Two-Photon Interference

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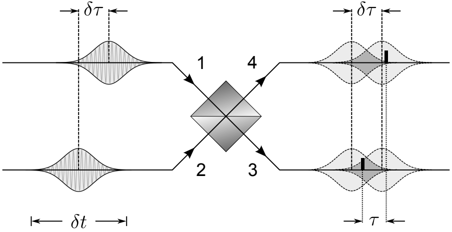
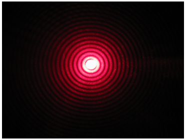
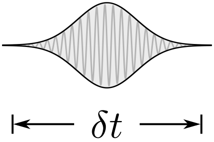
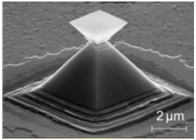


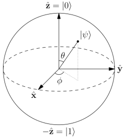
Why is two-photon interference so important?

- Show quantum nature of light
- Measurement of the length of a photon
- Characterization of single-photon sources
- Linear quantum information processing (QIP)







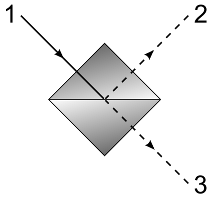


Outline

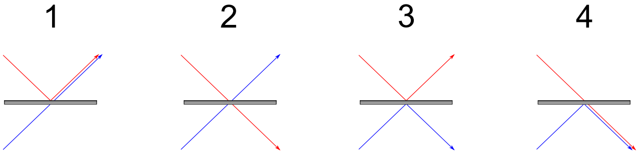
Outline

Physical Description

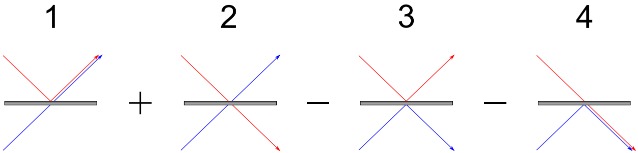
When a photon enters a beam splitter (BS), there are two possibilities: it will either be transmitted or reflected



Consider two photons, one in each input mode of a 50:50 BS. There are four possibilities for the photons to behave:



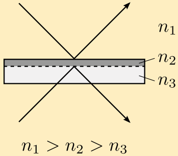
The state of the system after interference is given by a superposition of all possibilities for the photons to pass through the BS:



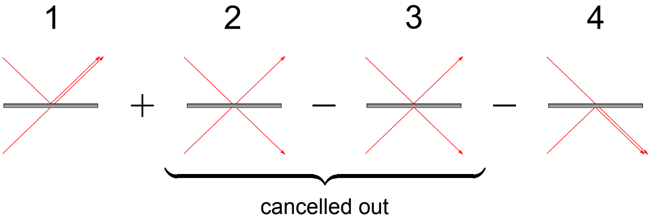
Where does the minus sign come from?

Reflection off bottom side $\Longrightarrow$ relative phase shift of π
(i.e. reflection off the higher index medium)

Reflection off top side $\Longrightarrow$ no phase shift
(i.e. reflection off the lower index medium).



Now let's assume that the two photons are identical in their physical properties (i.e., polarization, spatio-temporal mode structure, and frequency):



The photons will always exit the same (but random) output port!

Mathematical Description

- Consider two identical photons input ports A and B of 50:50 BS
- Quantum state given by applying photon-creation operators $\hat{a}^{\dagger}_{A,B}$ on vacuum state $|0\rangle$

$$|\Psi_i\rangle = |1_A 1_B\rangle = \hat{a}^{\dagger}_A \hat{a}^{\dagger}_B |0\rangle$$

- Detection of photon in output port C or D evaluated by applying photon-annihilation operators $\hat{a}_{C,D}$ to $|\Psi_i\rangle$
- Effect of 50:50 BS described by unitary transformation

$$\begin{pmatrix} \hat{a}_A \\ \hat{a}_B \end{pmatrix} \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} \hat{a}_C \\ \hat{a}_D \end{pmatrix}$$

Initial state in terms of photons created in output ports:

$$\begin{aligned} |1_A 1_B\rangle &= \hat{a}_A^\dagger \hat{a}_B^\dagger |0\rangle \\ &= \tfrac{1}{2}(\hat{a}_C^\dagger + \hat{a}_D^\dagger)(\hat{a}_C^\dagger - \hat{a}_D^\dagger)|0\rangle \\ &= \tfrac{1}{2}(\hat{a}_C^{\dagger 2} - \hat{a}_D^{\dagger 2})|0\rangle \\ &= \tfrac{1}{\sqrt{2}}(|2_C 0_D\rangle - |0_C 2_D\rangle) \end{aligned}$$

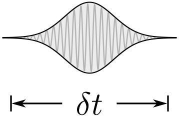
Remark: Since the operators $\hat{a}_{C,D}^\dagger$ act on different output ports their commutator vanishes: $[\hat{a}_C^\dagger, \hat{a}_D^\dagger] = 0$

The photons will always exit the same (but random) output port!

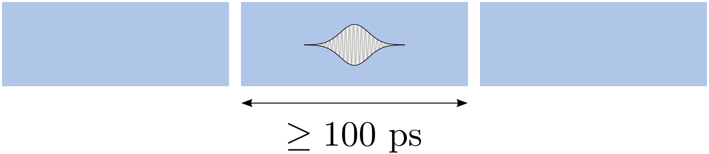
Outline

Hong-Ou-Mandel Interference

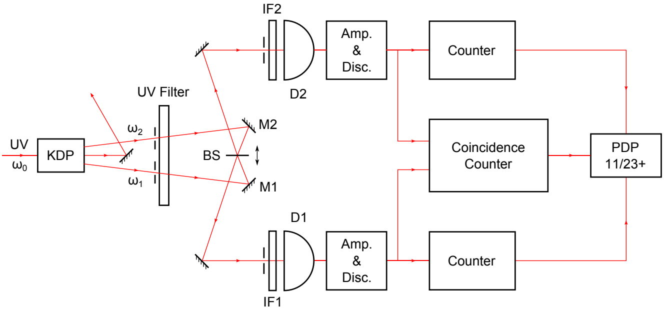
Aim: Measurement of photon wave packet length δt



Problem: Time resolution $\gg$ wave packet length



Experimental setup



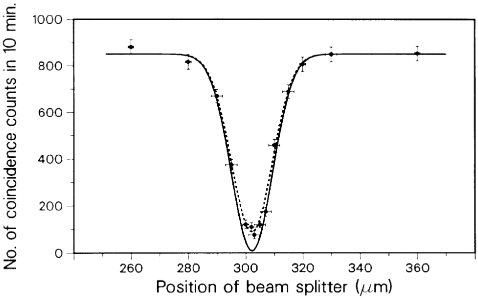
Photon source: Parametric down-conversion Type I ($\omega_0 = \omega_1 + \omega_2$)

Indistinguishability of photons:

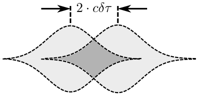
- Photon source ensures same polarization
- Pass bands of interference filters (IF) ensure (at most) same frequency
- BS is displaced (by $\pm c\delta\tau$) from symmetry position to ensure same time of arrival

Measurement of simultaneous detections N depending on BS displacement $\delta\tau$

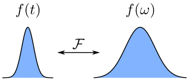
Hong-Ou-Mandel-Dip

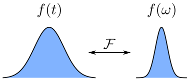


- Overlap controlled by BS displacement: no coincidences for perfect overlap



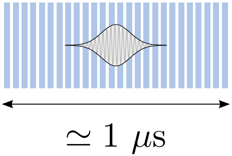
- Photon length from FWHM $= 16\ \mu\text{m} = c \cdot 50$ fs
- Width of dip connected to IF-bandwidth due to Fourier-limited photons



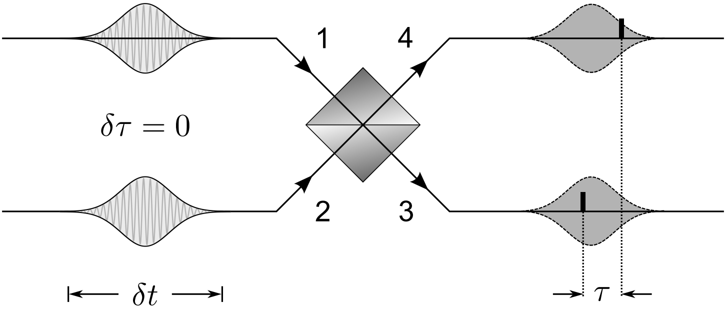


Outline

Quantum Beat of Two Single Photons



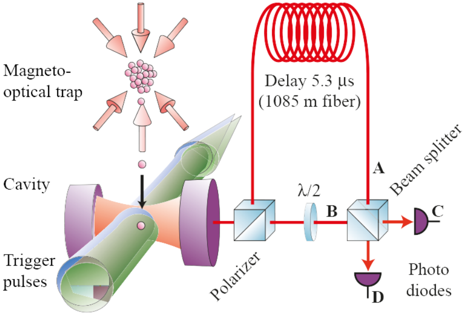
Now: Time resolution $\ll$ wave packet length
Photons impinge simultaneous on BS
Detection-time delay τ measured



Experimental Setup

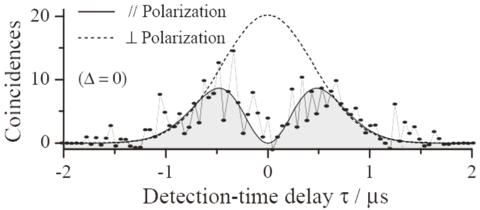
Photon source: Atom-cavity system

- Atom-cavity system emits unpolarized single photons with well determined frequency
- Polarizing beam splitter (PBS) randomly directs them along two paths
- Photon travelling along path A gets delayed through fiber



- Subsequent photon travelling along path B impinges on the BS simultaneously with delayed photon from path A
- A HWP along path B guarantees that both photons have the same polarization

Results 1

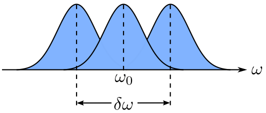


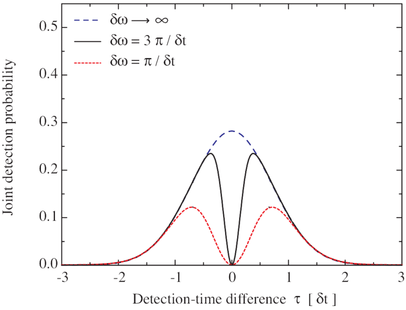
- Indistinguishable photons for parallel polarization: Correlation drops to minimum with width of 460 ns
- Width corresponds to inhomogenous broadening of photon spectrum of $\delta\omega/2\pi = 690$ kHz
- In general depth and width of minimum indicate initial purity of photon state, i.e. broadening of photon spectrum, frequency and emission-time jitter

Jitters

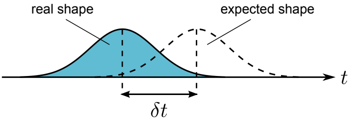
No perfect single-photon source $\Longrightarrow$ Consider more realistic scenario, in which stream of Fourier-limited photons shows a jitter in its parameters:

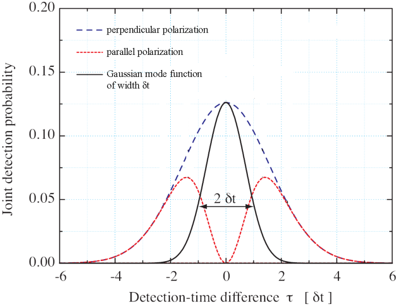
- Frequency jitter:



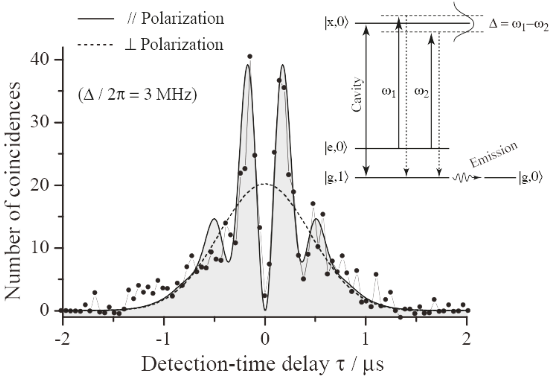


- Emission-time jitter:





Results 2



- Introducing a frequency difference of $\Delta\omega/2\pi = 3$ MHz: Quantum beat visible
- No coincidences for simultaneous detection
- Fringes with a visibility of almost 100% (classical: 50%)

Theoretical Prediction of Quantum Beat

- Initial state: $|\Psi_i\rangle = |1_A 1_B\rangle$
- Detection of photon at time t_0 in output C:

$$|\Psi_C(t_0)\rangle = \hat{a}_C |1_A 1_B\rangle = \frac{1}{\sqrt{2}}(|1_A 0_B\rangle + |0_A 1_B\rangle)$$

- Introduce frequency difference $\Delta = \omega_2 - \omega_1$. After time τ new state reads:

$$|\Psi_C(t_0 + \tau)\rangle = \frac{1}{\sqrt{2}}(e^{i\omega_1\tau} |1_A 0_B\rangle + e^{i\omega_2\tau} |0_A 1_B\rangle)$$

- Introduce global phase $|\Psi_C\rangle \longrightarrow e^{-i\omega_1\tau} |\Psi_C\rangle$:

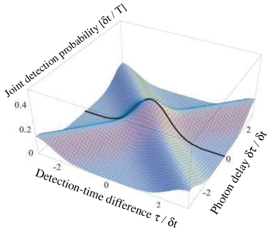
$$\Longrightarrow |\Psi_C(t_0 + \tau)\rangle = \frac{1}{\sqrt{2}}(|1_A 0_B\rangle + e^{i\Delta\cdot\tau} |0_A 1_B\rangle)$$

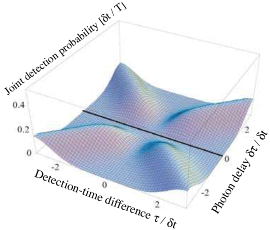
- Probability of detecting the second photon with either C or D:

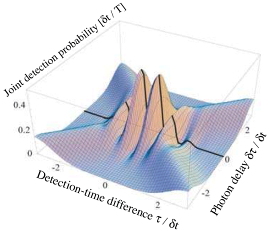
$$P_{CC} = \langle\Psi_C| \hat{a}_C^\dagger \hat{a}_C |\Psi_C\rangle = \frac{1}{2}[1 + \cos(\Delta \cdot \tau)]$$

$$P_{CD} = \langle\Psi_C| \hat{a}_D^\dagger \hat{a}_C |\Psi_C\rangle = \frac{1}{2}[1 - \cos(\Delta \cdot \tau)]$$

A frequency difference results in a quantum-beat signal







perpendicular polarization:
no interference

parallel polarization:
interference

no simultaneous detections
($\tau = 0$) for $\delta\tau = 0$

interference of photons with
different frequencies

even for distinguishable
photons no simultaneous
detections ($\tau = 0$)

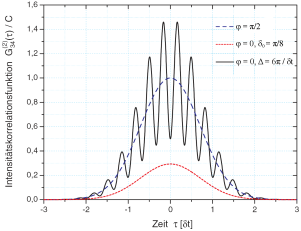
oscillation of coincidence
probability for $\delta\tau \simeq 0$

Comparison to HOM-Experiment:

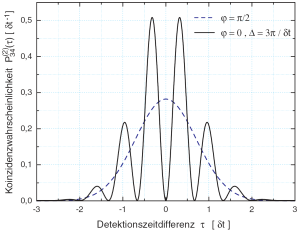
No time resolved measurement $\Longrightarrow$ Integrate over detection-time difference τ:
No difference between cases 1 and 3

Visibility

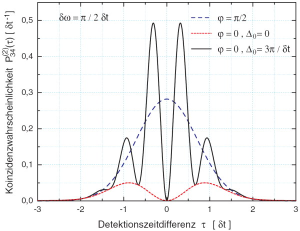
Classical fields: 50% visibility



QM two-photon intereference: 100% visibility



Fourier-limited photons

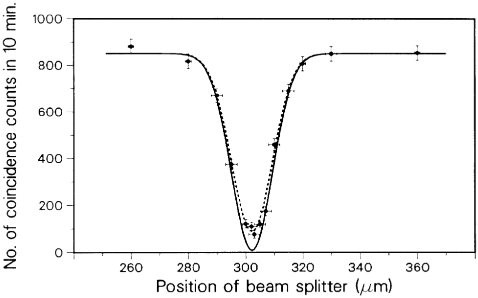


Inhomogenous broadened photons

Outline

Summary

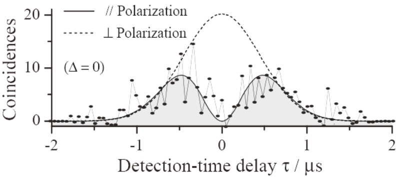
Hong-Ou-Mandel Interference
Photon source: PDC



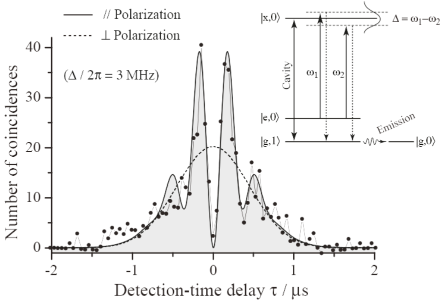
- No time-resolved measurement possible
- Width of dip connected to length of photon wave packet

Two-Photon Interference
Photon source: Single Photon Emitter

Identical Frequencies



Quantum Beat



- Time-resolved measurement possible
- Photon source can be characterized from width and depth of dip (i.e. broadening of photon spectrum, frequency and emission-time jitter)
- Frequency difference between photons induces quantum-beat with visibility of 100%

Thank you for your attention

and I look forward for your questions on this topic!

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