Interference and distinguishability of a particle

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Coherent superposition of quantum states

Coherent superposition of quantum states:

- $|0\rangle + e^{i\theta}|1\rangle$
- Plays a crucial role in quantum information protocols
- Manifested in quantum interferometric experiments

What is it good for? Superposition is a resource for various quantum information tasks

- Quantum key distribution
- Quantum computing
- Quantum imaging

Decoherence

- Many systems cannot preserve the superposition for long time $\rightarrow$ Decoherence

W. Zurek, Rev. Mod. Phys. **75**, 715 (2003)
M. Schlosshauer, Rev. Mod. Phys. **76**, 1267 (2004)

Mechanisms of Decoherence

- Fluctuation of macroscopic physical parameters $\rightarrow$ dephasing:
  $|0\rangle\langle 0| + |1\rangle\langle 1| + \exp i2\theta|0\rangle\langle 1| + e^{-i2\theta}|1\rangle\langle 0| \rightarrow N(\mu, \sigma)$:
  $|0\rangle\langle 0| + |1\rangle\langle 1| + e^{i2\mu-2\sigma^2}|0\rangle\langle 1| + e^{-i2\mu-2\sigma^2}|1\rangle\langle 0|$
- Coupling between system and environment: Einselection

W. Zurek Phys. Rev. D **26**, 1862 (1982)

- Mixing the system with some other system representing noise

Decoherence of our interest

We want study just the influence of an added particle on the interference of the signal particle

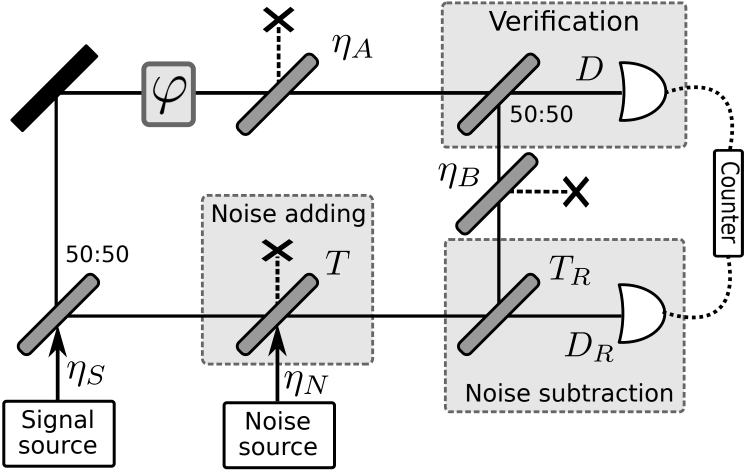
Relevant source of decoherence:

- Added noise particle
- Distinguishablity of the "signal" and "noise" particle

We assume:

- No fluctuation of parameters
- No coherent interaction between system and environment
- No spontaneus emission from the system
- No collision

Scheme of the interference experiment



Indistinguishable scenario

First assume indistinguishable noisy photon:

- $[|0\rangle + \exp(i\varphi)\,|1\rangle]/\sqrt{2}$
- dual rail encoding:
  $|\Psi\rangle_{AB} = [|1,0\rangle_{AB} + \exp(i\varphi)\,|0,1\rangle_{AB}]/\sqrt{2}$
- $a_B^\dagger|\Psi\rangle_{AB}$ reads
  $|\Psi'\rangle_{AB} = [|1,1\rangle_{AB} + \sqrt{2}\exp(i\varphi)\,|0,2\rangle_{AB}]/\sqrt{3}$
- $a_B|\Psi'\rangle_{AB}$ ending up with state
  $|\Psi''\rangle_{AB} = [|1,0\rangle_{AB} + 2\exp(i\varphi)\,|0,1\rangle_{AB}]/\sqrt{5}$
- applying attenuation $\eta_B = 1/4$ mode B.

Maximal visibility indistinguishable case

$$V_{\mathrm{ind}} = 1$$

Distinguishable scenario

Adding distinguishable noisy photon:

- $a^{\dagger}_{B'}|\Psi\rangle_{AB}|0\rangle_{B'}$
- $|\Phi'\rangle = [|1,0,1\rangle_{ABB'} + \exp(i\varphi)\,|0,1,1\rangle_{ABB'})]/\sqrt{2}$
  In principle could be filtered out: But, quite typically, our filters are not selective enough to enable it $\rightarrow$ technically indistinguishable
- randomly annihilate a single particle either from B or B' two "subtraction" operators: $S_1 = a_B \otimes 1_{B'}$ and $S_2 = 1_B \otimes a_{B'}$ equal weight.
- $\rho' = |\Phi'\rangle\langle\Phi'|$, i.e. $S_1\rho' S_1^{\dagger} + S_2\rho' S_2^{\dagger}$
  $\rho'' = 2/3\,|\Psi\rangle_{AB}\langle\Psi| \otimes |0\rangle_{B'}\langle 0| + 1/3\,|00\rangle_{AB}\langle 00| \otimes |1\rangle_{B'}\langle 1|$

Visibility bound

- $\eta_B = \eta_{B'}$ in modes B and B'. This transforms the total state to

$$\begin{aligned}\rho''' &= \frac{1}{2\eta_B}\Big[|100\rangle\langle 100| + \eta_B\,|010\rangle\langle 010| + \eta_B\,|001\rangle\langle 001| \\ &\quad + \sqrt{\eta_B}\left(e^{i\varphi}\,|010\rangle\langle 100| + e^{-i\varphi}\,|100\rangle\langle 010|\right)\Big]\,.\end{aligned}$$

- Maximal visbility if $\eta_B = 1/2$

Maximal visibility distinguishable case

$$V_{\mathrm{dis}} = \frac{1}{\sqrt{2}}$$

Visibility reduction

This reduction in visibility represents a fundamental impact of the principal distinguishablity of the signal and noise particle as well as elementary ignorance of our measurement apparatus (technical indistinguishablity)

Generalization

- With probability p the photons are indistinguishable in principle

$$V(p) = \sqrt{\frac{1+p}{2}}$$

- N distinguishable photons added simultaneously and then annihilated simultaneously

$$V_{\text{dis}} = \frac{1}{\sqrt{N+1}}$$

- N distinguishable photons added subsequently and then annihilated subsequently

$$V_{\text{dis}} = \left(\frac{1}{\sqrt{2}}\right)^N$$

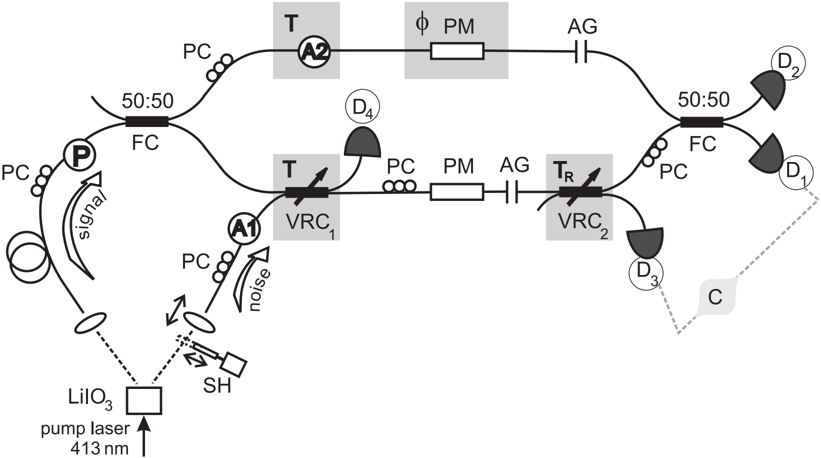
Experimental realization

- Photons in fibre-optics two-photon Mach-Zehnder interferometer
- Signal and noise photon generated in SPDC process added
- Distinguishablity controlled by time separation of the signal and noise photon

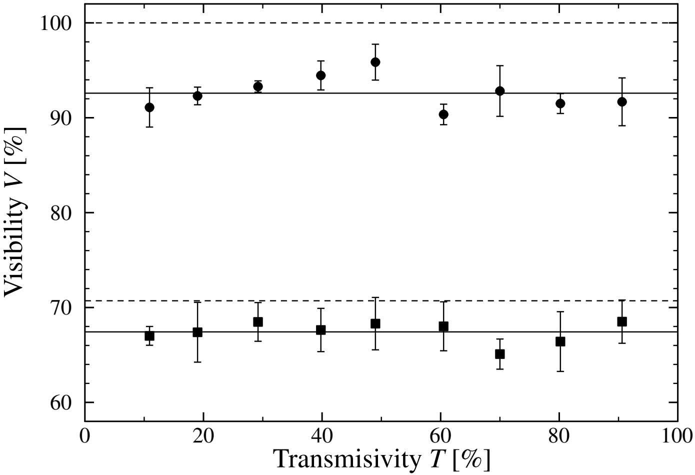
Theory & experiment

M. Gavenda, et. al., Phys. Rev. A **83**, 042320 (2011)

Experimental setup



Experimental Results



Summary & Outlook

1. The noise represented by an additional distinguishable particle can degrade interference
2. The principal distinguishability and technical indistinguishablity play role
3. Experimentally tested
4. Plan: correction by multiplexing