A new study of on-demand emission of indistinguishable single photons from single quantum dots

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Abstract: We present a comprehensive experimental and theoretical study of indistinguishable single photon emissions from various optical transitions and radiative cascades from the same single QD.
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Indistinguishable photons are a key ingredient in applications of quantum information processes, which make use of quantum interference phenomena between single photons, as a way to impose interaction between 'flying qubits'. In recent years this subject has been under increase research interest particularly with regard to on demand, single photon sources, such as semiconductor quantum dots (QDs) [1]. QDs confine single charge carriers into a three dimensional nanometer scale region, thus acting in many ways as isolated 'artificial atoms'. For the purpose of generating indistinguishable single photons, however, where ideally a Fourier-transform limited, time-energy relations are required, solid state emitters, such as QDs, suffer due to their strong coupling with the environment. This interaction introduces dephasing, which in turn reduces the photon indistinguishability. Another mechanism which reduces the indistinguishability is the time jitter resulting from the random nature of the relaxation following a non-resonant excitation scheme [2]. Recent works have therefore focused on measuring the indistinguishability of the emitted photons using resonant excitation, although jitter is still possible, due to randomness in relaxation, following the photon emission, like in the case of radiative cascades. [3]

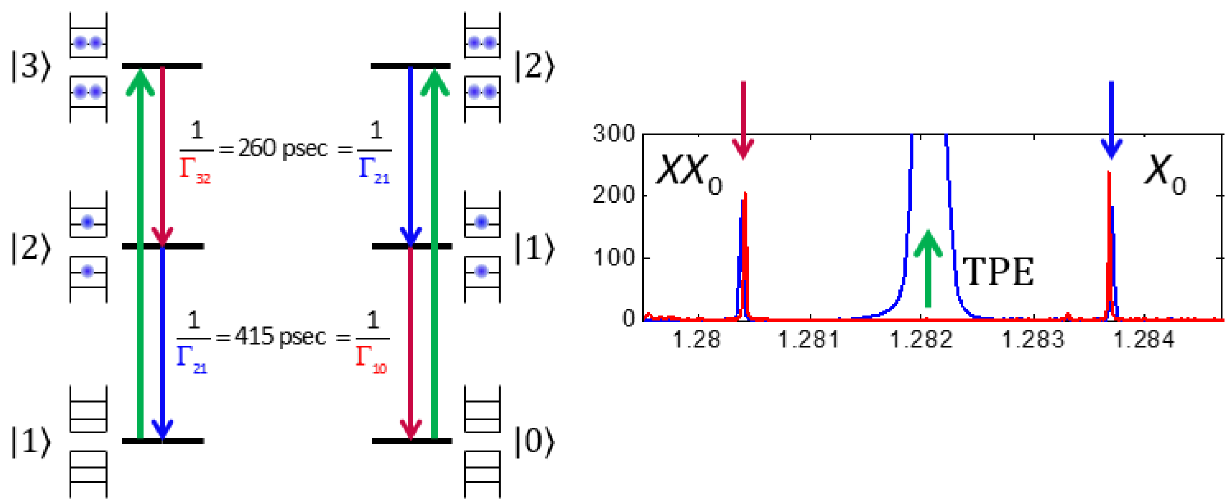

Fig. 1 Left panel: the energy levels and the optical transitions in the biexciton-exciton-vacuum radiative cascade in a semiconductor quantum dot. We show theoretically and experimentally that the indistinguishability between the emitted single photons is given by

$$\text{Ind} \equiv \Gamma_{21} / (\Gamma_{21} + \Gamma_{10}) * \Gamma_{32} / (\Gamma_{21} + \Gamma_{32})$$

where the various rates are described in the figure. Green upward arrow represents the exciting laser pulse, blue downward arrow, the relevant single photon radiative rate and red downward arrow describe the jitter in the exciton case and the broadening in the biexciton case.
Right panel: polarization sensitive photoluminescence spectra showing the laser light which resonantly excite the biexciton using its two-photon excitation resonance (TPE) (green upward arrow), and the emitted biexciton (XX^0 red downward arrow) and exciton (X^0 blue downward arrow) spectral lines.

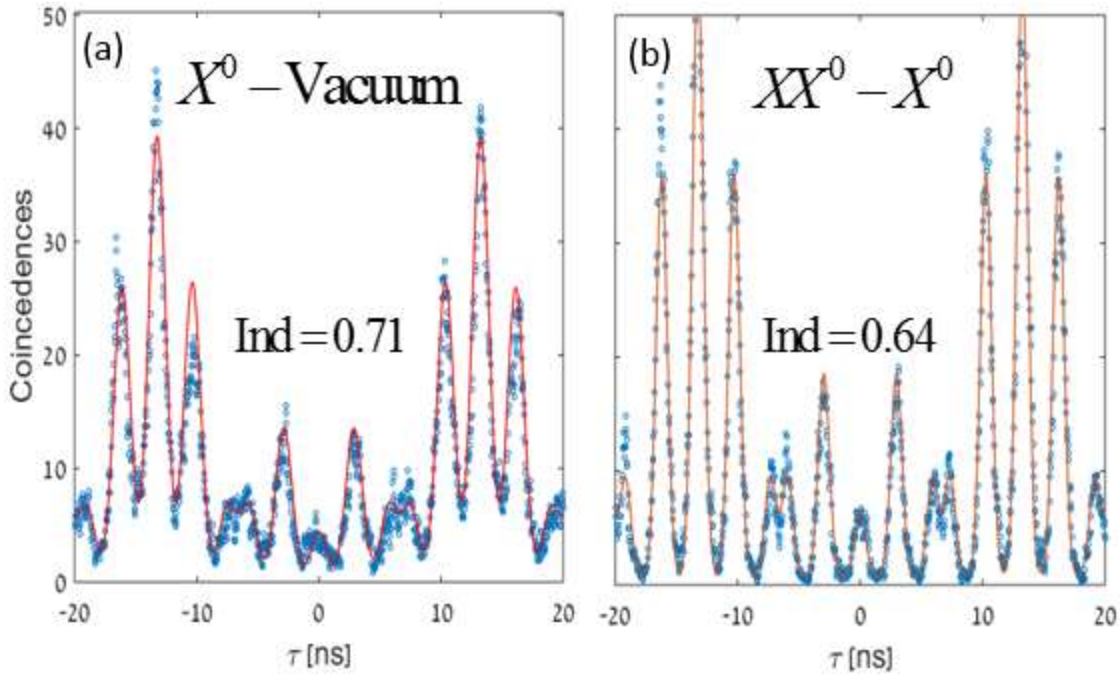

Fig. 2 Hong-Ou-Mandel measurements quantifying the indistinguishability of single photons emitted by the quantum dot from: (a) exciton-vacuum, and (b) biexciton-exciton optical transitions. Both these optical transitions are from the same biexciton-exciton-vacuum cascade presented in figure 1. Blue dots represent the measured data and solid red line represent our best model fit.

In this work we performed Hong-Ou-Mandel measurements to quantify the indistinguishability of various spectral lines, resulting from resonantly excited single semiconductor quantum dot. For these lines in separate experiments, we also measured radiative lifetimes, spectral widths, and relaxation rates, before and after the photon emission. In particular, we studied photon emission from a spin-blockade biexciton transition, which leaves a dark exciton in the QD [4, 5]. This optical transition, results in almost maximally entangled photon – dark-exciton pair [6]. We used it recently to demonstrate on-demand generation of a multi photon entangled state or cluster-state of entangled photons [6]. The measured indistinguishability of all these optical transitions fully agrees with the simple theoretical expression outlined in Fig. 1 above. Note that when the X0-vacuum transition was excited resonantly, Indistinguishability of 0.93 was obtained, limited only by the jitter of our pulsed laser source.

4. References

[1] C Santori. *et al*, *" Indistinguishable photons from a single-photon device" Nature*, **419**, 594-597 (2002)

[2] A. Thoma, *et al.*, *"Exploring Dephasing of a Solid-State Quantum Emitter via Time- and Temperature-Dependent Hong-Ou-Mandel Experiments"* Phys. Rev. Lett. **116**, 033601 (2016).

[3] M. Muller *et al*, *"On-demand generation of indistinguishable polarization-entangled photon pairs" Nat Photon,* **8**, 224-228 (2014)

[4] I. Schwartz *et al*, *"Deterministic Writing and Control of the Dark Exciton Spin using Short Single Optical Pulses." Phys. Rev. X* **5**, 011009 (2015).

[5] E. Poem et al. *"Accessing the dark exciton with light." Nat Phys,* **6**, 993-997 (2010)

[6] I. Schwartz *et al*, *"Deterministic Generation of a Cluster State of Entangled Photons." Science* **354**, 434-437 (2016).