Triggered & entangled photon pairs from quantum dots

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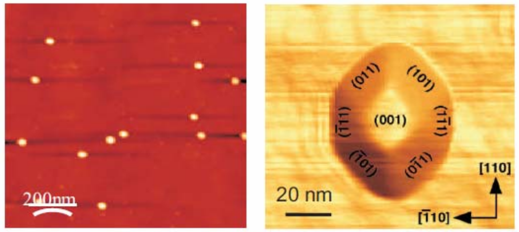
Seminar
Recent Progress in Nanooptics & Photonics
Prof. O. Benson

2009-06-10

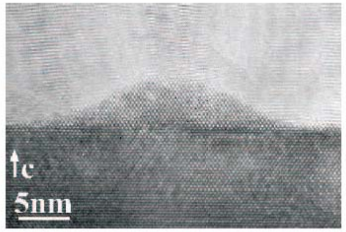
Outline

- Intro to QDs
- (Disputed) realization using selected QDs / tuning via Zeeman shift
- Realization using filters

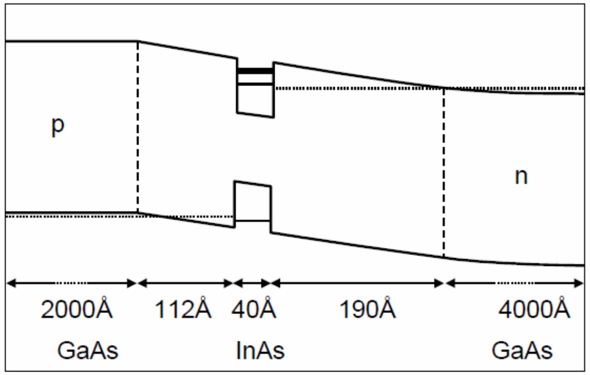
Quantum dots: Principles

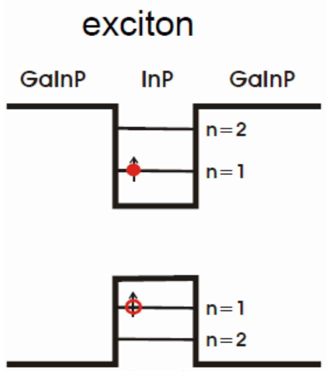


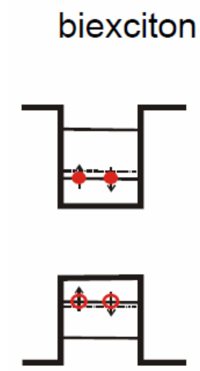
AFM images of InP/InGaP QDs

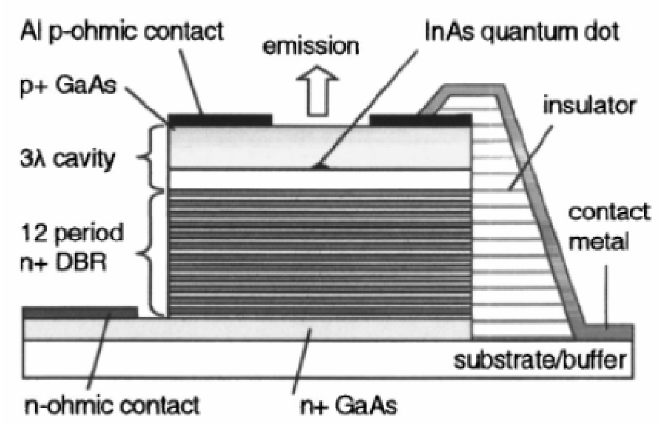


TEM image of a CdSe QD on ZnSe

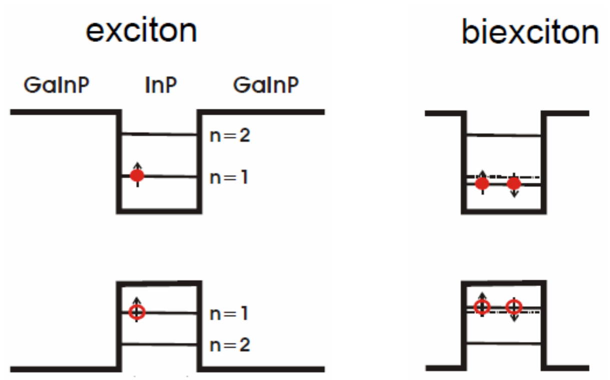


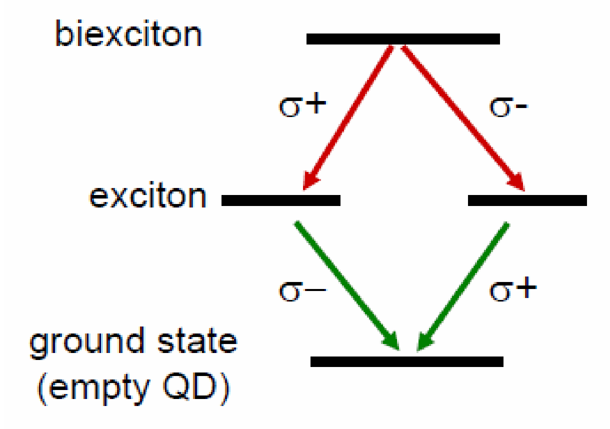






Entanglement from Bi-exciton decay





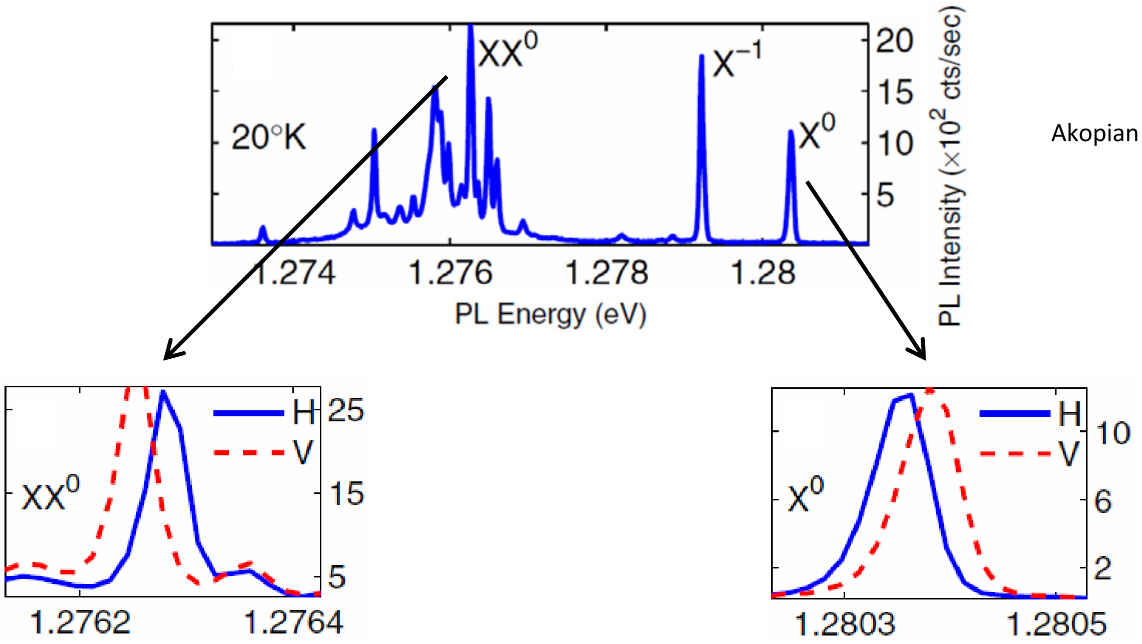
- Two decay paths:
  - First left, then right polarized Photon: $|\psi^{(1)}>=|\sigma^+>_1|\sigma^->_2$
  - Vice versa: $|\psi^{(2)}>=|\sigma^->_1|\sigma^+>_2$
- If paths are indistinguishable, we add amplitudes:

$$|\psi>=1/\sqrt{2}(|\sigma^+>_1|\sigma^->_2+|\sigma^->_1|\sigma^+>_2)$$

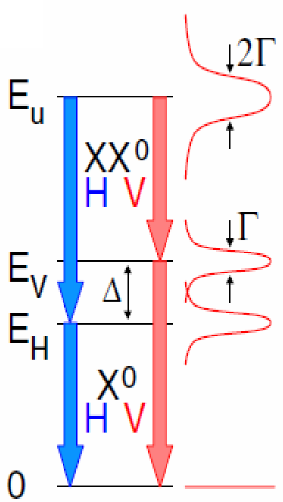
→ Entangled state!

Benson et al, PRL **84**, 2513 (2000).

However…



Akopian et al, PRL 96, 130501 (2006)



Polarization splitting provides which-path information!

Resolutions:

- Find QD with Δ≈0
- Tune splitting to zero
- Erase which-path information with narrow filter
- Erase which-path information by time reordering

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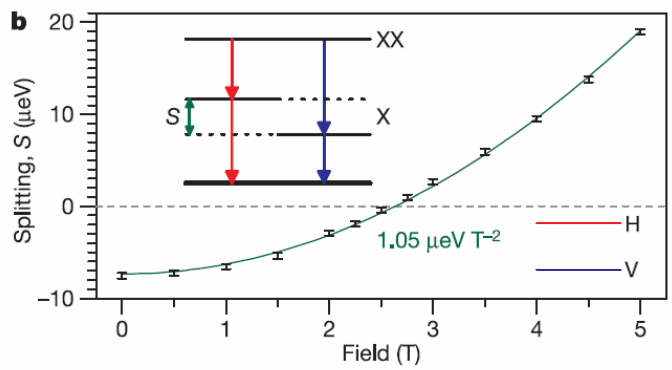
A semiconductor source of triggered entangled photon pairs

R. M. Stevenson[1], R. J. Young[1,2], P. Atkinson[2], K. Cooper[2], D. A. Ritchie[2] & A. J. Shields[1]

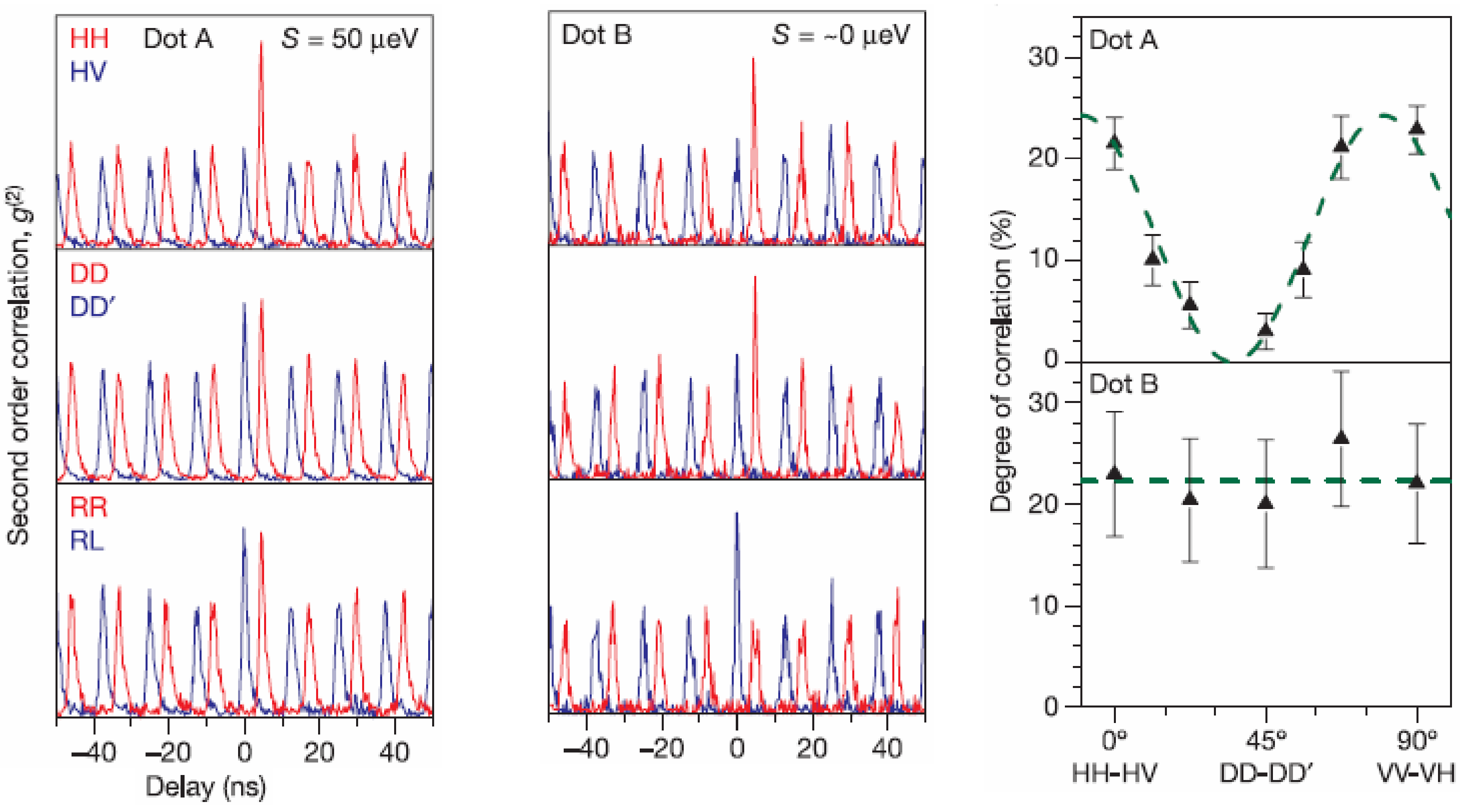
- Spectroscopy of 200 QDs @ 10 K
- 635 nm, 80 MHz pulsed excitation
- Rising emission energy correlates with falling splitting
- QDs emitting at 1.4 eV have smallest splitting (10 µeV)
- For QDs with „inverted“ splitting ($E_{XV} > E_{XH}$), splitting can be tuned using in-plane B-field
- Homogeneous linewidth Γ = 1.1 ± 0.5 µeV



→ make S < Γ

→ separate X-XX and H-V and record cross-correlations…

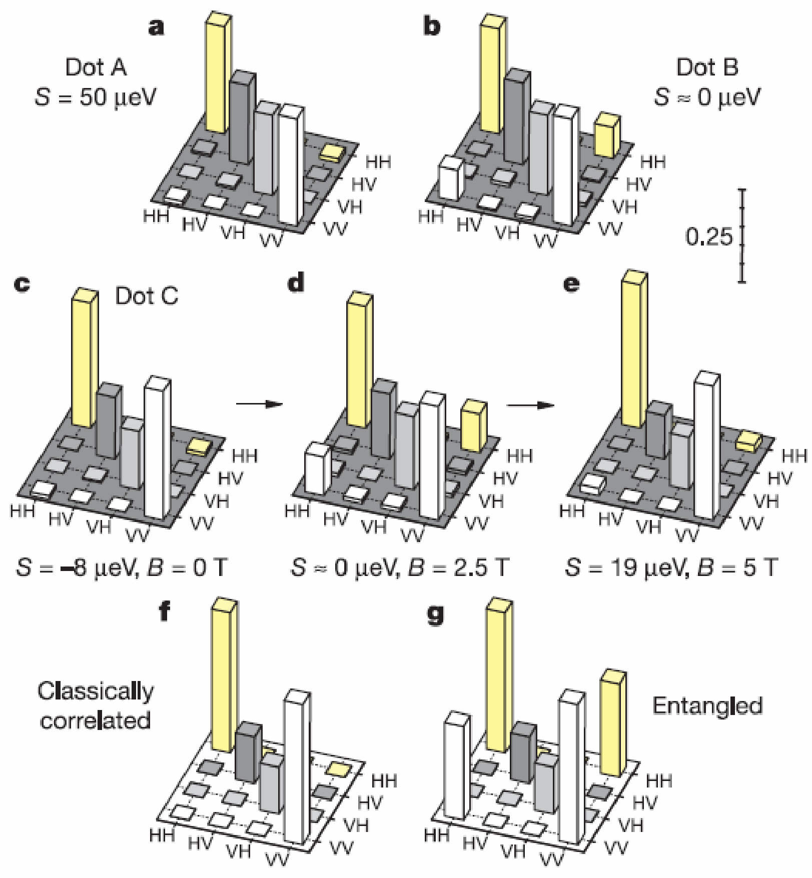
Entangled photons…



(red traces shifted horizontally for clarity)

$$\eta_{HH-HV} = \frac{C_{HH} - C_{HV}}{C_{HH} + C_{HV}}$$

Stevenson et al: Density matrices



- strong coherences
- but: background counts from
  - dark counts
  - wetting layer emission
  - scattering between intermediate X spin states
- Test for largest eigenvalue > 0.5 is positive after background substraction

(Largest eigenvalue is probability that source emits into a single polarization state. Always
< 0.5 for non-entangled source)

…or maybe not?

BRIEF COMMUNICATIONS ARISING NATURE|Vol 445|11 January 2007

QUANTUM INFORMATION

Source of triggered entangled photon pairs?

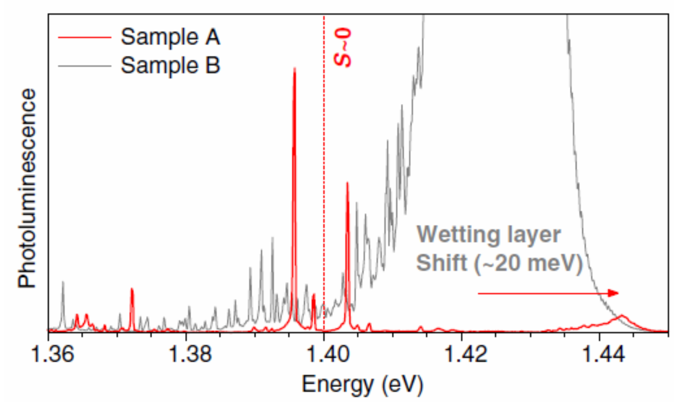
Arising from: R. M. Stevenson *et al. Nature* **439**, 179–182 (2006)

Criticism:

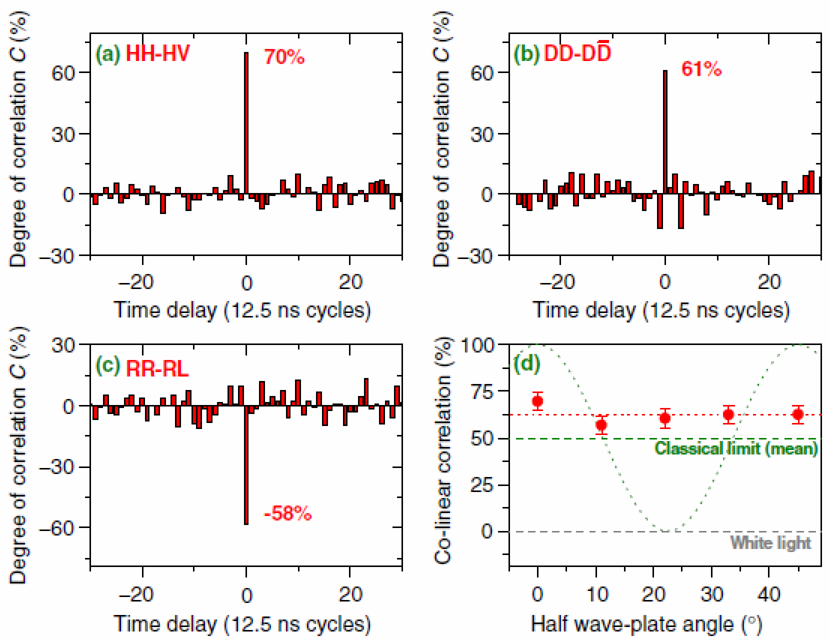
- Average linear correlation not above classical limit of 0.5
- Degree of correlation not really independent of basis
- Largest eigenvalue test only valid for unpolarized source (which is not quite the case)
- Standard quantitative tests for entanglement fail (projection onto Bell state, tangle, concurrence, …)

A few weeks later…

- Increased growth temperature by 20° to mix InAs wetting layer with surrounding GaAs
- Optimized bragg reflector for 1.4 eV



Result:



Test description	Test limit	Test result
$(\lvert HH\rangle + \lvert VV\rangle)/\sqrt{2}$ projection	>0.5	0.702 ± 0.022
Largest eigenvalue	>0.5[a]	0.719 ± 0.023
Concurrence [19]	>0	0.440 ± 0.029
Tangle [20]	>0	0.194 ± 0.026
Average linear correlation	>0.5	0.624 ± 0.024
Peres [21][b]	<0	-0.219 ± 0.021

In the meantime:

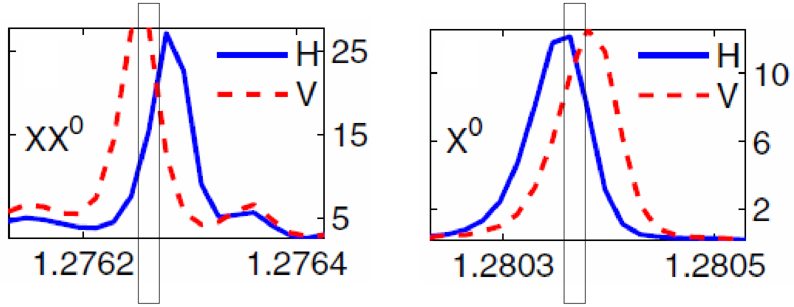
PRL 96, 130501 (2006) PHYSICAL REVIEW LETTERS week ending 7 APRIL 2006

Entangled Photon Pairs from Semiconductor Quantum Dots

N. Akopian, N. H. Lindner, E. Poem, Y. Berlatzky, J. Avron, and D. Gershoni*
Department of Physics, Technion—Israel Institute of Technology, Haifa 32000, Israel

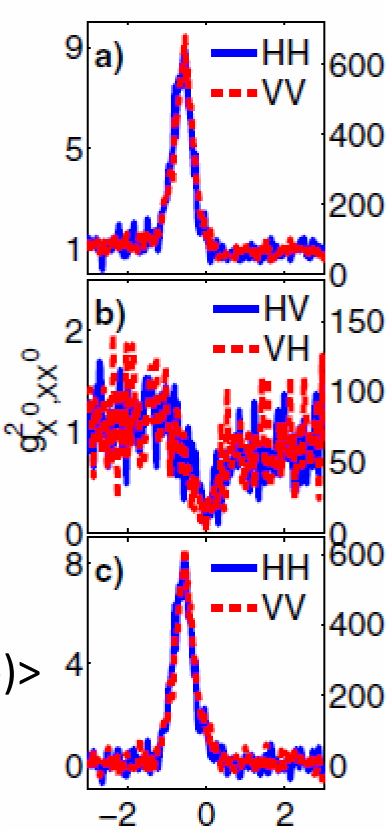
B. D. Gerardot and P. M. Petroff
Materials Department, University of California Santa Barbara, California 93106, USA
(Received 19 January 2006; published 6 April 2006)

- Filters with ΔE = 25 μeV centered between H and V peaks

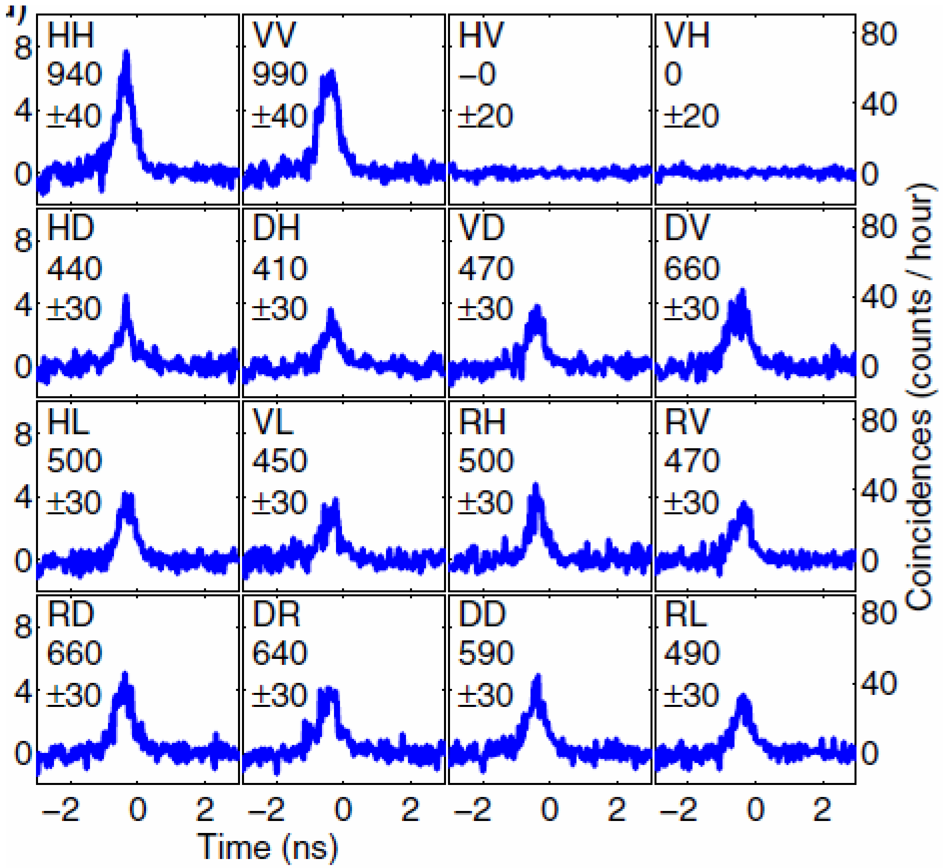


- This projection operation entangles the two photons by erasing the which-path information

Akopian et al. results



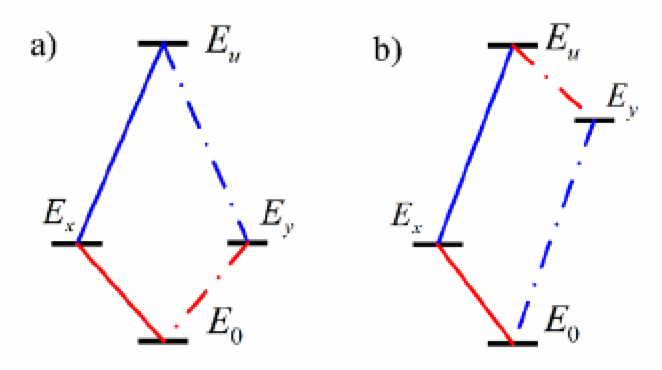
(a) – <(b)>



- Bunching for XX, then X / Antibunching for X, then XX
- By substraction: same-cascade photons only
- Results violate Bell's ineq., satisfy Peres criterion

Proposal: Time reordering

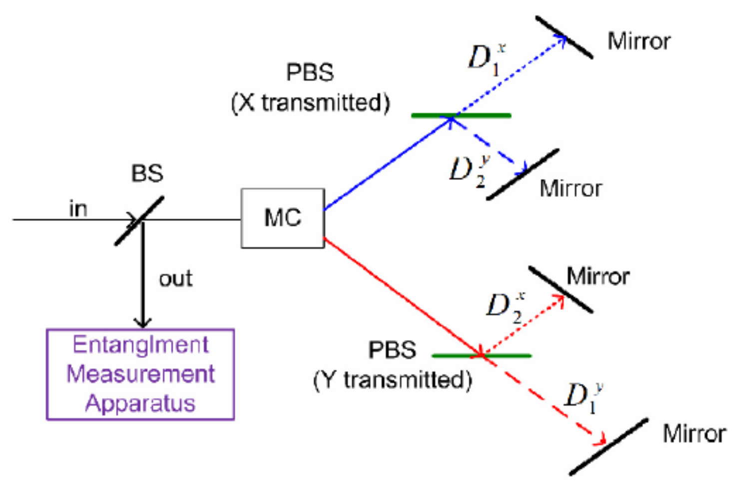
Avron et al., PRL 100, 120501 (2008).

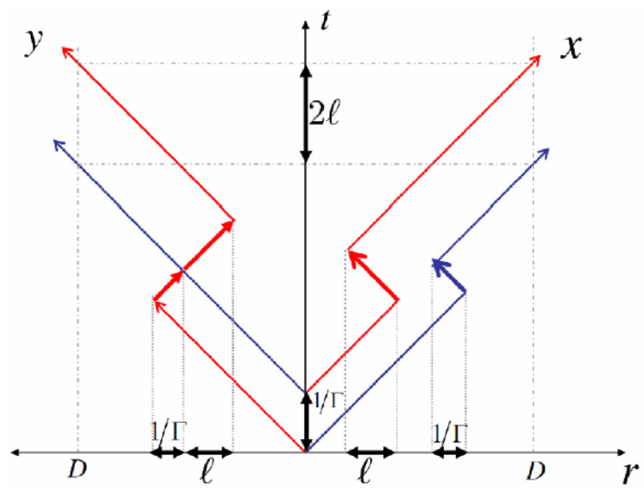


Make XX_H and X_V energies equal, and vice versa

→ which-path info only in temporal sequence

→ erase which-path in polarization-dependent delay line:





Summary

- Bi-exciton decay of single QDs emits polarization-entangled photons (70% fidelity @ 10 K)
- Polarization splitting of exciton levels is source of which-path information, destroying entanglement
- Erase which-path by:
  - Tuning splitting to 0
  - Using narrow filters
  - Time reordering (proposed)
- Know your entanglement measures!

Bibliography

Benson, O. et al. Regulated and Entangled Photons from a Single Quantum Dot. *Phys. Rev. Lett.* **84**, 2513(2000).

Stevenson, R.M. et al. A semiconductor source of triggered entangled photon pairs. *Nature* **439**, 179-182(2006).

Akopian, N. et al. Entangled Photon Pairs from Semiconductor Quantum Dots. *Phys. Rev. Lett.* **96**, 130501-4(2006).

Gilchrist, A., Resch, K.J. & White, A.G. Source of triggered entangled photon pairs? *Nature* **445**, E4-E5(2007).

Stevenson, R.M. et al. Source of triggered entangled photon pairs? (Reply). *Nature* **445**, E5-E6(2007).

Young, R.J. et al. Improved fidelity of triggered entangled photons from single quantum dots. *New Journal of Physics* **8**, 29(2006).

Hafenbrak, R. et al. Triggered polarization-entangled photon pairs from a single quantum dot up to 30 K. *New Journal of Physics* **9**, 315(2007).

Avron, J.E. et al. Entanglement on Demand through Time Reordering. *Phys. Rev. Lett.* **100**, 120501-4(2008).

- Asymmetric dot shape, strain, crystal anisotropy, etc.
- e-h exchange interaction leads to fine structure splitting $\Delta = O(10\ \mu eV)$

- Largest eigenvalue?