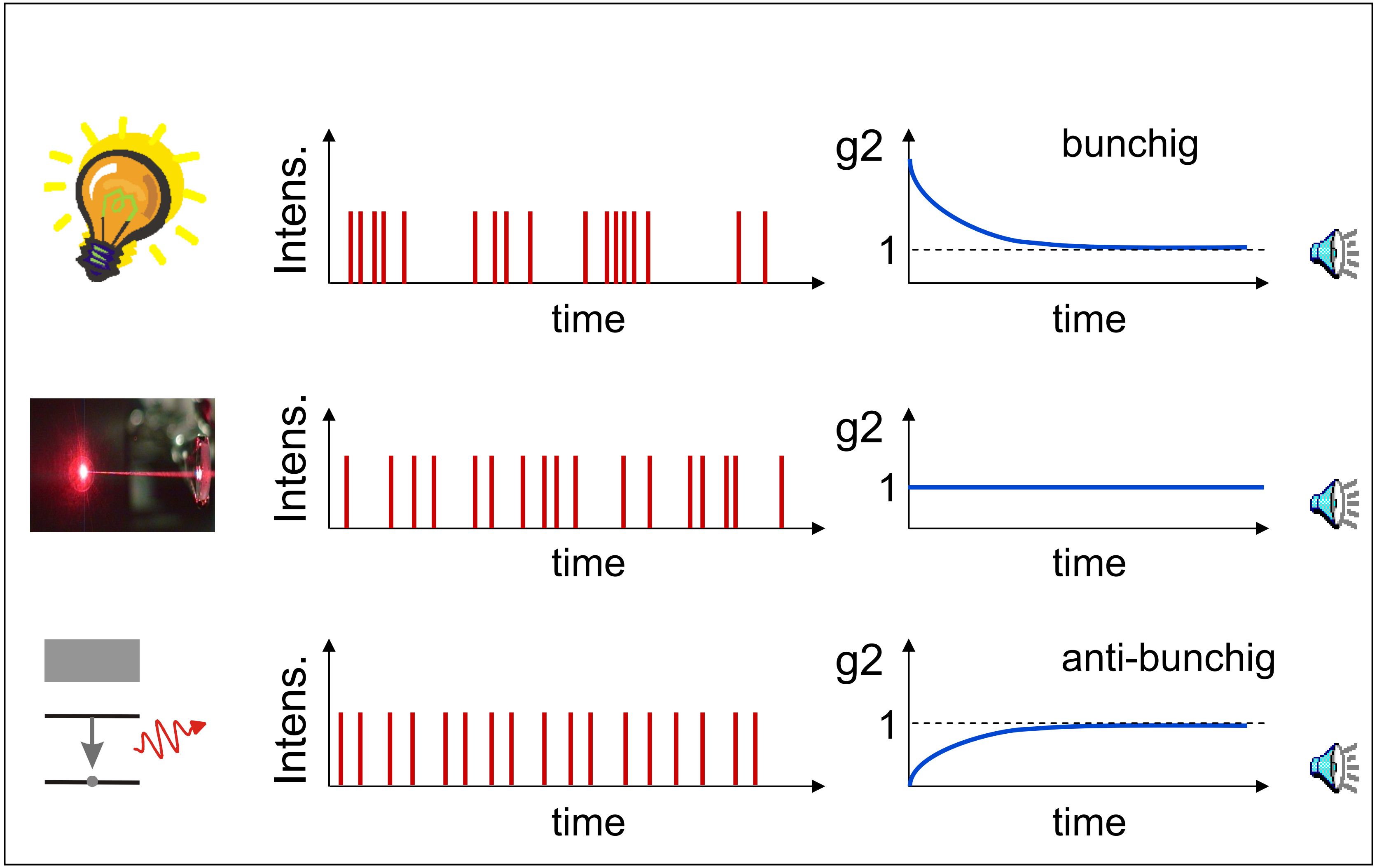
Single Photon Generation &

Application in Quantum Information Processing

- Quantum Dot Single Photon Sources
- Optical Properties of Quantum Dots
- Cascaded Emission from Quantum Dots
- Quantum Cryptography
- Indistinguishable Photons
- Generation of Entangled Photon Pairs

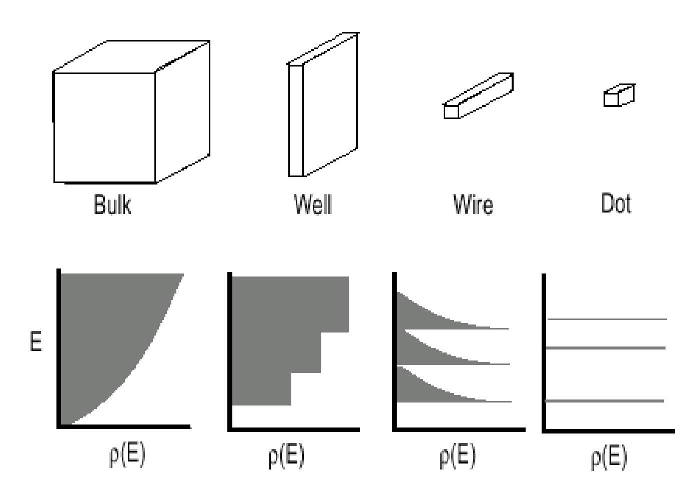
Single Photon Sources
Methods to Generate Single Photons on Demand



Quantum Dot Single Photon Sources

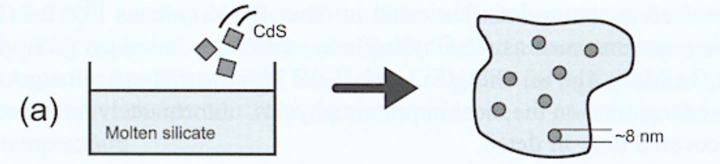
Quantum Dots

Semiconductor quantum dots are small semiconductor crystals that confine the charge carriers (electrons and holes) in all three dimensions.

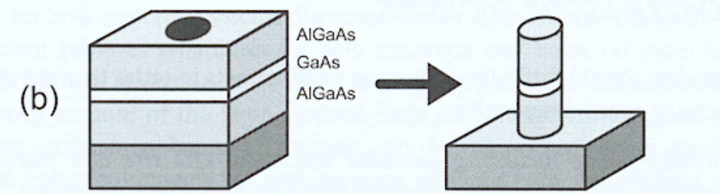


3D, 2D, 1D and 0D density of states

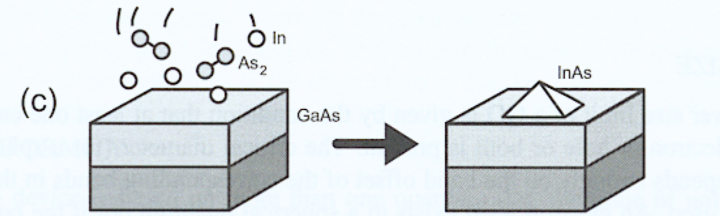
3 ways to make quantum dots:



chemical synthesis



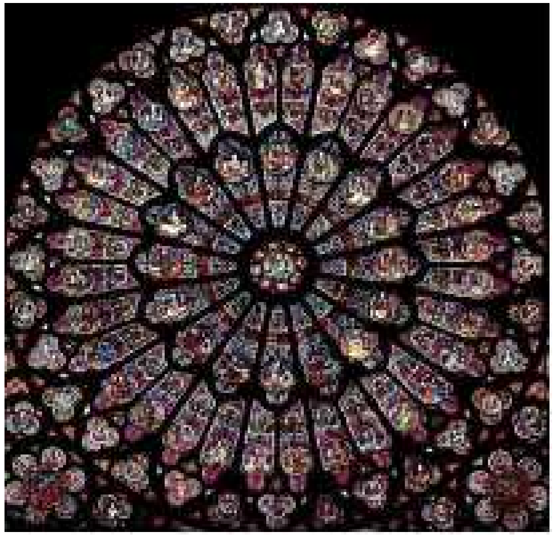
etching from 2D nanostructures



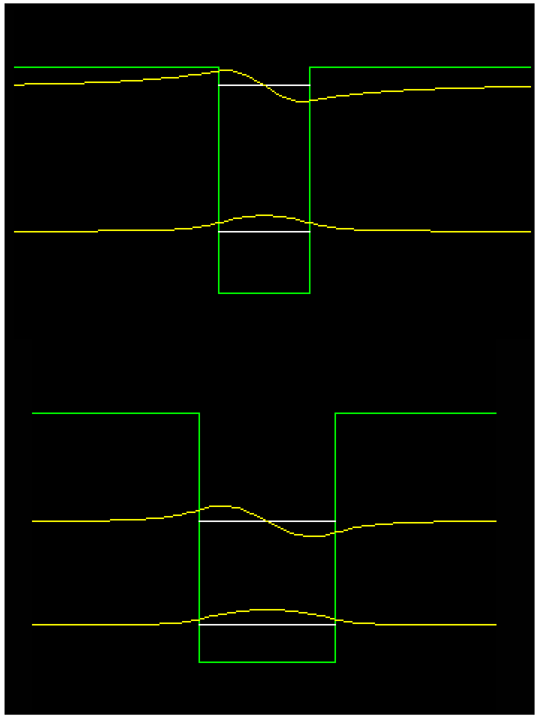
self organized growth

Nanocrystals

Quantum dots chemically synthesized from precursors in solution are called **nanocrystals**. They are nowadays commercially available, but have been used for many years in color glass or in color filters.



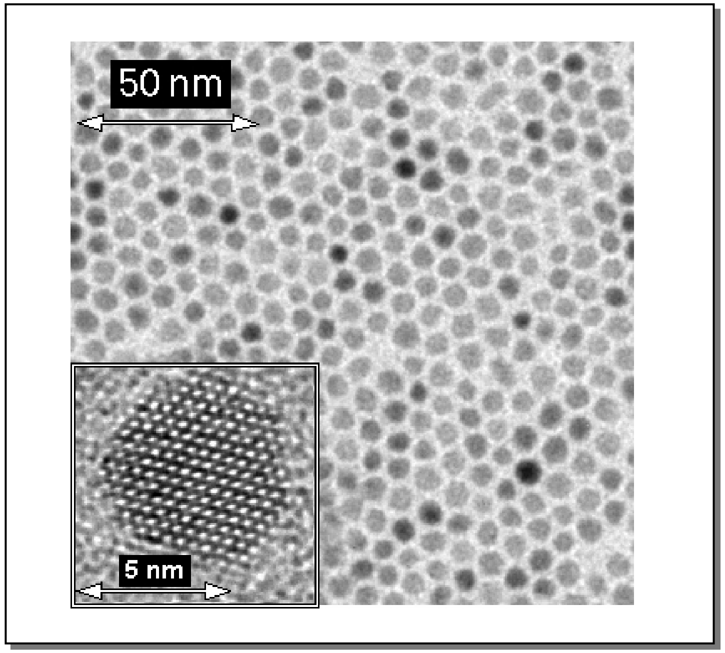
Notre Dame, rose window 1250-1260



eigenenergies and eigenfunctions of two dots of different size

The different colors of the emitted light are determined by the size of the nanocrystals, which varies from 1 to 10 nanometers.

Fluorescence from nanocrystals excited by UV light (left) and TEM images of nanocrystals (right) [provided by A. Rogach Univ. Munich]

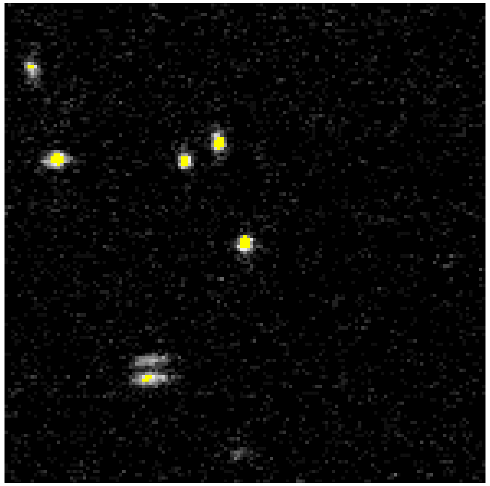


Nanocrystals or colloidal quantum dots:
- allow tuning of fluorescence
- provide a clean fluorescence spectrum
- have a high fluorescence yield
- have a high photostability

Obstacles:
- photobleaching
- blinking & spectral jumps
- non-uniform size distributions

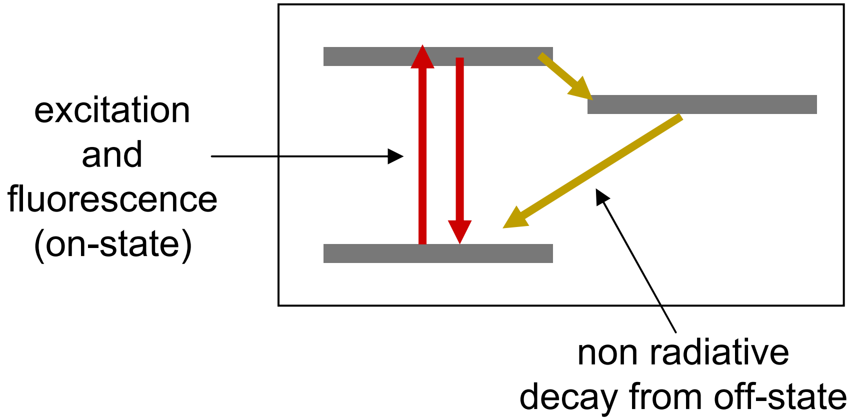
Nanocrystals have been used as optical markers in biochemistry and biophysics, but also in first photonic applications.

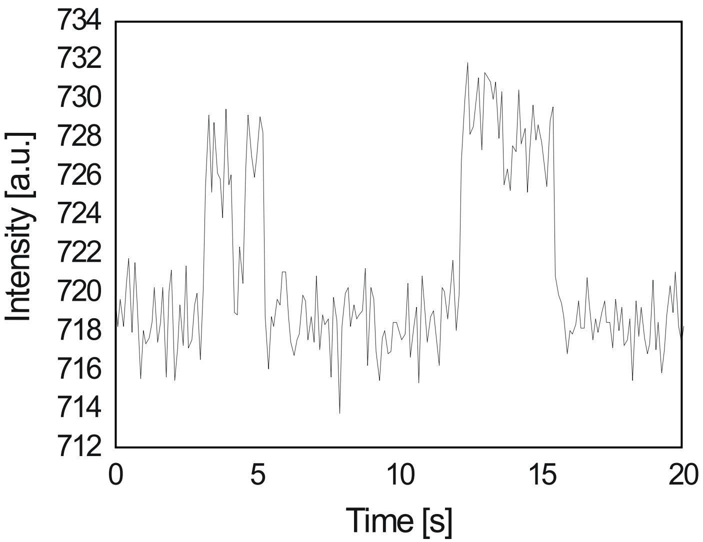
Blinking in quantum dot fluorescence

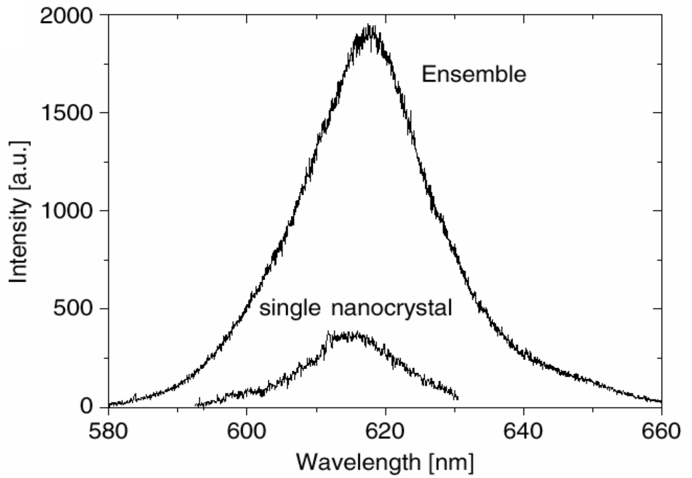


PL image

Spontaneous transition between on- and off states.





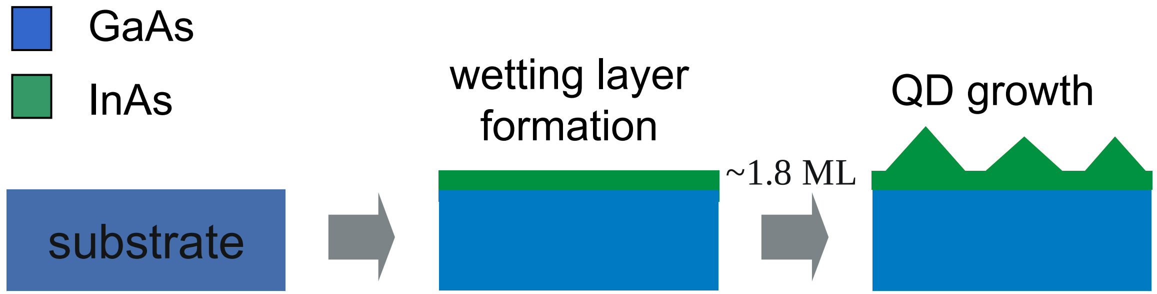


S. Götzinger et al., J. Opt. B 6, 154 (2004)

Self-organized Quantum Dots

MBE growth of slightly lattice mismatched materials (Stranski-Krastanow mode) produces very stable quantum dots.

The difficult task: **Low density** QD samples of high quality

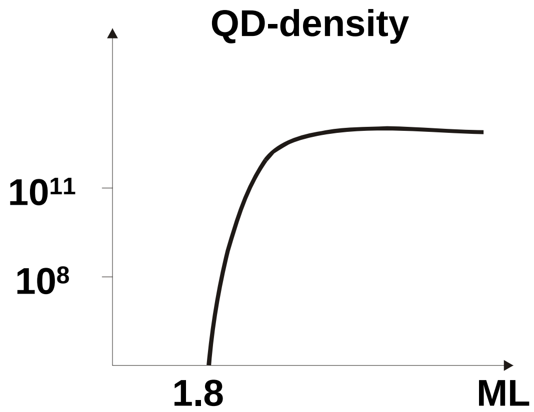


QD-density:

~ 10^8 cm^{-2}

<u>Growth parameter</u>

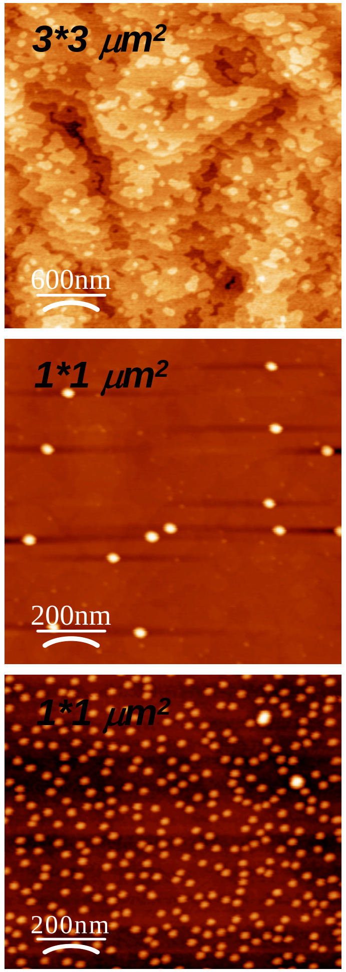
- Ratio of As to In: 50:1
- Temperature: 510 °C
- Rate: ~ 0.04 ML/s



Leonard et al.,

Appl. Phys. Lett. **63**, 3203 (1993)

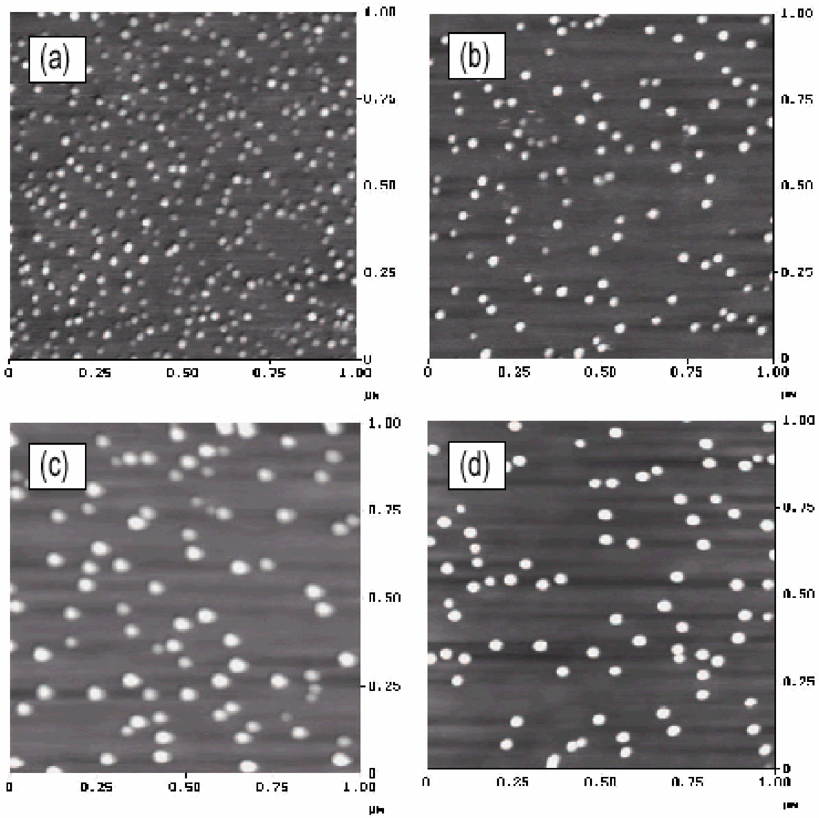
From wetting layer to quantum dots:



1.7 MLs
< critical thickness

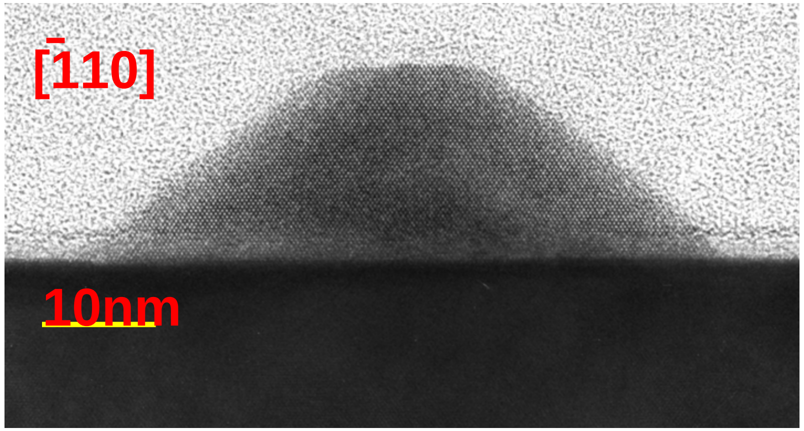
1.8 MLs
≈ critical thickness

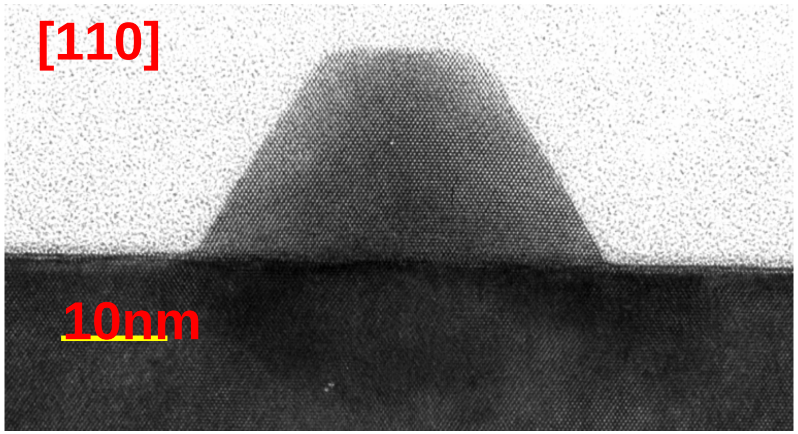
3 MLs
>> critical thickness

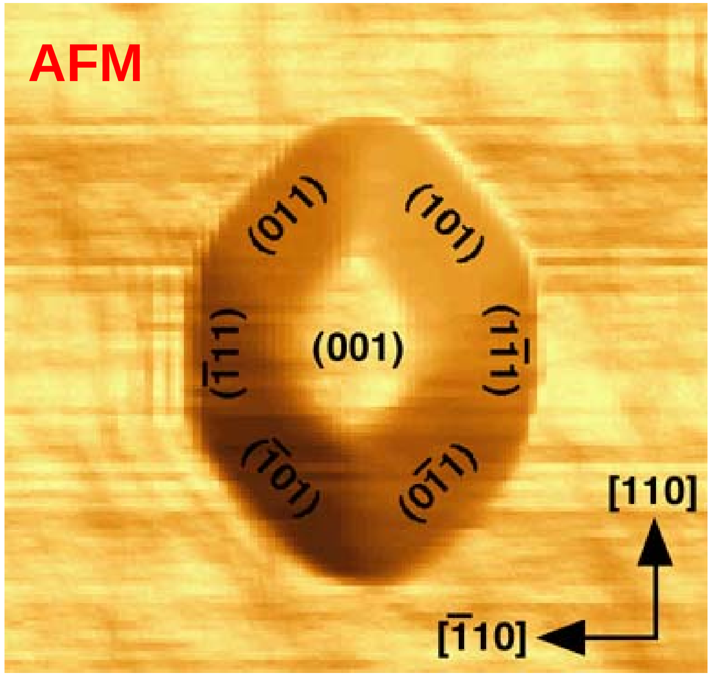


Control of dot density and size:
AFM image of samples grown at 480° (a), 487° (b), 498° (c), and 520° (d)

Transmission electron microscope images





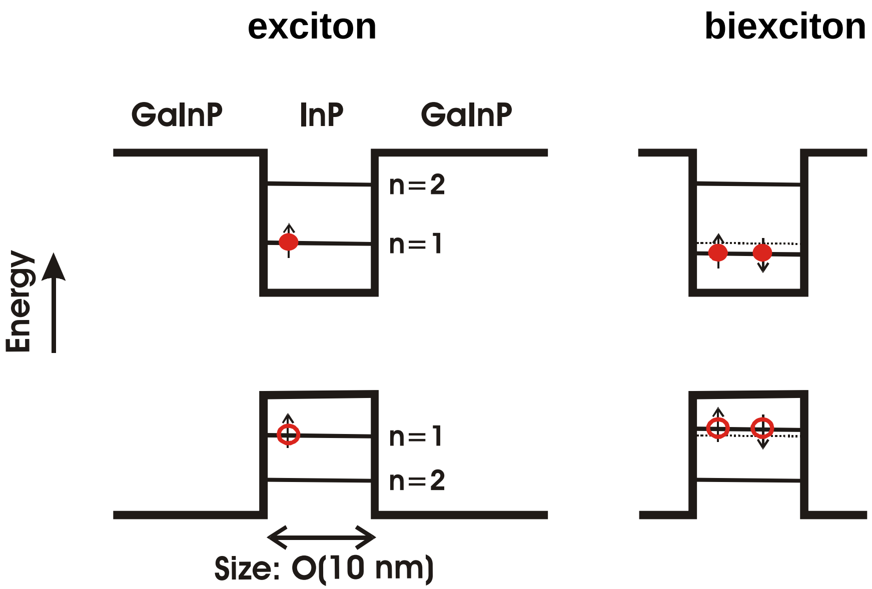


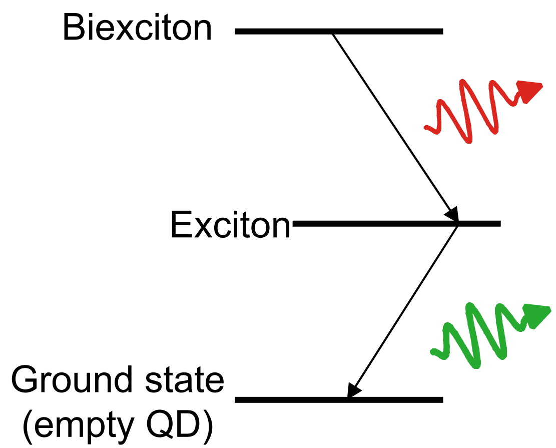
Contains ~10000 atoms

InP dots grown on GaInP

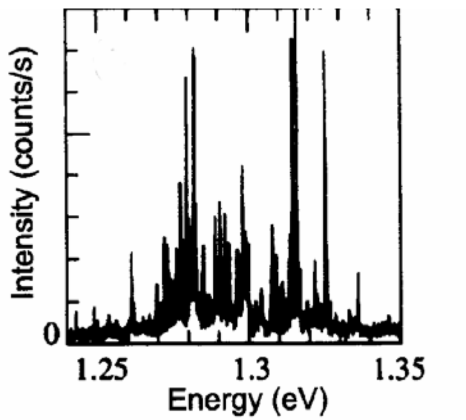
K. Georgsson et al., Appl. Phys. Lett. 67, 2981 (1995)

Self-organized quantum dots are embedded in a semiconductor with a larger bandgap. They represent a **heterostructure**.

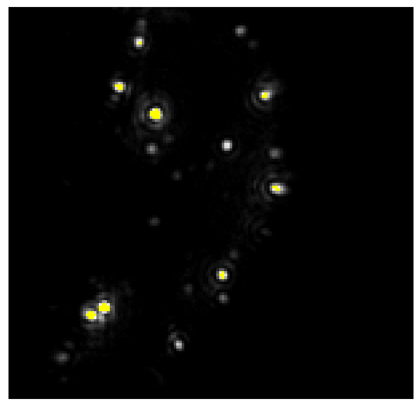




Photoluminescence of an ensemble of InAs quantum dots



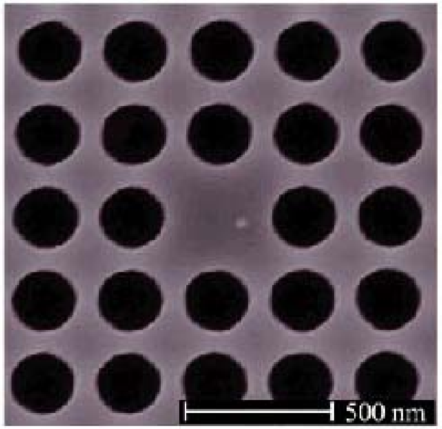
Photoluminescence image of a set of InP quantum dots



Due to their atomic-like properties quantum dots are sometimes referred to as **artificial atoms**.

Specific advantages of single quantum dots

- Stability
- Compatible with chip-technology
- Wide spectral range
- Electrical Pumping
- High repetition rate
- Strong interactions “available”

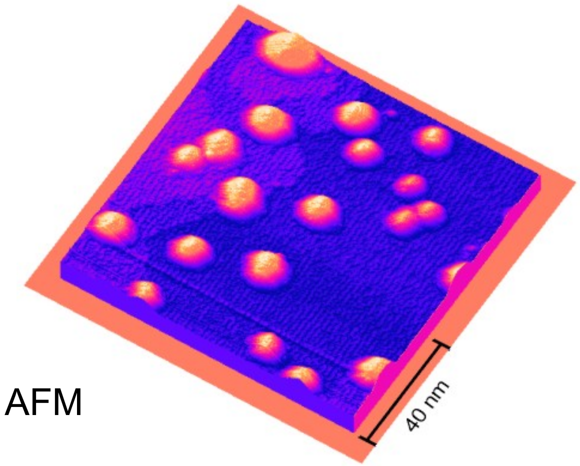


A. Badolato, et al., Science 20, 1158 (2005)

Specific disadvantages of single quantum dots

- Low temperature operation
- non-uniformity
- Device production yield
- Decoherence
- Efficiency

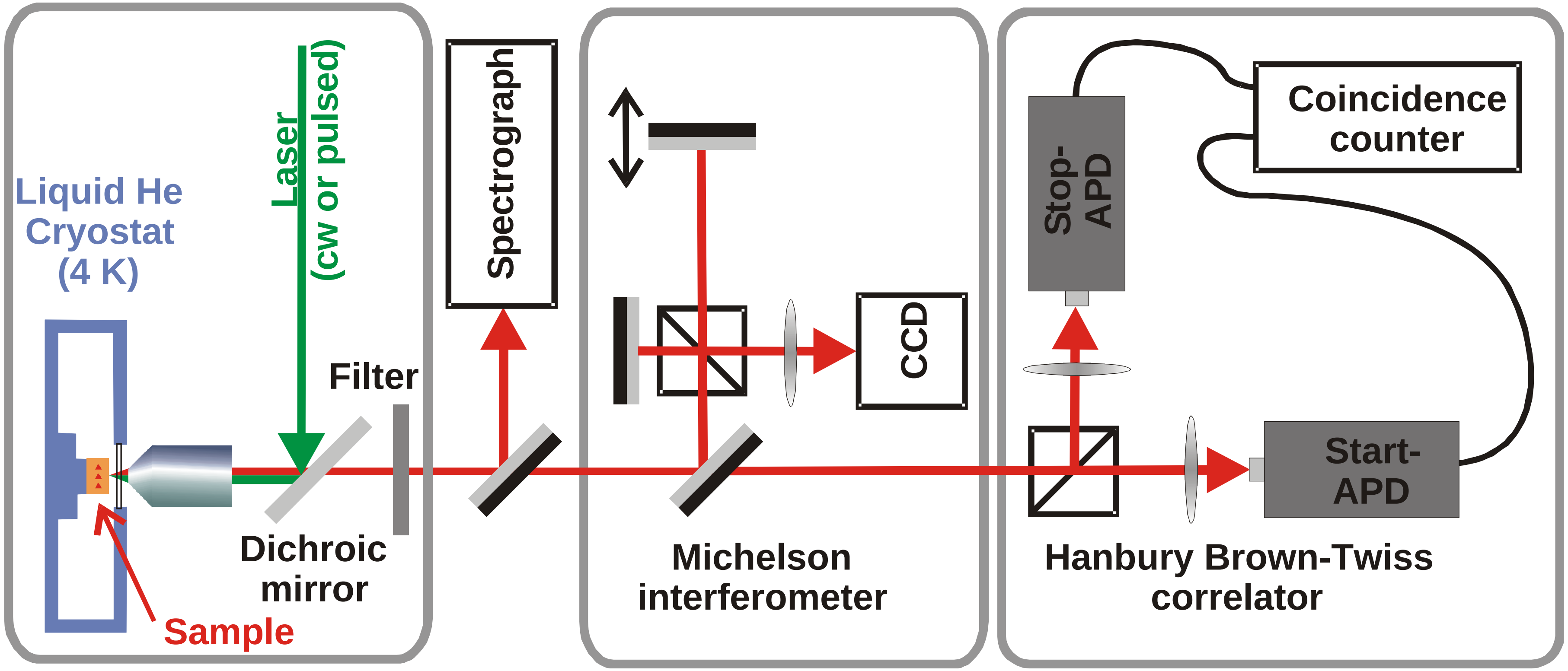
AFM



Optical Properties of Quantum Dots

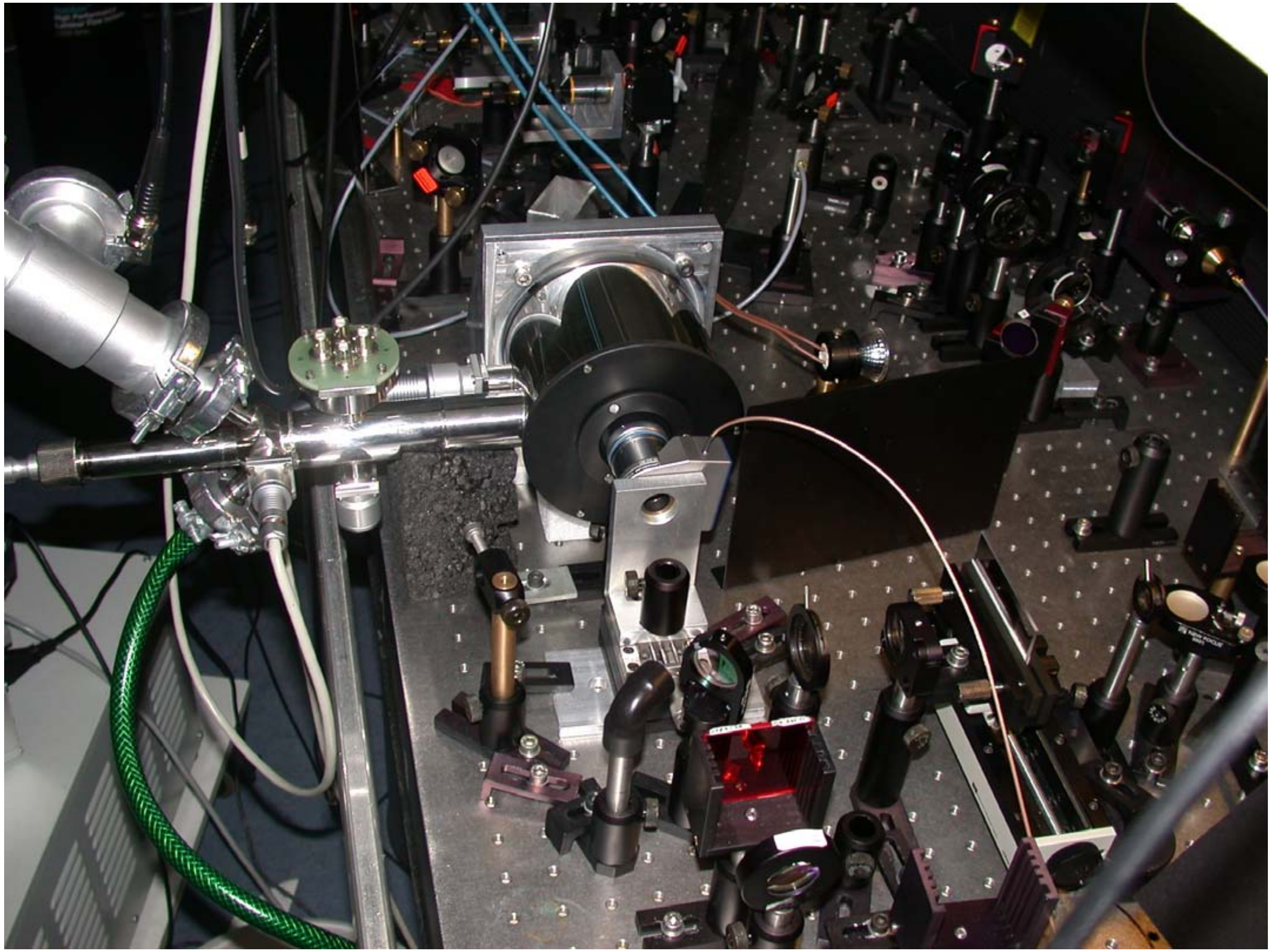
Experimental Setup

The following picture shows a setup to study the optical properties of single quantum dots:



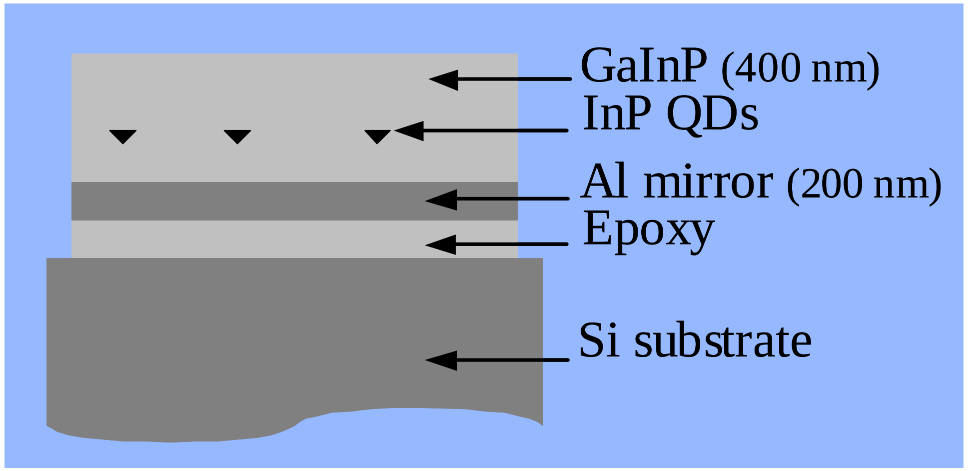
SPS **g1** **g2**

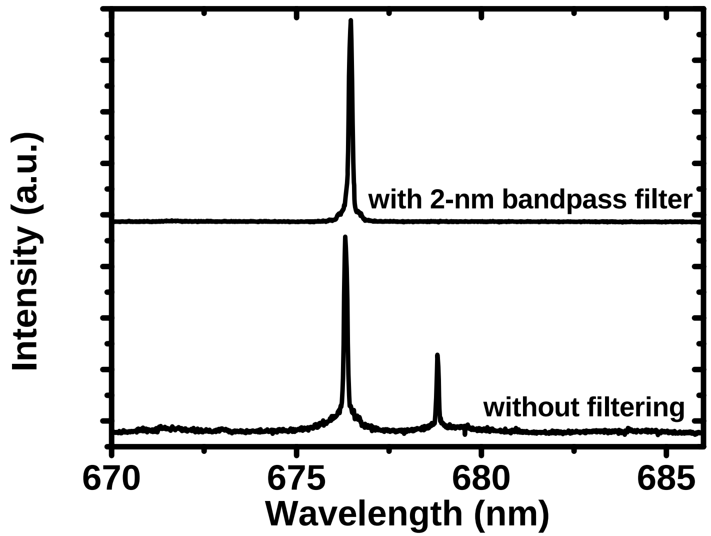
Experimental Setup



Some Details About the Quantum Dot Sample

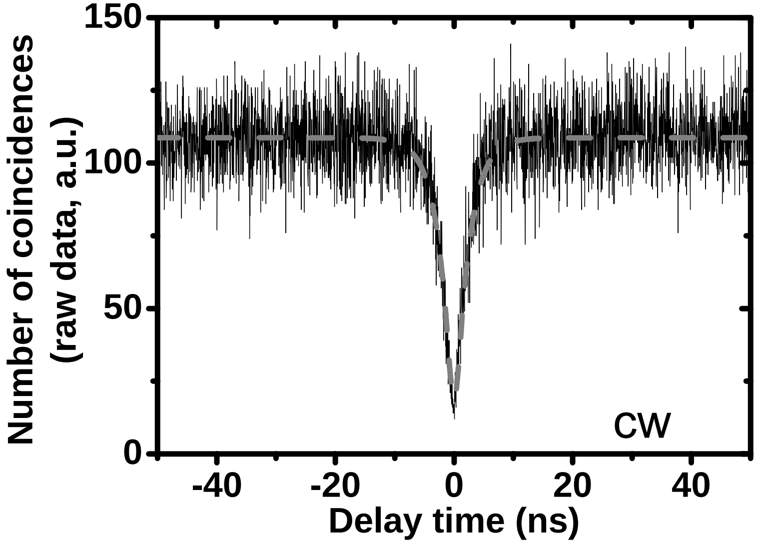
- Emission around 690 nm
  (@ maximum detection efficiency of Si detectors !)
- Lifetime around 2 ns
- Dot density: 10^8 cm^{-2}

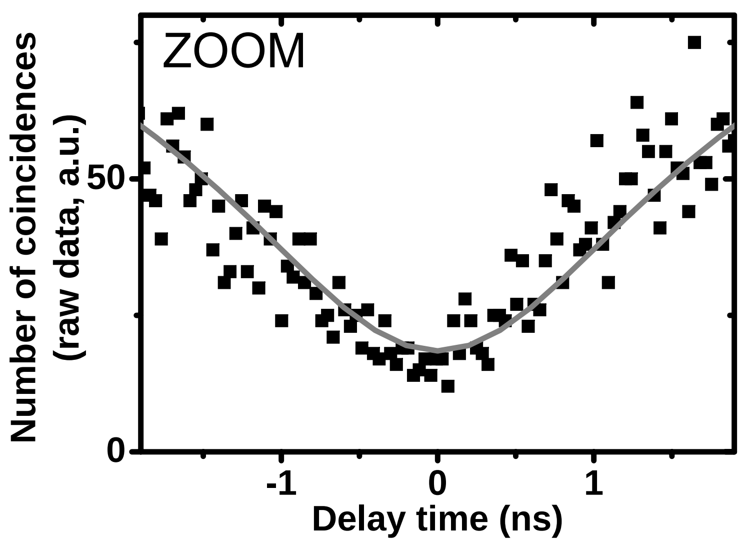




The additional mirror increases the photon emission rate by more than a factor of 2!.

Intensity Correlation Measurements ($g^{(2)}(\tau)$)



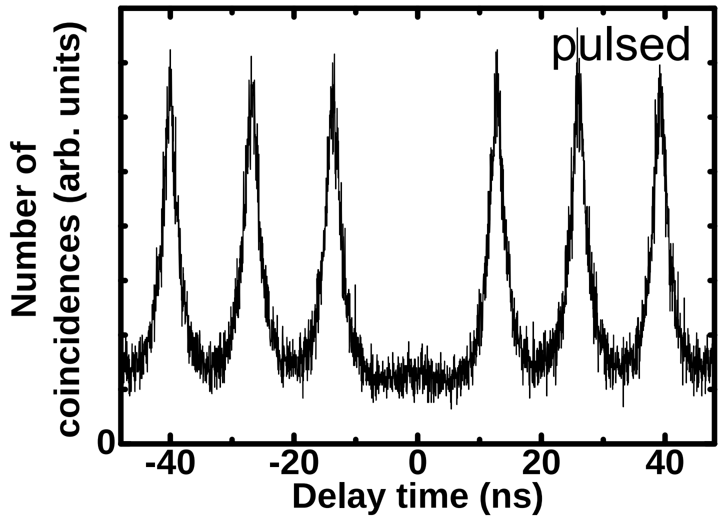


Measurement of $g^{(2)}(\tau)$ under cw and pulsed optical excitation:

• Central peak vanishes nearly completely

⇨ generation of only one photon per pulse

• Single photon generation @ 670 nm
observed up to 40 K

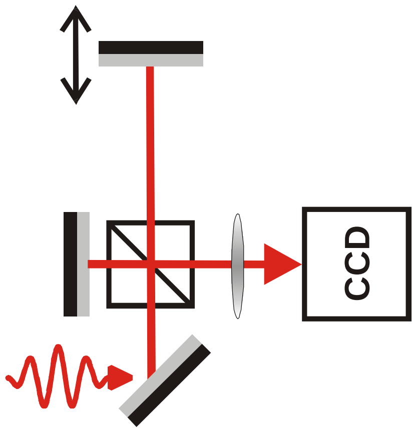


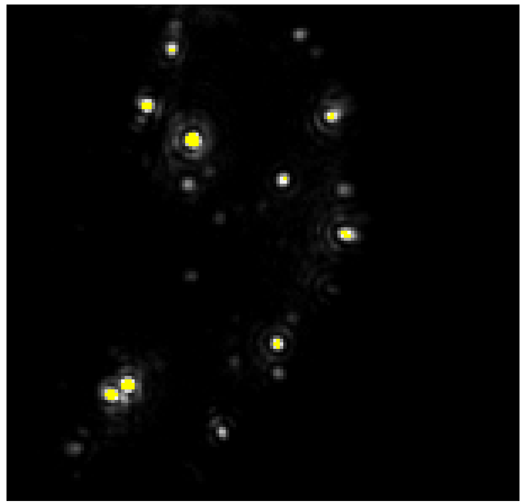
V. Zwiller, et al., Appl. Phys. Lett. 82, 1509 (2003)

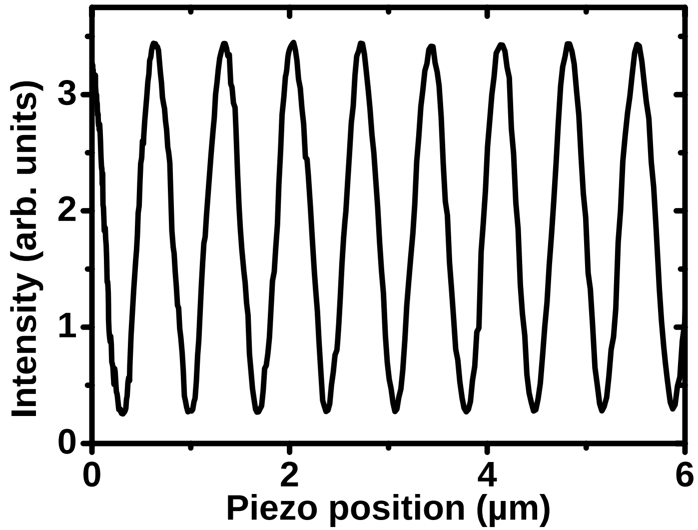
Fourier Spectroscopy ($g^{(1)}(\tau)$)

Measurement of G(1) of several dots simultaneously imaging on a CCD camera

V. Zwiller, et al., Phys. Rev B (2004)





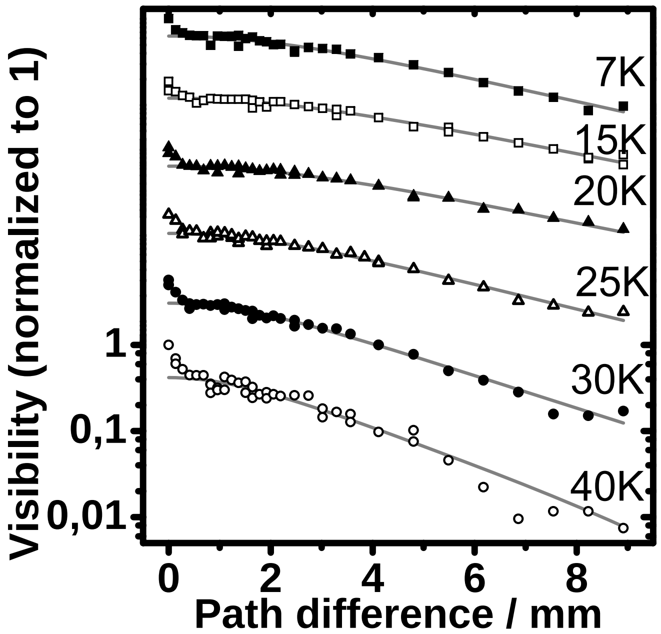


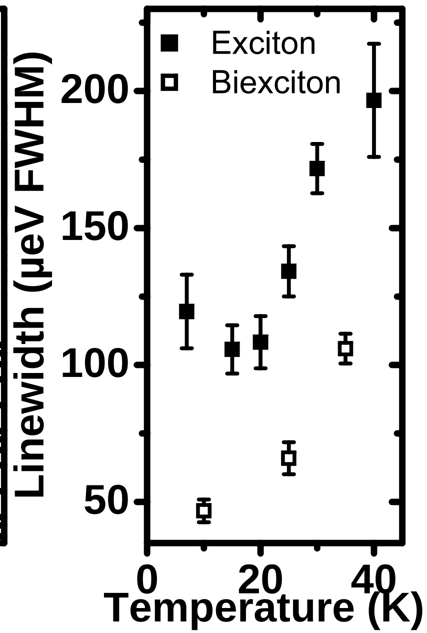
Visibility of the interference fringes:

$$v = (I_{max} - I_{min}) / (I_{max} + I_{min})$$

$$\Delta\nu = 50 \times \Delta\nu_{rad}$$

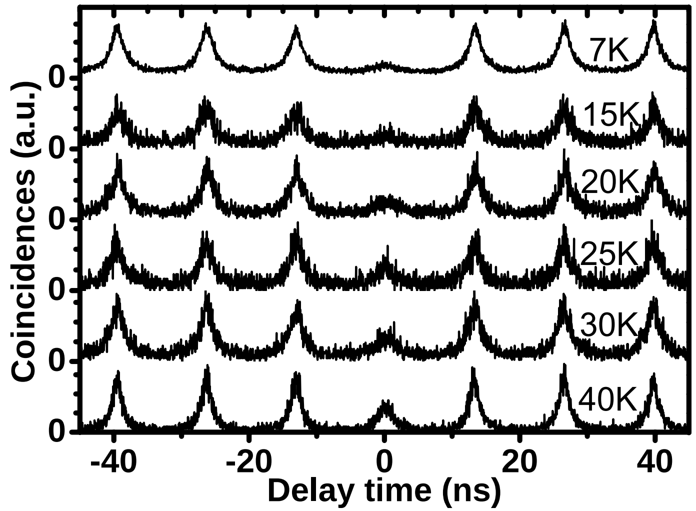
Fourier transform of $g^{(1)}(\tau)$ gives the linewidth of the emitted light.





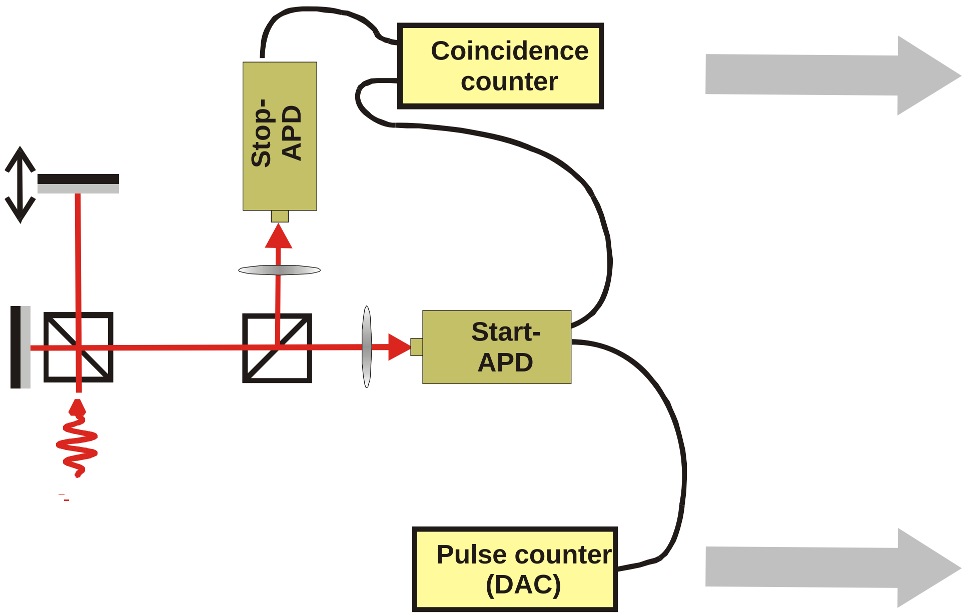
linewidth increases by a factor of two by increasing temperature from 7 to 40 K

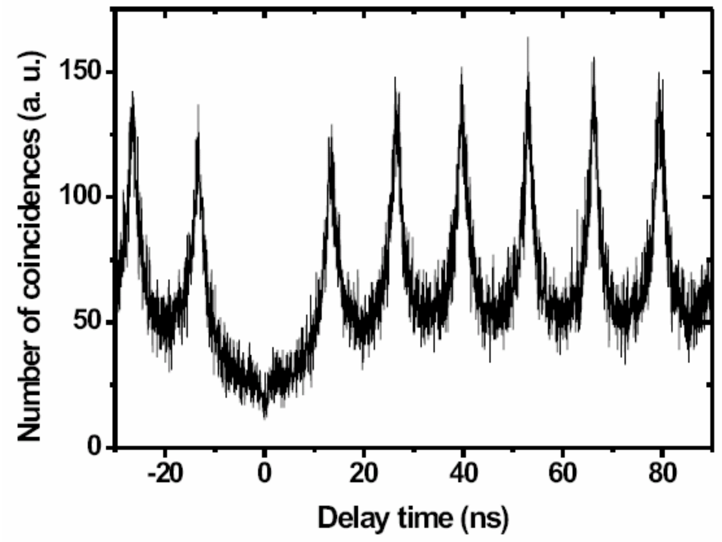
Single photon generation (anti-correlation below 0.5) up to 40 K

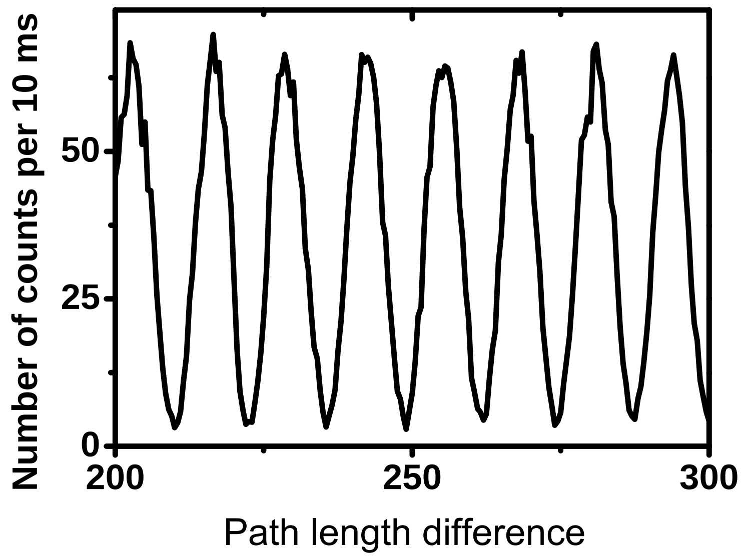


Wave and Particle Aspects

A single photon source allows to perform an interesting variation of Taylor's experiment.







Taylor-experiment (1906)

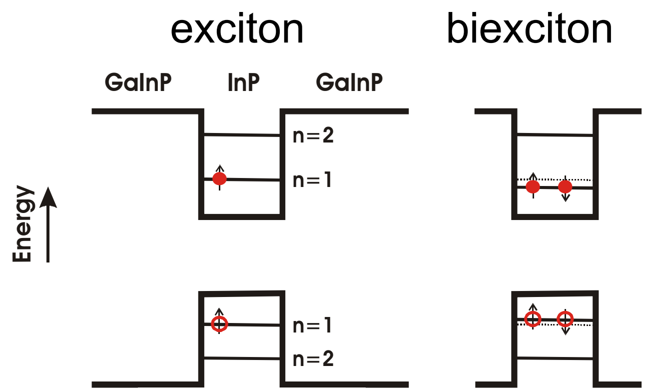
T. Aichele, et al., AIP proc. Vol. 750, 35 (2005)
V. Jacques, et al. Eur. Phys. J. D 35, 561 (2005)
J. T. Höffges, et al. *Opt. Comm.*, 133, 170–174 (1997)

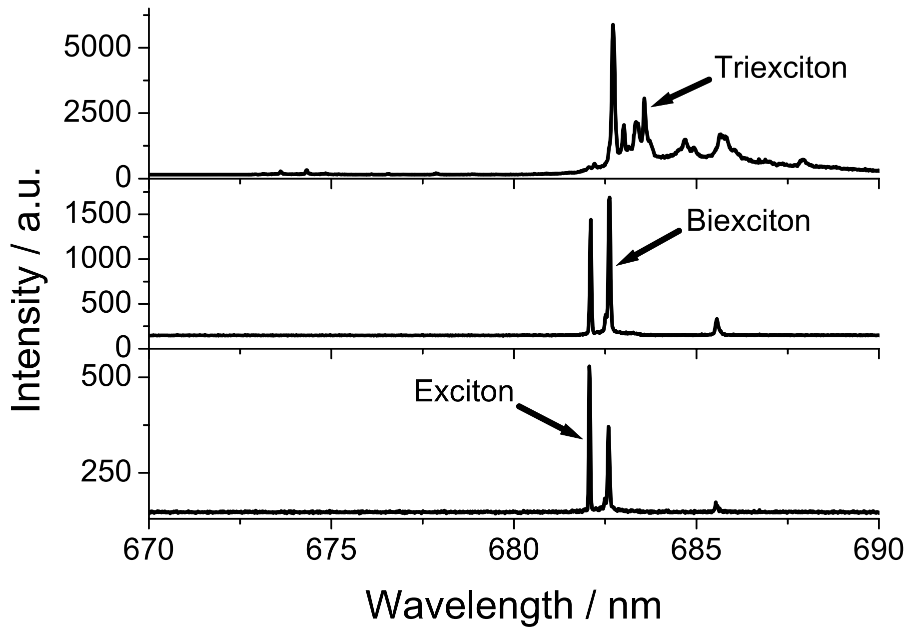
Cascaded Emission from Quantum Dots

Multicolor Sources

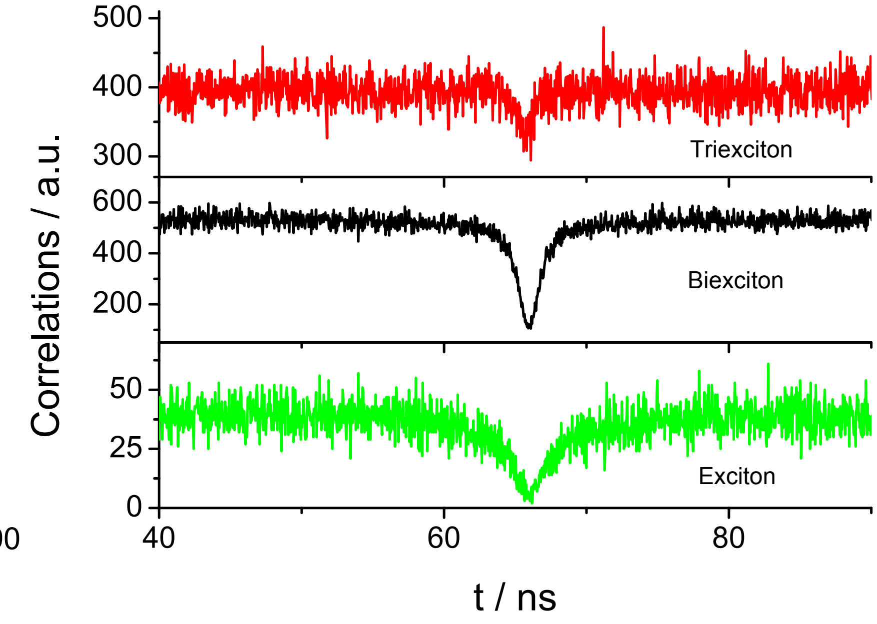
It is straightforward to create complex quantum states in quantum dots by adding electrons or holes.

The decay of these states provide:
- photon cascades
- multicolor photon sources
- sources for complex photonic states



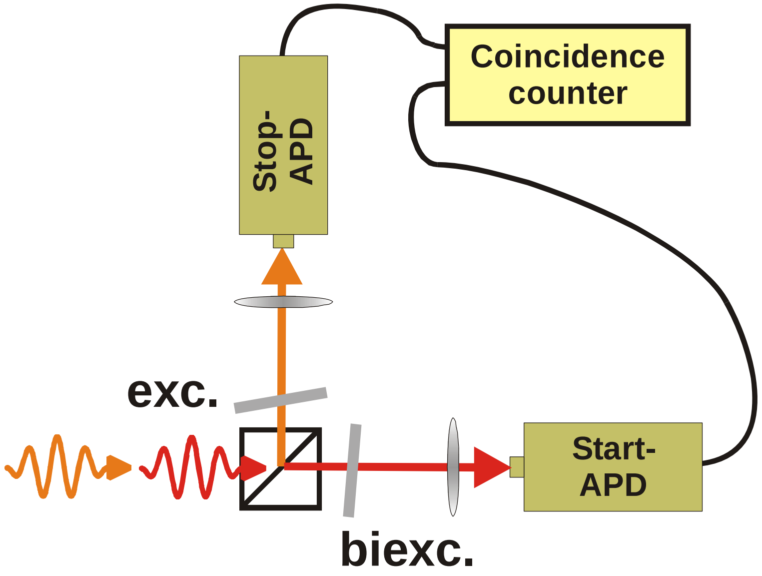


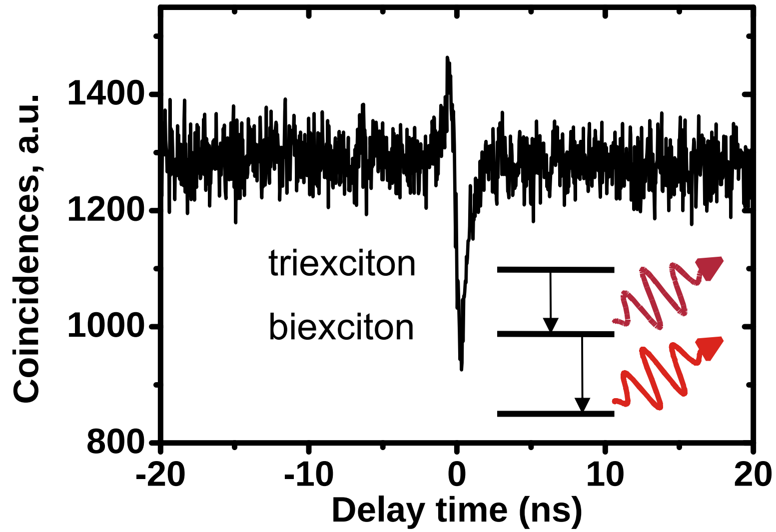
Spectra with increasing excitation power



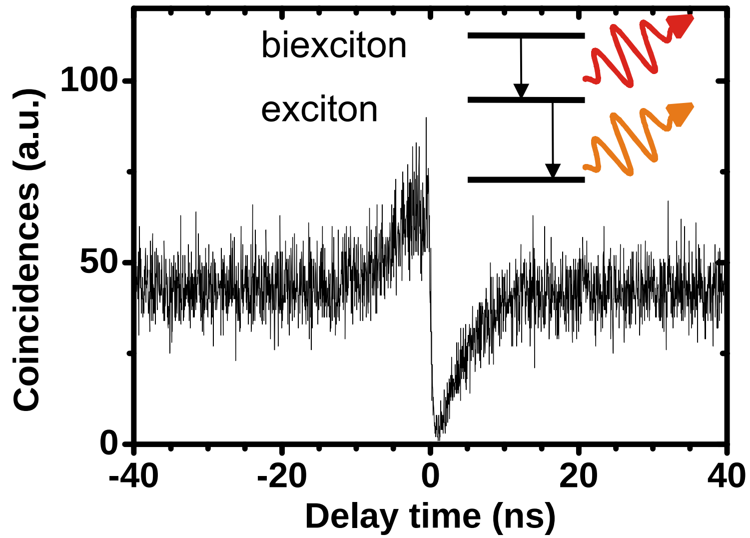
$g^{(2)}$ measurements for individual spectral lines

Cascaded decay can be proven in a modified HBT setup with narrow-band spectral filters in each arm.





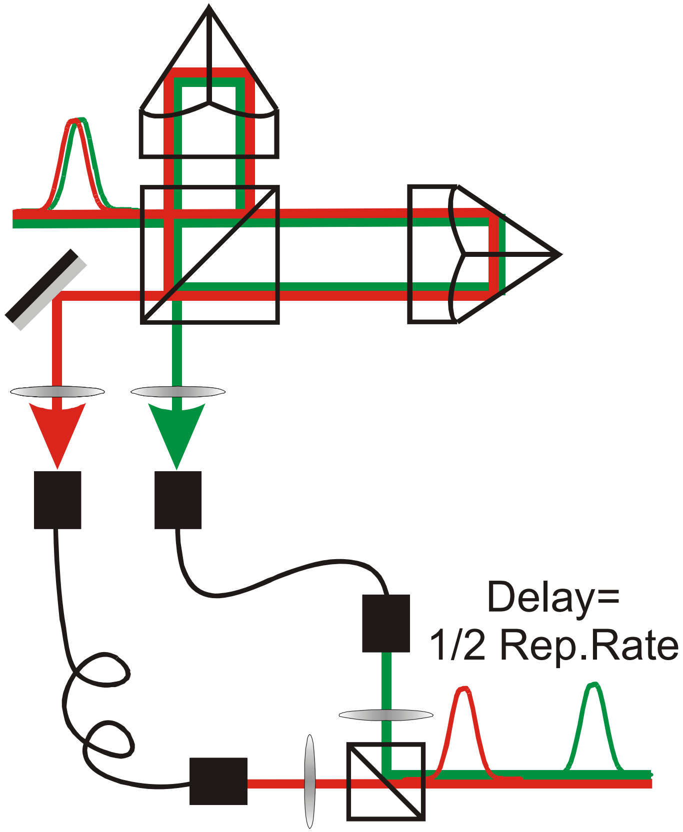
Correlation measurements reveal dynamics of multiphoton cascades

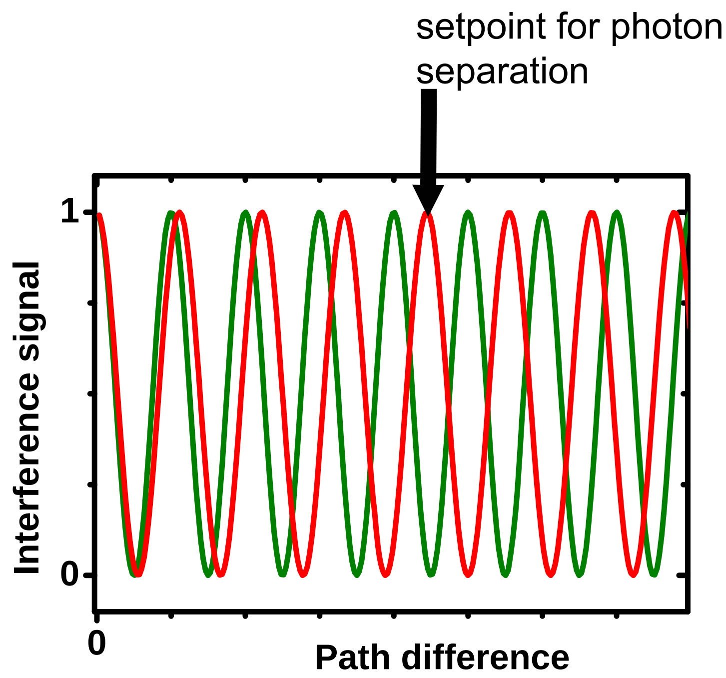


J. Persson et al., Phys. Rev. B 69, 233314 (2004)
D. V. Regelmann, et al. Phys. Rev. Lett. 87, 257401(2001)
E. Moreau et al., Phys. Rev. Lett. 87, 163601 (2001)
A. Kiraz et al. Phys. Rev. B 65, 161303 (2002)

The photons emitted in a cascade have different wavelengths due to the additional Coulomb binding energy of the biexciton, triexciton, etc..
A cascaded emitter is thus a multi-color single photon source.

The photons can be separated with high efficiency using interferometric techniques.

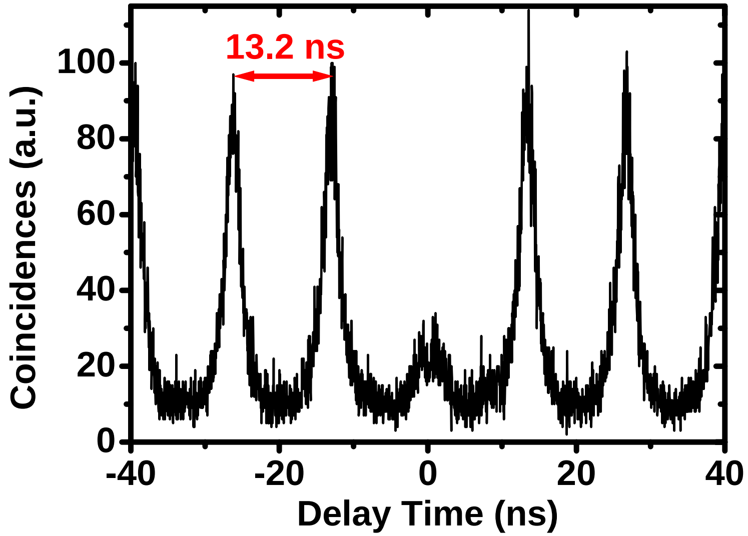




Autocorrelation of the exciton transition.

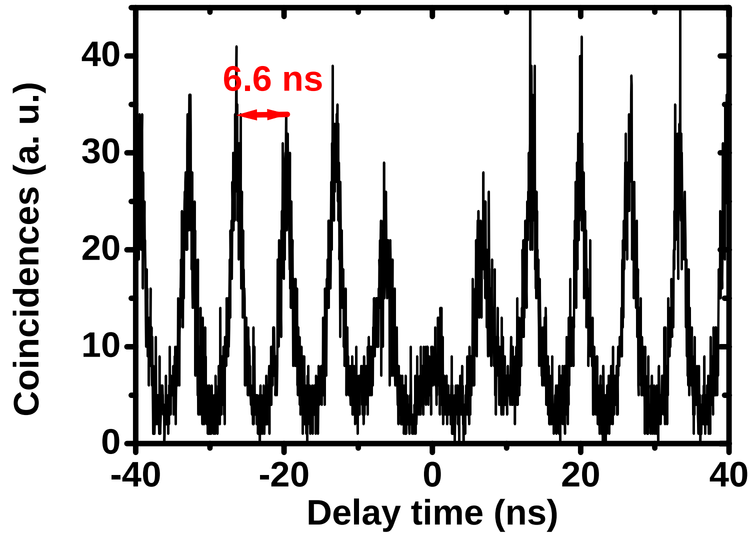
The peak at τ=0 is due to background counts.

→ One quantum emitter acts as two independent single photon sources.

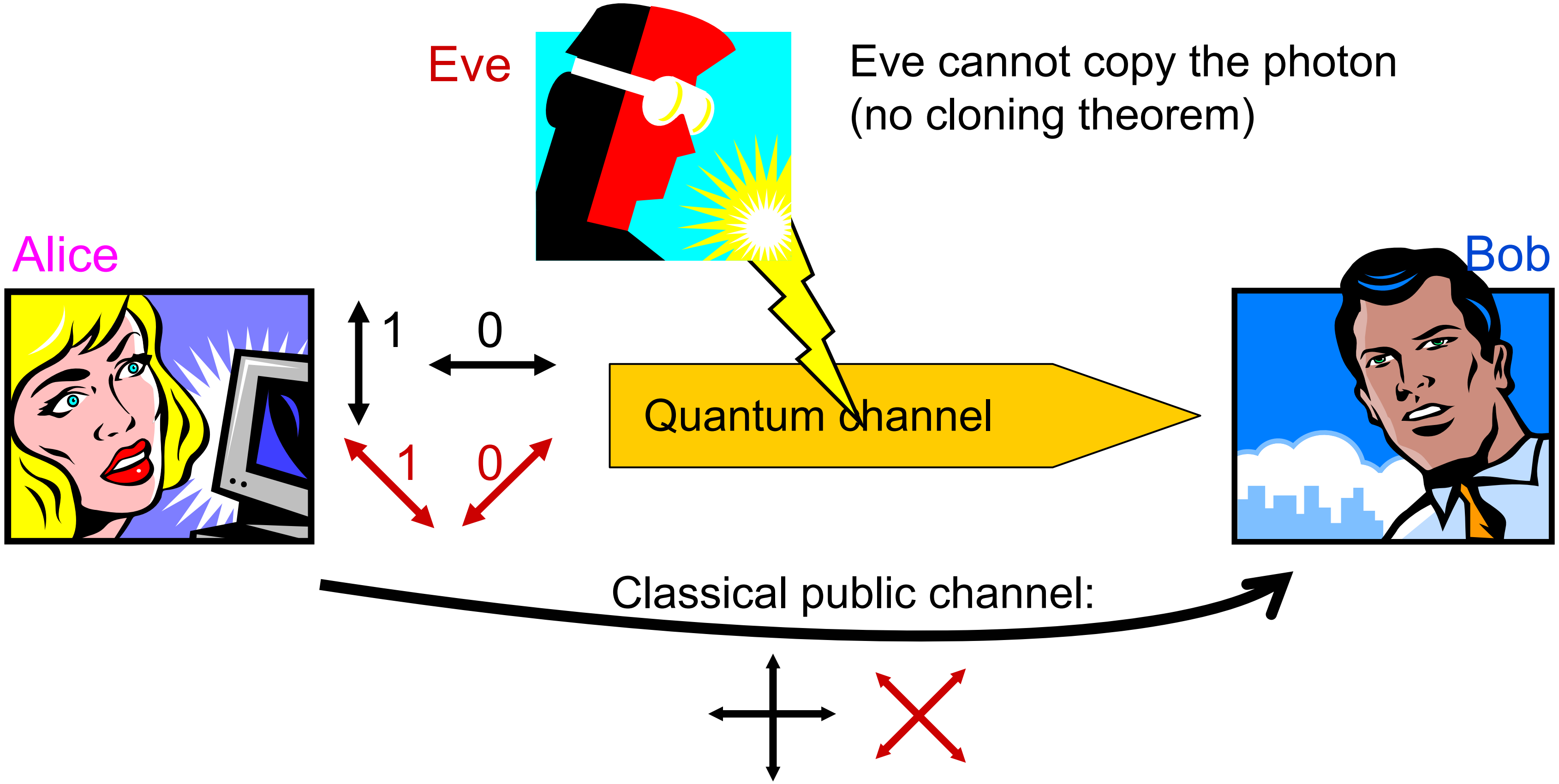


Autocorrelation after delaying and recombining the exciton and biexciton line
Delaying the two photons by half the excitation repetition time doubles the photon rate.

→ Generation of photons beyond the maximum rate limited by the natural transition lifetime

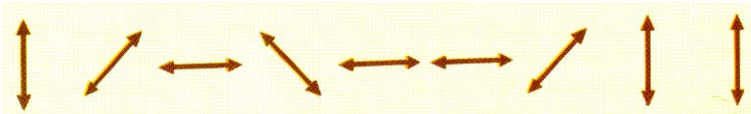


Quantum Cryptography
The BB84 Protocol



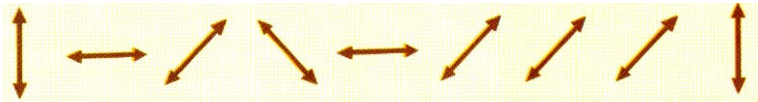
Bennett, Brassard, Proc. IEEE Int. Conf. on Computers, Systems & Signal Processing (1984),
First realization with QDs: Waks et al., Nature 420, 762 (2002)

- Alice sends randomly polarized photons (0, 45, 90 or 135°) to Bob.



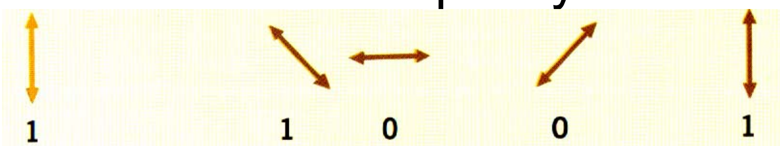
- Bob randomly measures in the straight or diagonal base.

- Bob keeps his results secret.

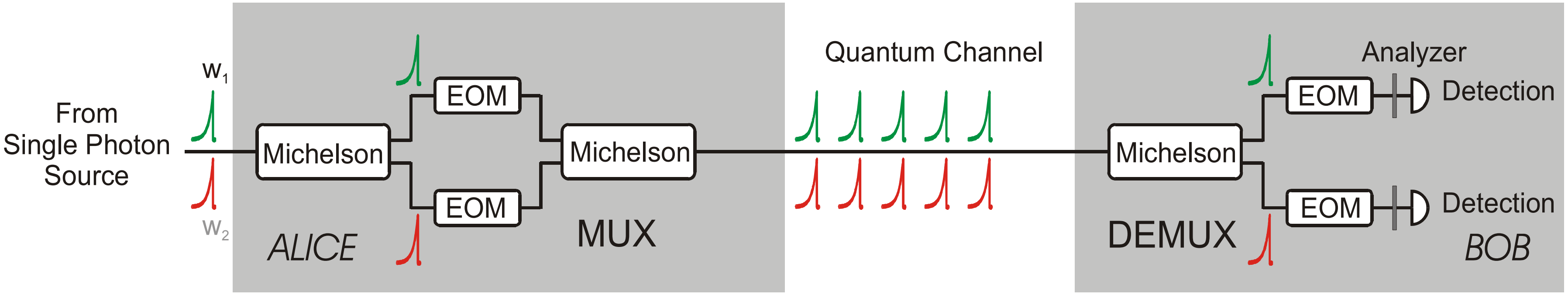


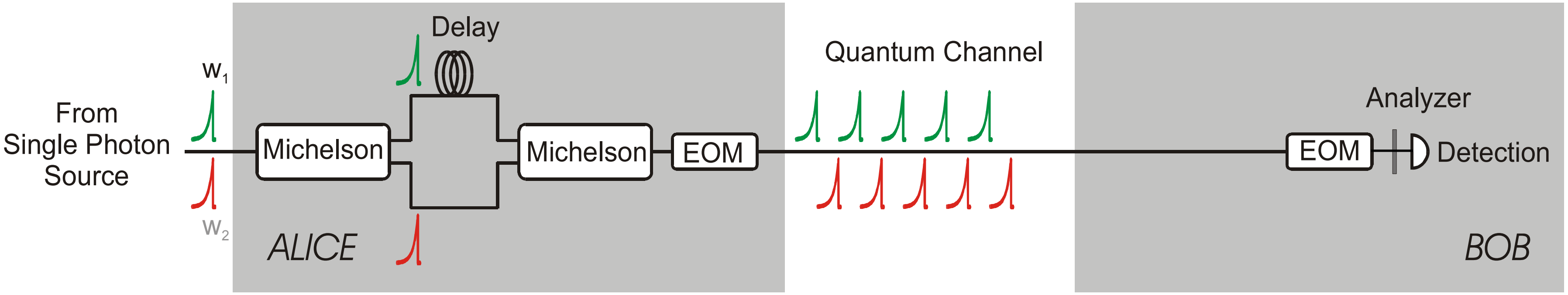
- Bob publically tells his measurement bases (not the results!). Alice publically tells him if he chose the right base.

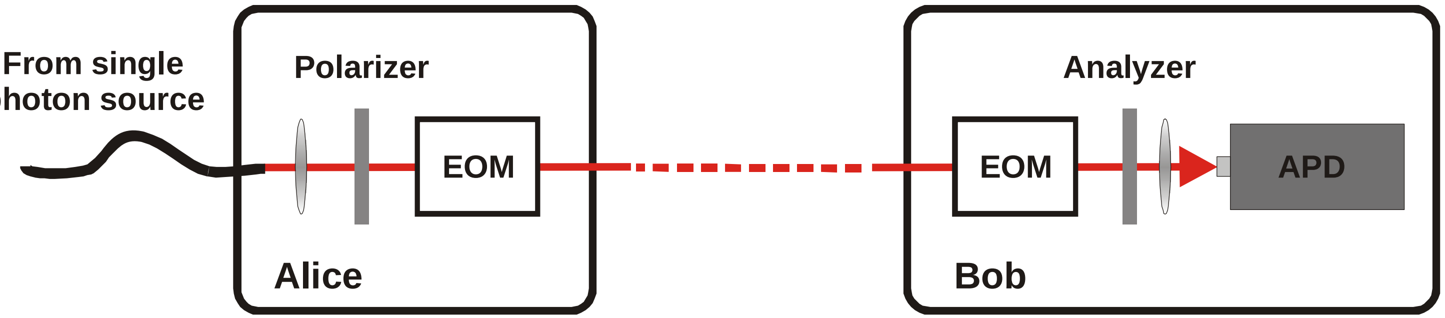
- Alice and Bob keep only the results with the common bases.



- They both have now a common and random key: 1 1 0 0 1 ...


w1
From
Single Photon
Source
w2
Michelson
EOM
EOM
Michelson
ALICE
MUX
Quantum Channel
Michelson
DEMUX
Analyzer
EOM
Detection
EOM
Detection
BOB


w1
From
Single Photon
Source
w2
Delay
Michelson
Michelson
EOM
ALICE
Quantum Channel
Analyzer
EOM
Detection
BOB



Transmission to Bob: 30 successfull counts/s at a laser modulation of 20 kHz

Similarity between Alice´s and Bob´s keys: 95%

T. Aichele, G. Reinaudi, O. Benson, Phys. Rev. B, 70, 235329 (2004)

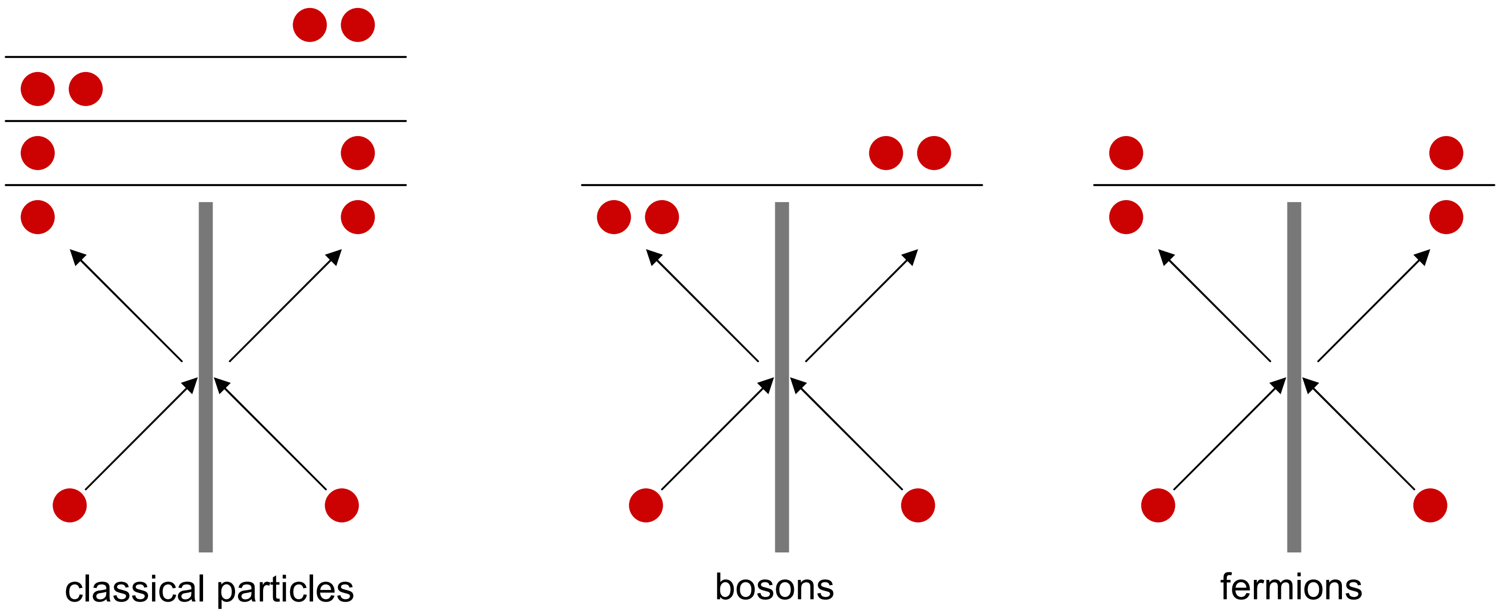
Indistiguishable Photons

The KLM Proposal

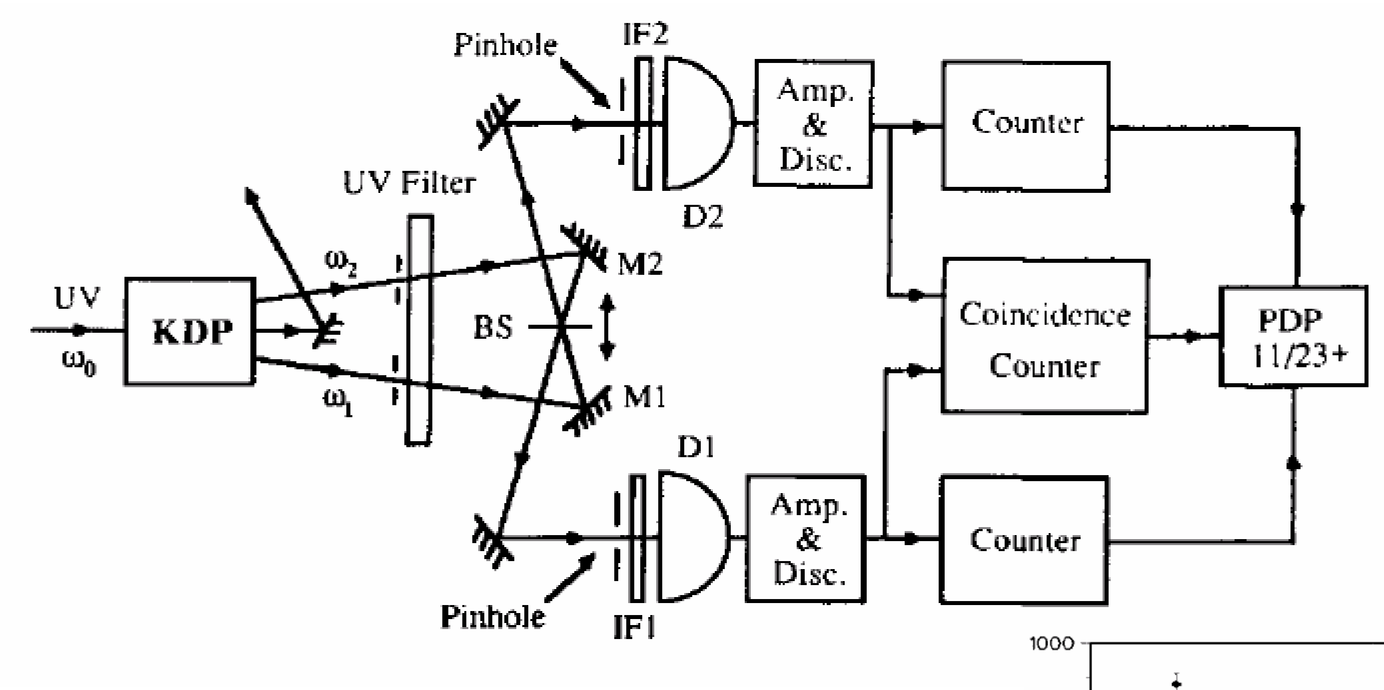
Knill, Laflamme, and Milburn [Knill, Laflamme, Milburn, Nature 409, 46 (2001)] suggested a *probilistic* two-qubit gate implemented with single photons and linear optical elements.

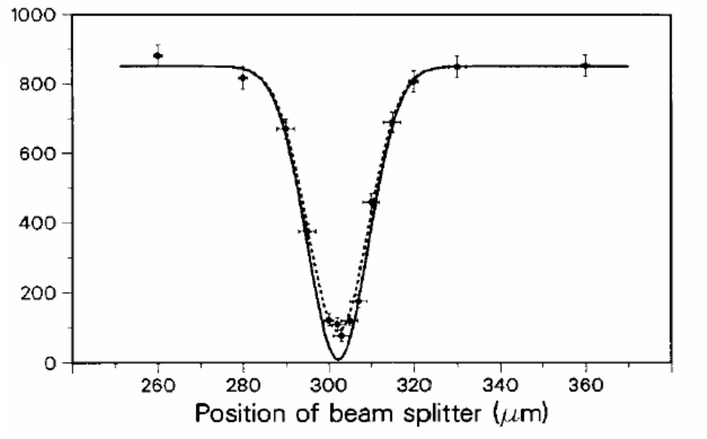
The gate requires photon number resolving counters and additional so-called *ancilla states* represented by photons which have to be **indistinguishable**.

It relies on two-photon quantum interference, e.g. at a beam splitter:



The quantum interference of bosons at a beam splitter was first measured by Hong, Ou, and Mandel [Phys. Rev. Lett. 59, 2044 (1987)] and is known as Hong-Ou-Mandel dip:





The depth of the HOM dip gives the „degree of indistinguishability“ of two photons.

With the help of HOM interference a fundamental two qubit gate, the CZ or *controlled-phase gate*, can be realized.

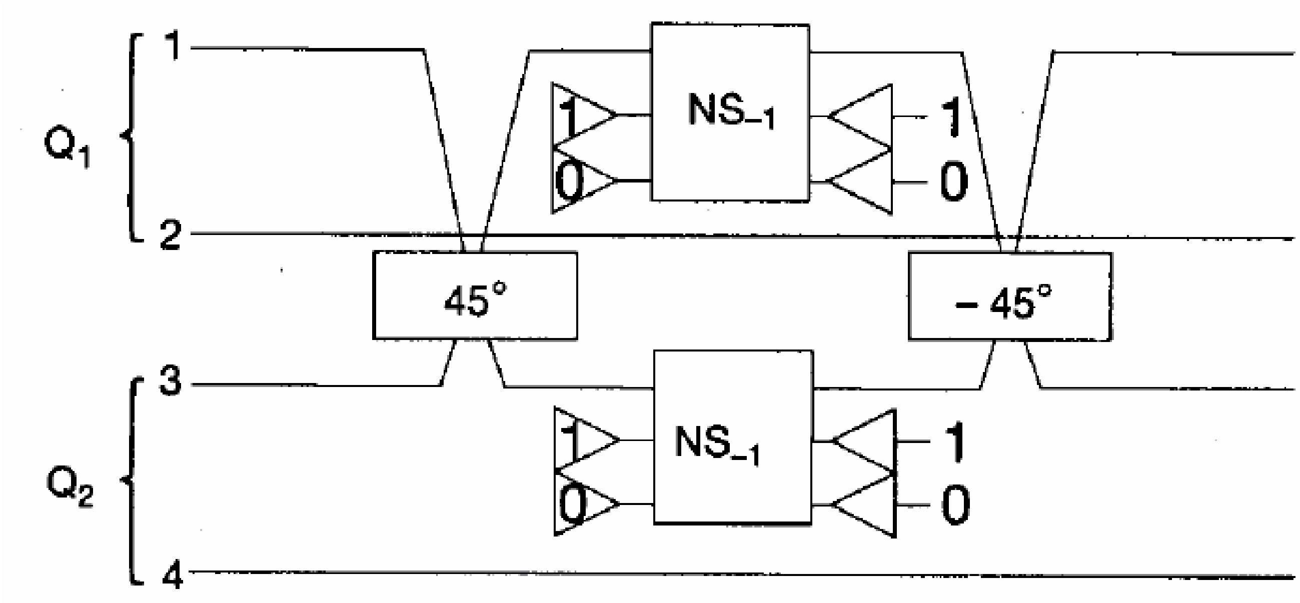
$$|C,Z\rangle \longrightarrow (-1)^{C\cdot Z}|C,Z\rangle$$

Control	Target	CZ	CNOT
$\|0\rangle$	$\|0\rangle$	$\|0,0\rangle$	$\|0,0\rangle$
$\|0\rangle$	$\|1\rangle$	$\|0,1\rangle$	$\|0,1\rangle$
$\|1\rangle$	$\|0\rangle$	$\|1,0\rangle$	$\|1,1\rangle$
$\|1\rangle$	$\|1\rangle$	$-\|1,1\rangle$	$\|1,0\rangle$

A CZ gate can be constructed with the help of the controlled phase shift gate $\mathbf{NS_{-1}}$:

$$|\psi\rangle = \alpha_0\,|0\rangle + \beta_1\,|1\rangle + \gamma_1\,|2\rangle \longrightarrow \alpha_0\,|0\rangle + \beta_1\,|1\rangle - \gamma_1\,|2\rangle$$

NS_{-1} gate



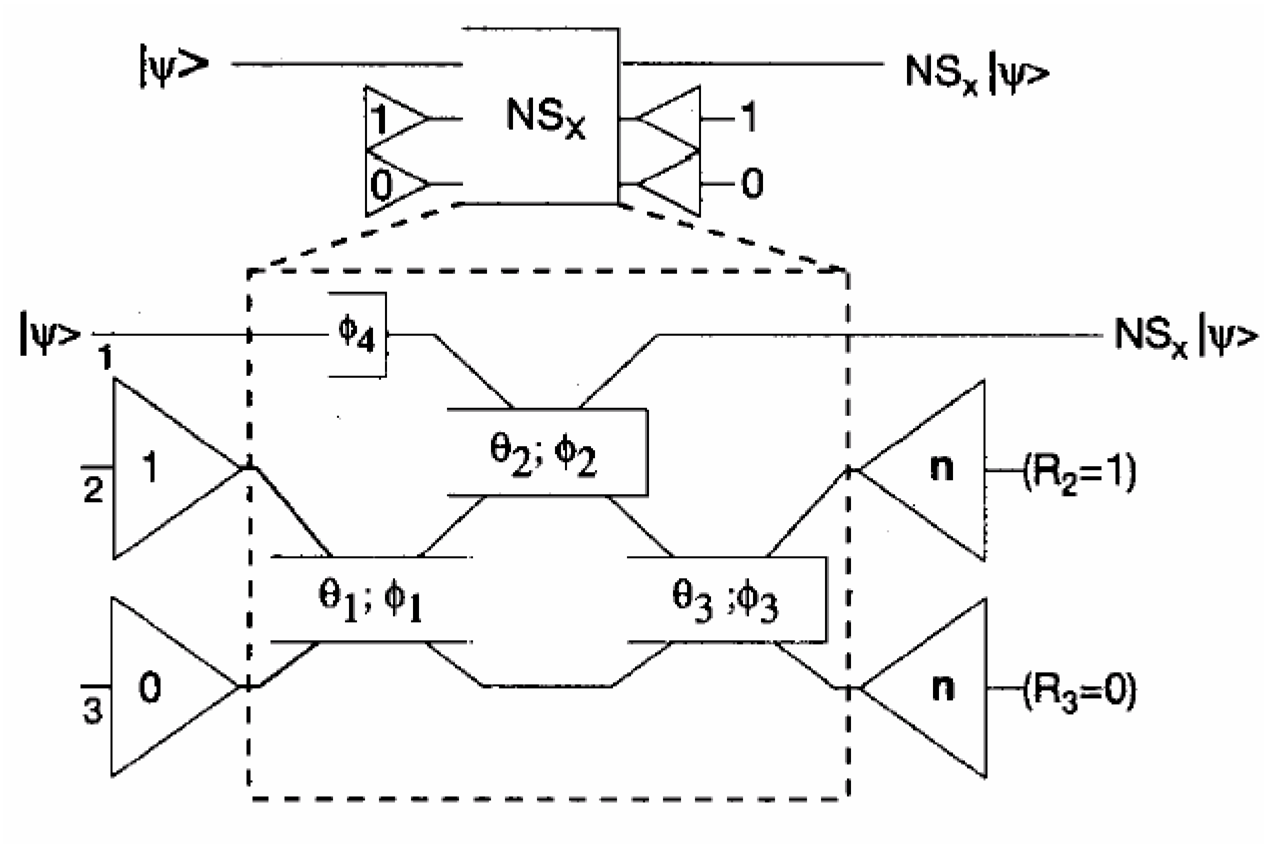
construction of a CZ gate with two NS_{-1} gates

How to make an NS_{-1} gate?

The original KLM gate uses ancilla states. These are measured after passing the gate. The operation of the gate is accepted only if a specific outcome is measured. Otherwise the operation has to be started again.

Thus the gate is *probabilistic* with success probabilty 1/4

It acts on arbitrary initial states |ψ>.



x = -1

if

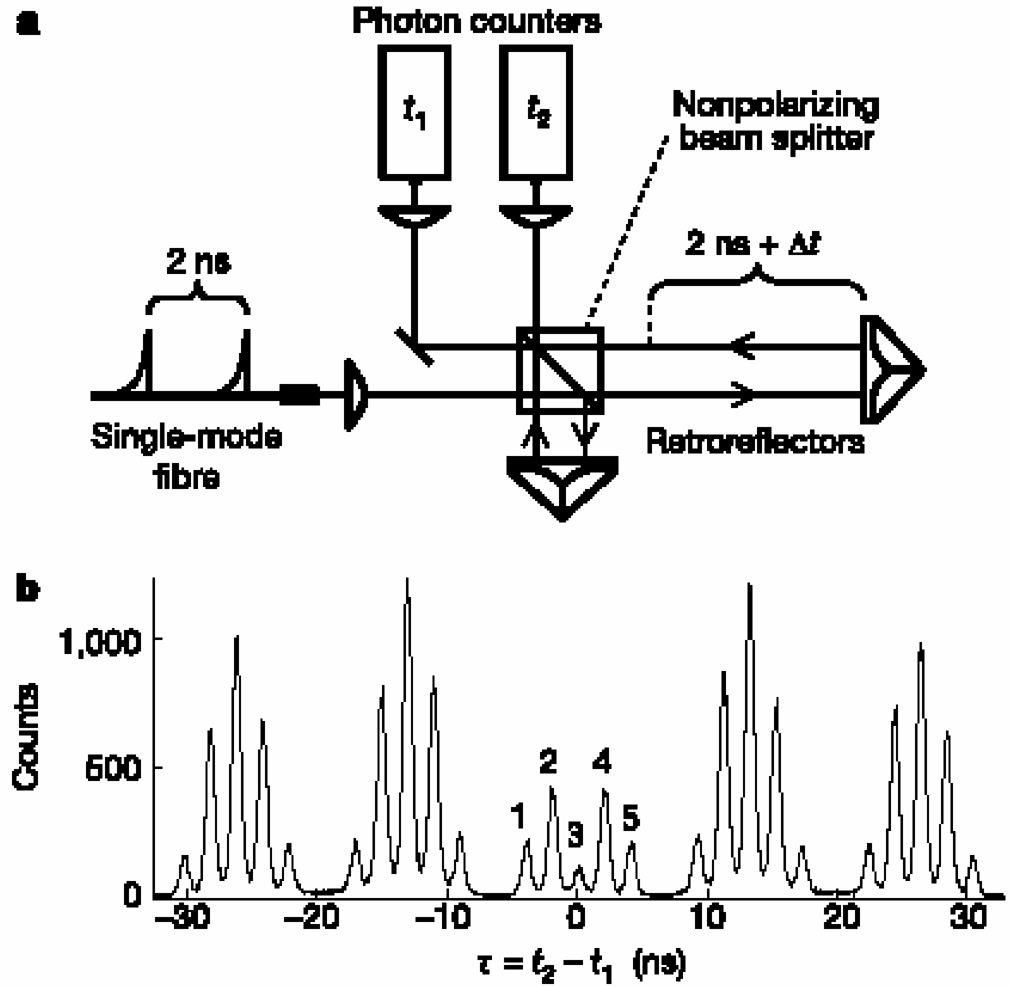
$\phi_1=\phi_2=\phi_3=0,\ \phi_4=\pi$

$\theta_1=-\theta_3=\pi/8,\ \theta_2=3\pi/8$

Sources for Ancilla States: On-demand Photons From a Single Quantum Dot

In an important experiment the Yamamoto group at Stanford was able to demonstrate the indistinguishability of subsequent photons from a quantum dot.

Realization of indistinguishable photons and entangled photon pairs in the experiment by Yamamoto [Santori, et al., Nature 419, 594 (2002)]:



A next breakthrough would be to demonstrate the generation of indistinguishable photons from two different quantum dots.

Hong-Ou-Mandel dip for three different quantum dots
[Santori, et al., Nature 419, 594 (2002)]

A next breakthrough would be the demonstration of indistinguishable photons from two different quantum dots.

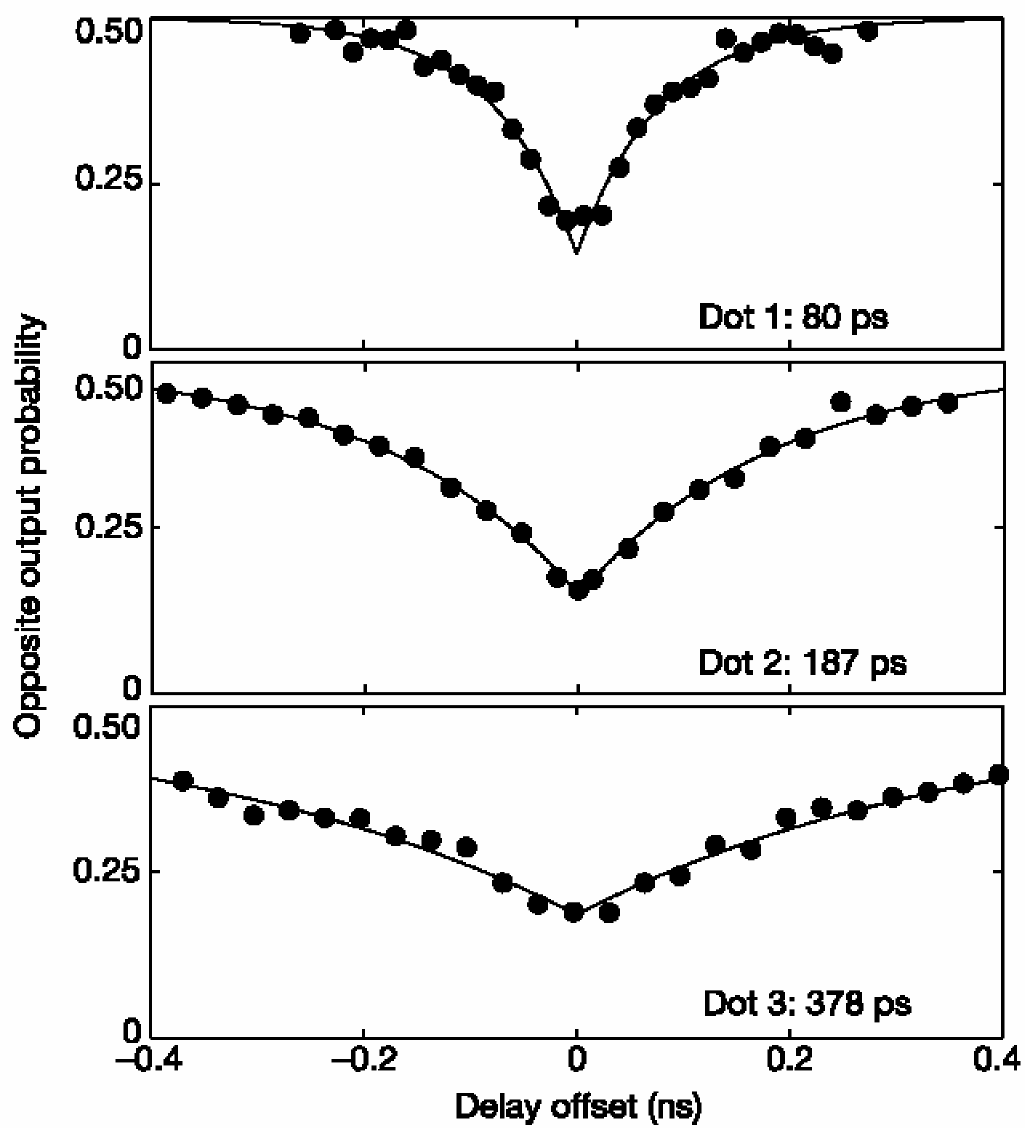
Figure of merit for linear optical quantum computation (LOQC) with single photons:

$$\eta_S \eta_D > 2/3$$

detector efficiency

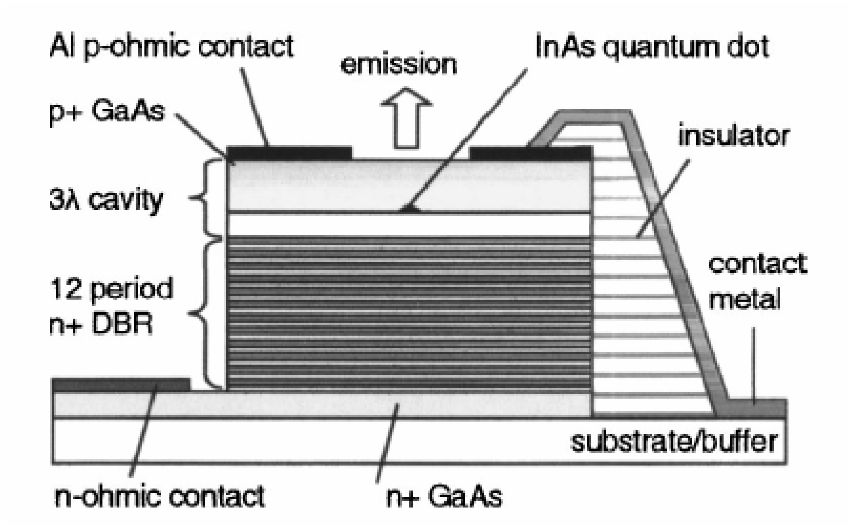
source efficiency

[Varnava et al., PRL 100, 060502 (2008)

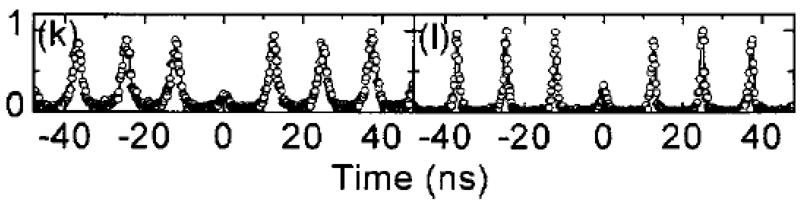


Indistinguishable Photons From a Single Quantum Dot LED

In a more recent experiment the group by Andrew Shields demonstrated emission of indistinguishable photons from a light emitting diode (LED).
[Bennett et al., APL 86, 181102 (2005)]

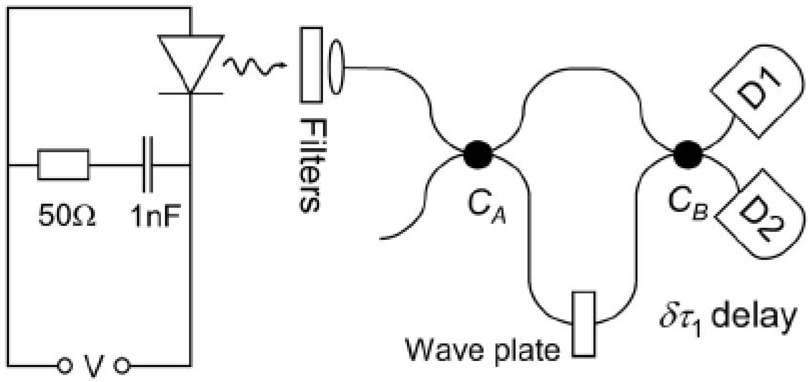


Left: Schematic of the device structure.
A single QD within a cavity (formed by a Bragg mirror and the top interface) is isolated with an aperture in the metallic contact.
The cavity enhances the collection efficiency of photons.



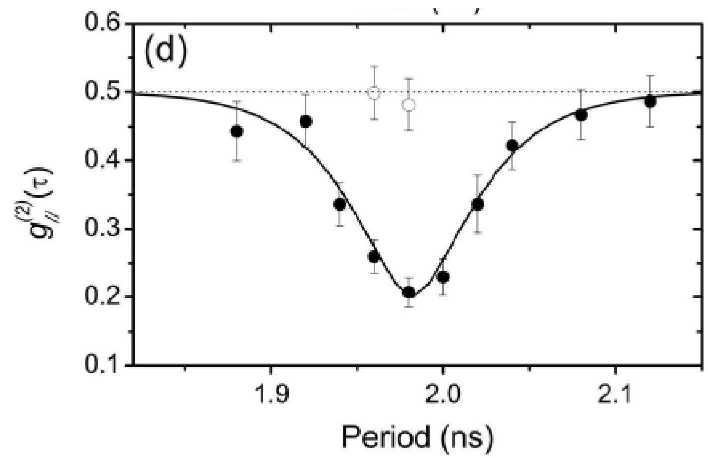
Under pulsed electrical excitation antibunching is observed both from the exciton (k) and from the biexciton (l).
The lines are filtered out with a monochromator.

Single photons are sent in an unbalanced (Fiber-)Mach-Zehnder interferometer. When the repetition period of the exciting AC voltage matches the time difference between of the two arms, photons meet at the second beamsplitter. Distinguishability can be enforced with a $\lambda/2$ plate. [Bennett et al., APL 86, 181102 (2005)]



Schematic of the setup

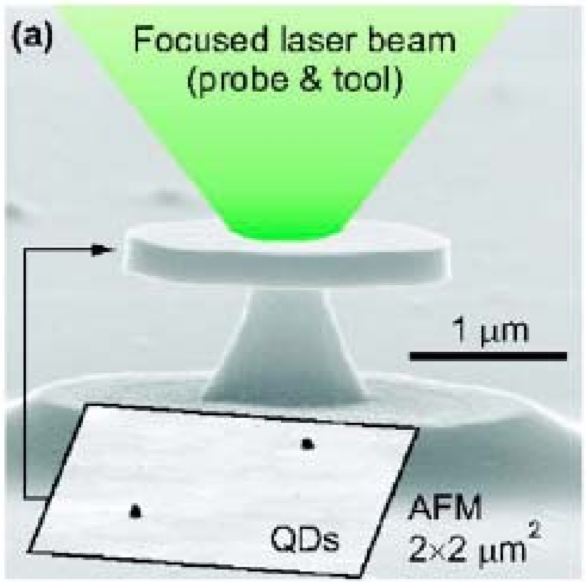
A clear Hong-Ou-Mandel dip is observed when the two photons have the same polarization, i.e. when they are (nearly) indistinguishable.

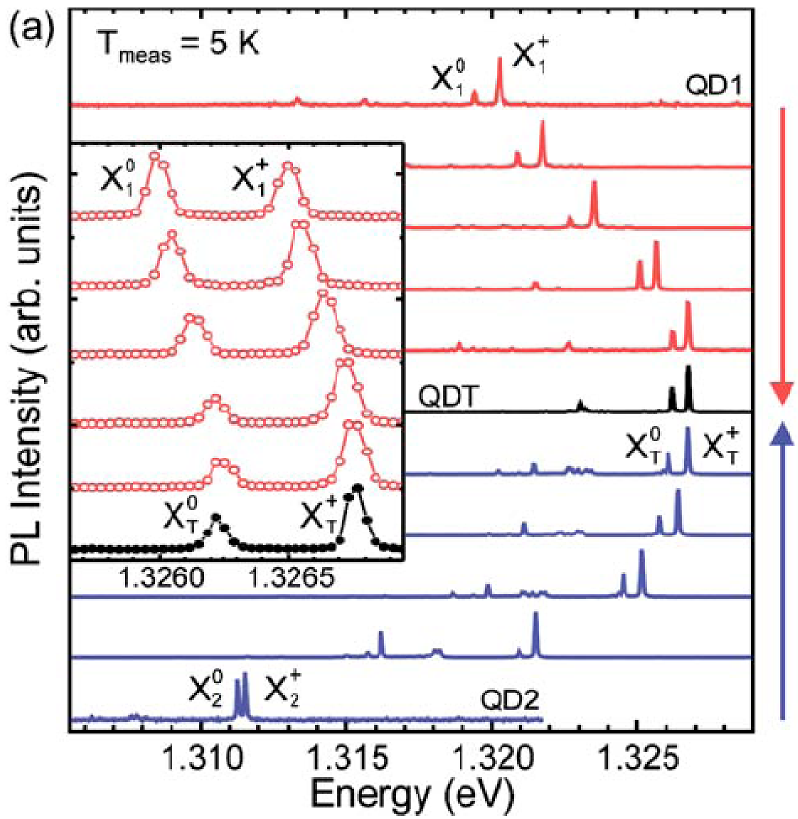


In Situ Tuning of Single Quantum Dots

In striking contrast to atoms artificial atoms (quantum dots) are not identical.
An additinal „tuning knob“ is required, e.g. by applying external fields.

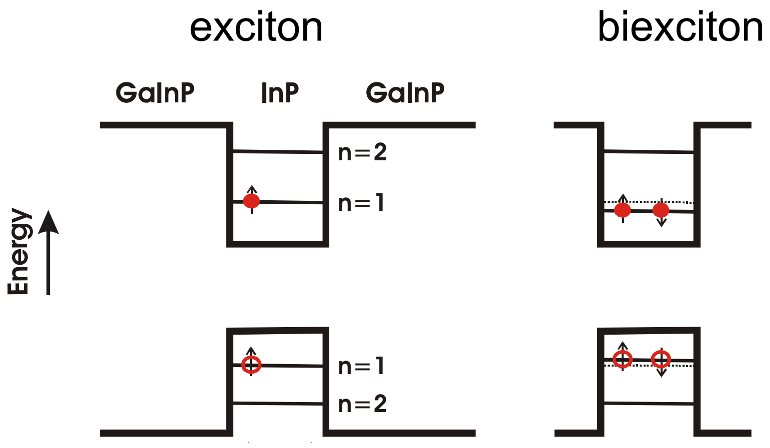
Rastelli et al. [APL 90, 073120 (2007)] developed the method of in situ laser processing:
A focussed laser causes heating to above 1000 K and thus intermixing of In and Ga atoms in the quantum dots producing a blueshift.

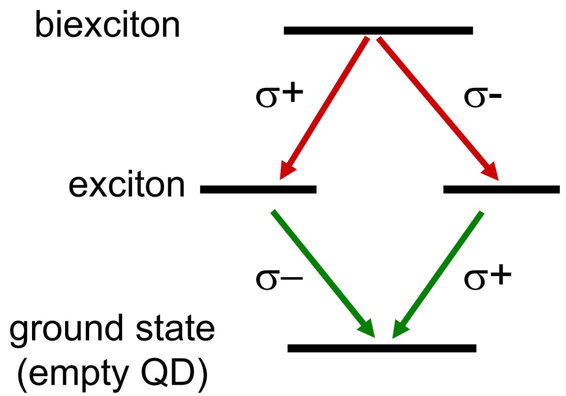




Left: heating of quantum dots in a microdisc
Right: tuning three quantum dots to the same emission wavelength

Generation of Entangled Photon Pairs





In a symmetric quantum dot there are two possible decay paths to conserve angular momentum:

1) First a right, then a left circularly pol. photon: $|\psi^{(1)}> = |\sigma^+>_1 |\sigma^->_2$

2) First a left, then a right circularly pol. photon: $|\psi^{(2)}> = |\sigma^->_1 |\sigma^+>_2$

If both paths are indistinguishable quantum mechanics requires to add probability amplitudes:

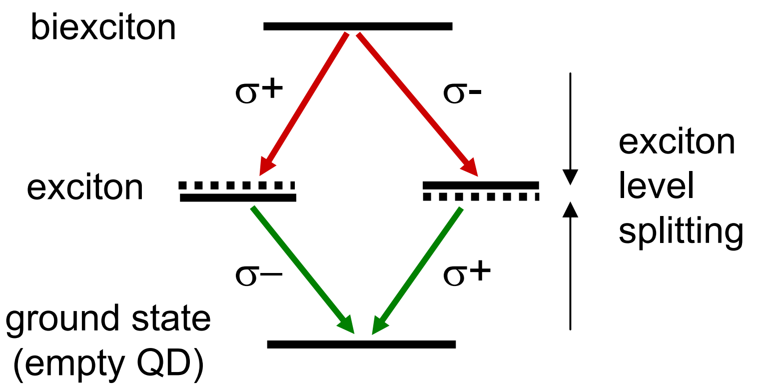
$$|\psi> = 1/\sqrt{2}(|\sigma^+>_1 |\sigma^->_2 + |\sigma^->_1 |\sigma^+>_2)$$

The state is an entangled state!

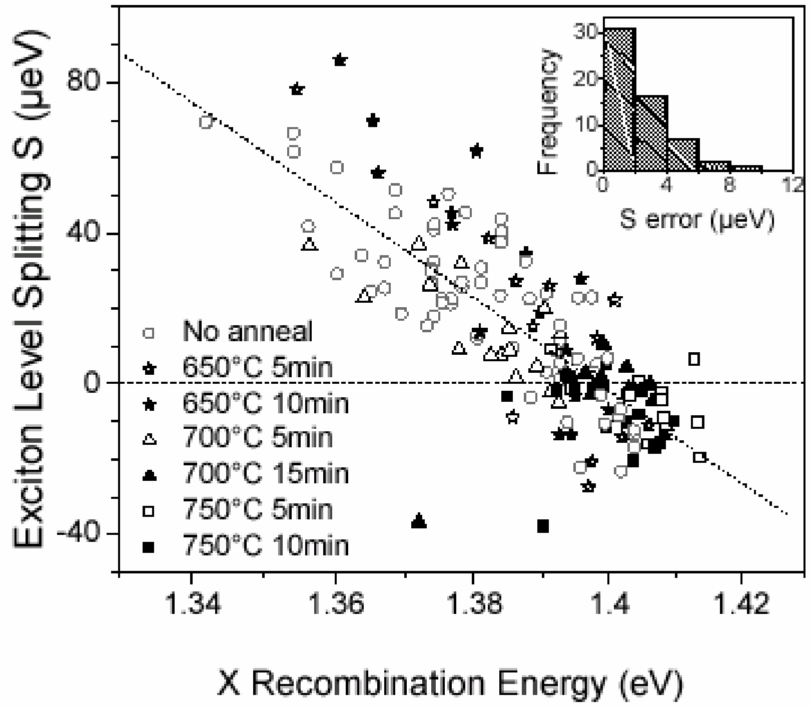
Benson & Yamamoto, PRL 84, 2513 (2000)

Unfortunately, a quantum dots state is usually not symmetric. There are: asymmetric dot shape, crystal anisotropy, piezoelectric fields, anisotropic strain, etc.

The asymmetry is „tested“ by the electron-hole exchange interaction and leads to a splitting of the exciton state. The decay produces two classically correlated linearly polarized photons.



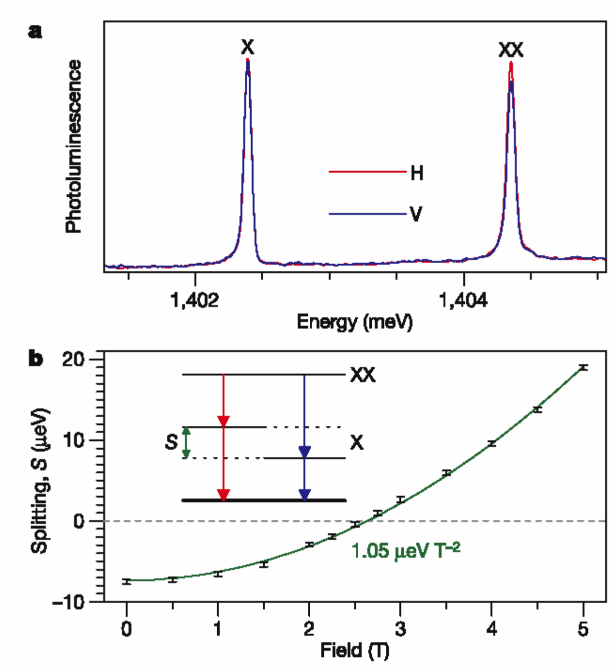
Recent work was successful in reducing the splitting below the natural linewidth.

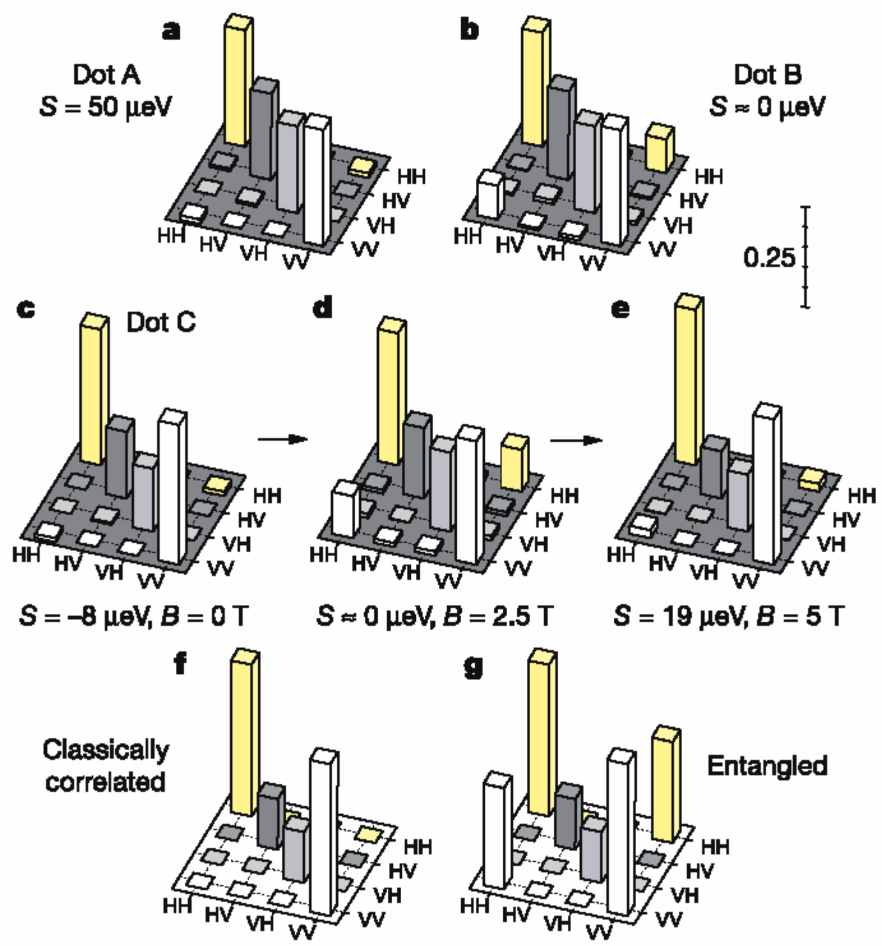


Young et al., PRB 72, 113305 (2005)

A result on the generation of entangled photon pairs. The excition splitting was reduced by (a) annealing & selection of appropriate dots, (b) by an in-plane magnetic field

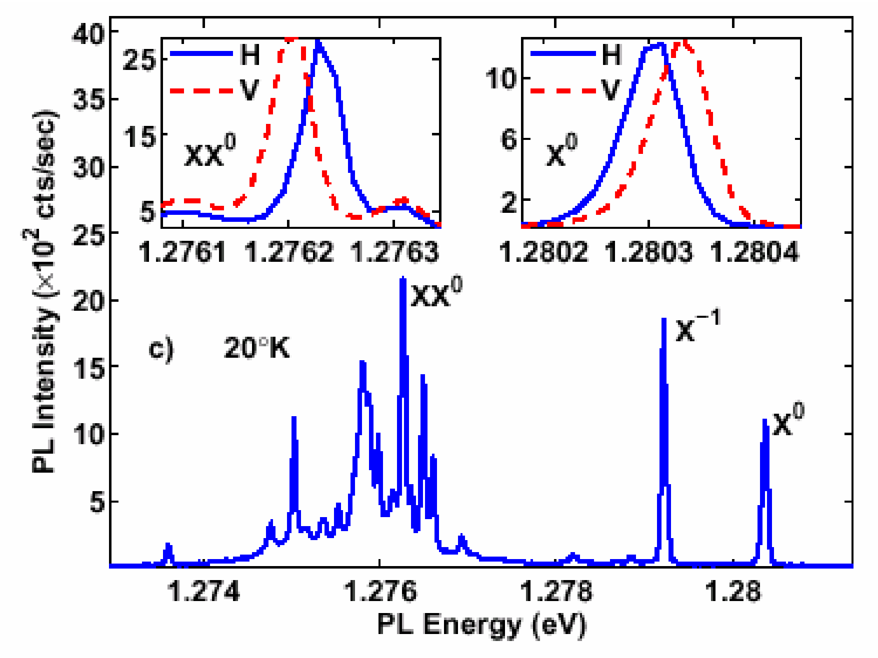
[Stevenson et al, Nature 439, 179 (2006); Hafenbrak et al., NJP 9, 315 (2008)]

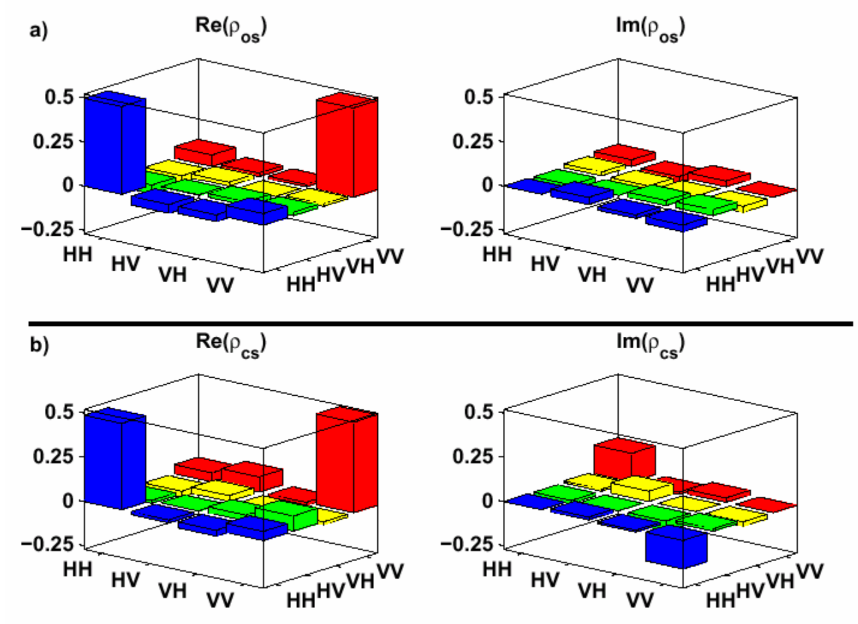




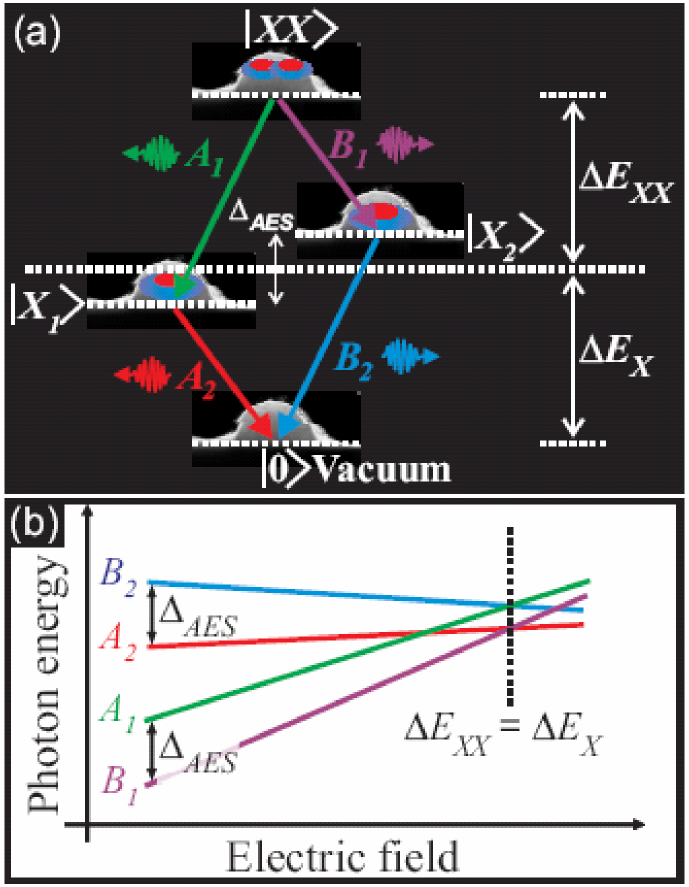
Another result on the generation of entangled photon pairs. Here, a subset of indistinguishable photons was selected by spectral filtering.

[Akopian et al, PRL 96, 130501 (2006)]





Yet another proposal to create entangled photon pairs relies on erasing the distinguishability between pairs of biexciton (XX) to exciton (x) decays. If both the difference in energy and in emission time is absent, entangled photons are emitted. [Avron, et al., PRL 100, 120501 (2008)]



Left: creating degeneracy of the XX-X and X-0 transitions [Reimer, arXiv: 0706.1075v1]

Bottom: Apparatus to erase timeing information