Single Photon
Generation & Application
Photon Pair Generation:

Parametric down conversion is a non-linear process, where a wave impinging on a non-linear crystal creates two new light beams obeying energy and momentum conservation:

\[ \omega_0 = \omega_1 + \omega_2 \quad \text{(energy conservation)} \]
\[ k_0 = k_1 + k_2 \quad \text{(momentum conservation)} \]

The Hamiltonian for such a non-linear process assuming a strong (classical) pump is:

\[
H = \sum_{i=1}^{2} \hbar \omega_i (\hat{n}_i + 1/2) + \hbar g [a_1^+ a_2^+ \alpha_0 e^{-i\omega_0 t} + h.c.
\]

with \([\hat{n}_1 - \hat{n}_2, H] = 0\) which means that the two photons are always created together.
A rigorous theoretical treatment [Mandel & Wolf, „Optical Coherence and Quantum Optics“] of down-conversion leads to the following state for the emitted light:

\[
|\psi(t)\rangle = \exp \left\{ \frac{1}{i\hbar} \int_0^t dt' H_I(t') \right\} |0\rangle \approx |0\rangle + \frac{1}{i\hbar \mathcal{L}^3} \chi \alpha_0 \sum_{k',\sigma'} \sum_{k'',\sigma''} \prod_{m=1}^3 \frac{\sin(\frac{1}{2} k_m)}{\frac{1}{2} k_m} \frac{\sin(\frac{1}{2} \tilde{\omega} t)}{\frac{1}{2} \tilde{\omega} t} |k', \sigma'\rangle |k'', \sigma''\rangle + \tilde{O}(2)
\]

This state can not be factorized in single photon states \( |k', \sigma'\rangle \)

If one fixes two directions (with according energies and polarizations, resp.) the state is:

\[
|\psi\rangle = \frac{1}{\sqrt{2}} \left\{ |\omega_s\rangle_{k_1} |\omega_i\rangle_{k_2} + |\omega_i\rangle_{k_1} |\omega_s\rangle_{k_2} \right\}
\]
Using this state a measurement of one photon in one arm on a state with a certain direction, polarization, and energy projects the photon in the other arm inevitably to an appropriate single photon state.

\[ |\psi\rangle = \frac{1}{\sqrt{2}} \left\{ |\omega_s\rangle_{k_1} |\omega_i\rangle_{k_2} + |\omega_i\rangle_{k_1} |\omega_s\rangle_{k_2} \right\} \]

Presently, down-conversion is the method to generate well-defined photon states for applications, e.g., in quantum information processing. Other single photon sources have to compete with this source!
Spontaneous Emission From Single Emitters

This is the simplest approach. It requires a single quantum system. It has been demonstrated with:

- atoms, molecules, color centers, quantum dots, ...under
- optical, electrical and STIRAP excitation

M: Brunel et al., PRL 83, 2722 (1999)
DC: Kurtsiefer et al., PRL 85, 290 (2000)
    Beveratos et al., PRA 64, 061802(R) (2001)
QD: Kim et al., Nature 397, 500 (1999)
    Michler et al., Science 290, 2282 (2000)
    Santori et al., PRL 86, 1502 (2001)
    Yuan et al., Science 295, 102 (2002)
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

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

QD-density: ~ $10^8$ cm$^{-2}$

From wetting layer to quantum dots:

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

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

![Exciton and Biexciton Diagram](image)

**Exciton**
- GaInP
- InP
- GaInP
- Energy
- Size: $O(10 \text{ nm})$
- $n=1$
- $n=2$

**Biexciton**
- GaInP
- InP
- GaInP
- Energy
- Size: $O(10 \text{ nm})$
- $n=1$
- $n=2$

Photoluminescence of an ensemble of InAs quantum dots

Photoluminescence image of a set of InP quantum dots
More than hundred luminescent color (defect) centers in diamond are known.

Few have shown single emitter characteristics.

No blinking! No bleaching!

**bulk material**
- natural diamonds
- (HPHT) or CVD growth

**nanocrystals**
- detonation reactors
- CVD growth
Nitrogen Vacancy (NV) Centers

NV center

schematics of energy levels of NV⁻

ensemble spectrum of NV centers at 300 K and 1.8 K

NV as single photon source:
Schröder et al., Nano Lett. 11, 198 (2010)
Hanbury Brown Twiss correlator:
anti-bunching
a proof of single photon emission

Experimental Setup

The following picture shows a setup to study the optical properties of single quantum dots:
Experimental Setup
Knill, Laflamme, and Milburn [Knill, Laflamme, Milburn, Nature 409, 46 (2001)] suggested a probabilistic 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.
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:

$$\eta_S \eta_D > \frac{2}{3}$$

[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)]

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