpose of the



**Fig. 3** (online colour at: [www.pss-b.com](http://www.pss-b.com)) Density matrix of the photon pair polarization state as obtained from the tomography: a) for temporal window of  $1.5 \text{ ns}$  and b) for window of  $0.6 \text{ ns}$ .

matrix has marginal negative value of  $-0.03 \pm 0.05$ . For the window of 0.6 ns (Fig. 3 b) we minimize the number of events from distinct cascades while maintaining reasonable same cascade statistics. The obtained density matrix has partial transpose with negative eigenvalue of  $-0.15 \pm 0.07$ , clearly satisfying Peres criterion for entanglement [18].

## 4 Conclusions

By using spectral filtering and temporal gating we demonstrate that cw excited single quantum dots become sources of entangled light. The entangled photons generated in this work are not event ready since we used continuous excitation and since the erasure introduces randomness. If one can tolerate lower rates, the excitation can be triggered on demand. In this case no temporal gating is required. The randomness can then be overcome by monitoring the photons which were filtered out spectrally. This monitoring will not demolish the entangled pair. By reducing the detuning [15] and increasing the radiative width through the Purcell effect [7] entanglement may be achieved even without spectral filtering.

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## References

- [1] J. S. Bell, *Rev. Mod. Phys.* **40**, 229 (1968).
- [2] J. F. Clauser et al., *Phys. Rev. Lett.* **24**, 549 (1970).
- [3] A. Ekert, *Phys. Rev. Lett.* **67**, 661 (1991).
- [4] C. H. Bennett et al., *Phys. Rev. Lett.* **70**, 1895 (1993).
- [5] D. F. V. James et al., *Phys. Rev. A* **64**, 052312 (2001).
- [6] P. Michler et al., *Science* **290**, 2282 (2000).
- [7] C. Santori et al., *Nature* **419**, 594 (2002).
- [8] Z. Yuan et al., *Science* **295**, 102 (2001).
- [9] D. Loss, and D. DiVincenzo, *Phys. Rev. A* **57**, 120 (1998).
- [10] O. Benson et al., *Phys. Rev. Lett.* **84**, 2513 (2000).
- [11] D. Fattal et al., *Phys. Rev. Lett.* **92**, 037903 (2004).
- [12] N. Akopian et al., *Phys. Rev. Lett.* **96**, 130501 (2006).
- [13] E. Moreau et al. *Phys. Rev. Lett.* **87**, 183601 (2001).
- [14] D. V. Regelman et al., *Phys. Rev. Lett.* **87**, 257401 (2001).
- [15] M. Bayer et al., *Phys. Rev. B* **65**, 195315 (2002).
- [16] T. M. Stace et al., *Phys. Rev. B* **67**, 085317 (2003).
- [17] C. Santori et al., *Phys. Rev. B* **66**, 045308 (2002).  
S. M. Ulrich et al., *Appl. Phys. Lett.* **83**, 1848 (2003).
- [18] A. Peres, *Phys. Rev. Lett.* **77**, 1413 (1996).