Applied Physics B manuscript No.
(will be inserted by the editor)

Experimental Demonstration of Complementarity with Single Photons

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Received: August 28, 2002/ Revised version: date

Abstract We demonstrate the principle of complementarity in quantum mechanics in a single photon interference experiment. In our scheme, single photons are provided by isolated, optically pumped nitrogen-vacancy centers in diamond, which can be easily addressed by confocal microscopy. In order to observe the particle-like behavior of photons, we perform an elementary Welcher-Weg measurement detecting photons behind a beam-splitter. In contrast, if we dispense with this Welcher-Weg information, we observe interference fringes with a visibility of about 96 %, revealing the wave nature of the photon.

1 Introduction

Equipped with the well-established laws of classical physics, understanding quantum mechanics is known to be a puzzling task for many students. A major reason for this is the extensive incompatibility of our daily-life related vocabulary with phenomena observed in quantum experiments, in particular the principle of complementarity. In 1927, Niels Bohr introduced that term in order to interpret the strange results obtained in the famous Young's double-slit experiment [1]. Discrete quantum particles—like photons for example—passing through a double-slit cannot yield Welcher-Weg information, thereby exhibiting particle character, and at the same time contribute to an interference pattern and show wave character. It is even impossible to observe the complementary properties of an object with one measurement apparatus. The measurement configuration affects the measured results and must be taken into account together with the quantum state to be investigated.

Single-photon interference as a specific non-classical phenomenon has been investigated in experiment and theory since the earliest days of quantum mechanics. Up to the 1980's, all experiments performed significantly failed due to the lack of a true single-photon source[4].

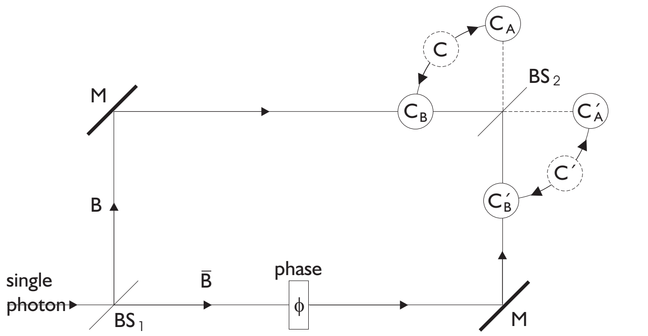

Fig. 1 Single-photon interference experiment with beam-splitters BS_1 and BS_2, two mirrors, a phase shifter ϕ and two detectors C and C' which are either positioned behind the first beamsplitter BS_1 for Welcher-Weg measurements or behind the second beamsplitter BS_2 for observation of interference fringes.

In these attempts, thermal or classical light beams were simply attenuated to an extremely low intensity level. But it has to fall short to prove fundamental quantum phenomena, because this procedure still does not generate a single photon state with its particular properties. Remarkable progress could be achieved by Grangier et al. [5], whose triggered two-photon cascade was used to demonstrate single photon interference. However, a true and practicable single-photon generator was still missing, a problem that has been now overcome by the recent development[6–10].

In this paper, we describe an experiment which illustrates the principle of complementarity in terms of the wave-particle duality of light with true single-photon states. Suggested by A. Aspect and coworkers [5], the setup provides a quite straightforward and vivid way to demonstrate complementarity in quantum optics. Let us discuss the basic idea of the experiment by means of the scheme shown in fig. 1.

The single photon interferometer consists of two beam-splitters BS_1 and BS_2, two mirrors M, a phase shifter ϕ and two movable detectors C and C'. Single photons are provided by a suitable source; one possible implementation will be explained below. Having passed the first beamsplitter BS_1, the photon moves in a superposition along the alternative paths B and $\bar{B}$ towards the second beamsplitter BS_2, that joins both paths again. The actual outcome of the photon detection measurement now depends on the position where our two detectors C and C' are located.

Let the detectors first be set after the first beamsplitter BS_1. In this case, the detection at one of the two detectors localizes the photon either in path B or $\bar{B}$. On the other hand, if we overlap the two paths on the beamsplitter BS_2, and thereby dispense the Welcher-Weg information, interference fringes are obtained for detectors C and C' placed behind the second beamsplitter BS_2. Whereas the first measurement led us to the conclusion that we find the photon *either* in arm B *or* in arm $\bar{B}$, we observe in the second measurement an interference pattern which depends on the path length difference of the two arms, i.e., a property of *both* arms B and $\bar{B}$. Although the components are the same for both parts of the experiment, it is their arrangement which results in different functionalities thereby showing the principle of complementarity also for the chosen measurement apparatuses.

Due to its tutorial clarity, this experiment could become an elementary part of every student lab on quantum mechanics. However, the lack of simple single photon sources made such experiments a challenging task even for specialized quantum optics laboratories. Here we present the implementation of the interference experiment described above based on a recently developed source of single photons.

2 Experimental set-up

Ideally, single photons are provided by fluorescence obtained from a single excited two-level quantum transition. It turned out, that isolated, naturally occurring nitrogen-vacancy (NV) centers in diamond represent a stable version of such a two-level system. Described elsewhere in detail [6], we will outline here only the most important features of this new source of single photons. Fig. 2 shows the optical apparatus required to extract single-photon fluorescence properly.

An isolated NV center is optically excited from the ground level to a second level by light of a frequency doubled cw-Nd : YVO_4-Laser at a wavelength of 532 nm. To get a suitable point defect into focus, the diamond sample can be positioned accurately in 3 dimensions using a translation stage. The emitted fluorescence light is coupled via a confocal microscope arrangement into a single-mode optical fiber. A dichroic mirror together with a color filter keeps fluorescence clean from pump light. A two-dimensional scan of the sample transverse to the pump direction yields an image with an apparent source width of 450 nm FWHM (inset of fig. 2).

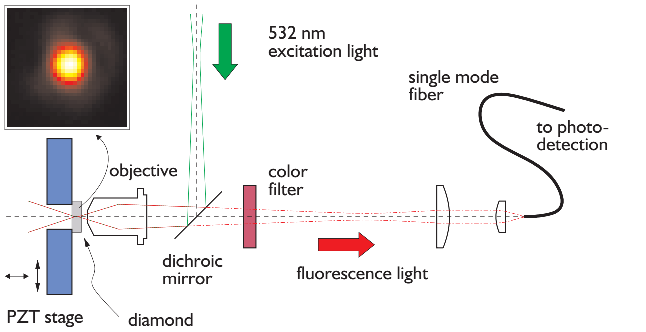

Fig. 2 Structure of the single-photon source. Fluorescence light produced by laser-excited single Nitrogen-Vacancy centers in diamond is collected in a confocal microscope setup.

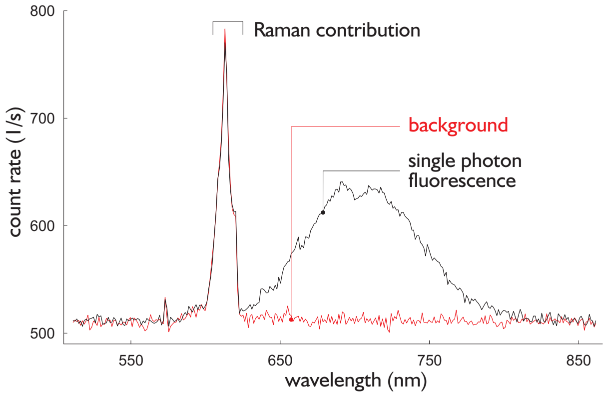

Fig. 3 Spectral characteristics of our single-photon source. In addition to NV-center fluorescence light, Raman peaks of 1^{st} and 2^{nd} order occur due to inelastic scattering of incoming laser light at the diamond bulk. To avoid pollution of single-photon emission, Raman lines are blocked by a red color glass filter.

Spectral analysis of the NV-center selected for the present experiment shows the typical shape for such a defect. The spectrum, plotted in fig. 3, was recorded at an excitation power of 4 mW, slightly above the saturation of the quantum transition.

The detected light exhibits a relative broad fluorescence emission in the red region, accompanied by one- and two-phonon Raman scattering contributions between 570 and 620 nm. As no single-photon statistics is expected from the Raman scattered light, it light must be blocked with an additional red color glass filter at the entrance of the interferometer.

The single photons are transferred via single mode optical fibers to the Mach-Zehnder interferometer as the second essential part of our setup. An overview of the configuration of optical components is given in fig. 4. Contrary to a standard Mach-Zehnder setup (see fig. 1), mirrors M and the 2^{nd} beamsplitter BS_2 are replaced by two retroprisms, which reflect beams back into the single beamsplitting cube.

This scheme has the advantage of an easily variable arm length difference without any mismatch of the interfering beams by simply moving one of the prisms with a

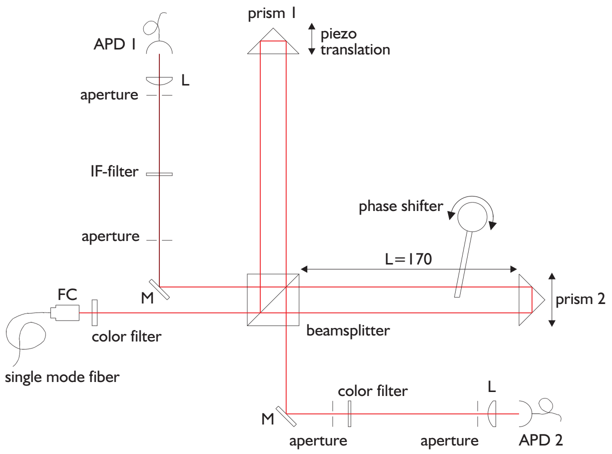

Fig. 4 Optical setup of the experiment. The interferometer is of a modified Mach-Zehnder-type, where the beam(s) pass the same beamsplitter two times before they enter the detectors APD_1 and APD_2. For the Welcher-Weg measurement both detectors are placed directly behind the beamsplitter.

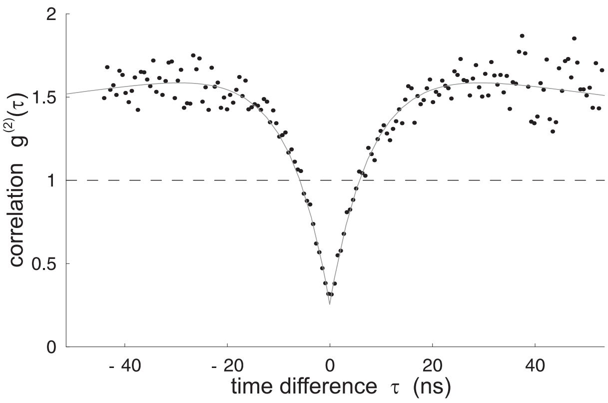

Fig. 5 Second order correlation function observed behind the first beamsplitter showing clear anticorrelation of the detection events. The finite value for $\tau = 0$ is due to uncorrelated background events.

piezo-driven translation stage. To guarantee precise positioning over the whole measurement time, stabilization by a feedback mechanism was implemented (not shown in fig. 4). For this purpose, we used a second cw-laser beam at a wavelength of 532 nm, attenuated to a few μW. This beam passed the same Mach-Zehnder configuration about 10 mm below the single-photon light. The intensity difference of the two output beams of the interferometer serves as the error signal for a PID controller. A 1 mm thick glass plate in one of the stabilization laser beams inside the interferometer acts as phase shifter. Since the stabilization unit undoes the phase change by moving one of the prisms, rotation of this plate indirectly changes the phase for the single photon interferometer in a reproducible way. Interference and color glass filters together with diaphragms protect the single photon detectors from residual green illumination.

The single photon beams are focused on silicon avalanche photo diodes (Si-APD's) with a detection efficiency around 50%, dark count rates of 200 s^{-1} and a dead time of $\approx 1\,\mu$s between successive detection events. The interference filter and an additional short pass window (not shown in fig. 4) block the detector cross talk due to photons with a wavelength above 750 nm created in a detection avalanche of the APDs [11].

3 The experiment

The first step of the experiment is the demonstration of the particle properties of single photons. For this purpose we position one detector in each arm right behind the beamsplitter. If there is only one photon emitted by the source, the particle picture tells us that the photon can be detected only in one of the two outputs of a beamsplitter, but not in both. (A wave split equally into the two ports would result in detections in both outputs.)

We analyze this behaviour using the second order correlation function $g^{(2)}(\tau)$, which is proportional to the conditional probability $P_c(\tau|0)$ that a photon is registered at time $t = \tau$, given a detection event at time $t = 0$. For this purpose, a time-to-digital converter (TDC) measures the time difference between two successive detection events, which is then collected in a histogram for the evaluation of $g^{(2)}(\tau)$. In the experiment, the source of single photons, the NV-center, is excited continuously. For a given decay rate and excitation time, we obtain a certain probability for an emission of a photon after a given time. However, there are never two photons emitted simultaneously, and thus it should be thus impossible to observe simultaneous detection events in the two arms in the particle picture. The correlation function $g^{(2)}(\tau)$ therefore is equal to zero at $\tau = 0$ and increases to one for times significantly longer than the inverse of the decay rate.

Fig. 5 shows the significant decrease of the correlation function for time difference $\tau = 0$. The residual value of $g^{(2)}(\tau) = 0.25$ is due to background events, which are of course independent of and uncorrelated with the real detection events and thus also occur at $\tau = 0$. This measurement clearly shows that, according to its particle character, the single photon can be detected only in *one* of the two arms behind the beamsplitter.

For the second step we overlap the possible paths of the photon at a second beamsplitter (or as it is the case in the actual configuration, at another position of the same beamsplitter). If we now record the probability to find the photon in one of the outputs of this beamsplitter, we observe a count rate depending sinusoidally on the path length difference $\Delta\ell$ due to interference (Fig. 6). The first step showed that we find the photon either in arm B or in arm $\bar{B}$, but not in both. Yet, now we observe an intensity which depends on $\Delta\ell$, a common property of both arms, clearly revealing the wave nature of the photon.

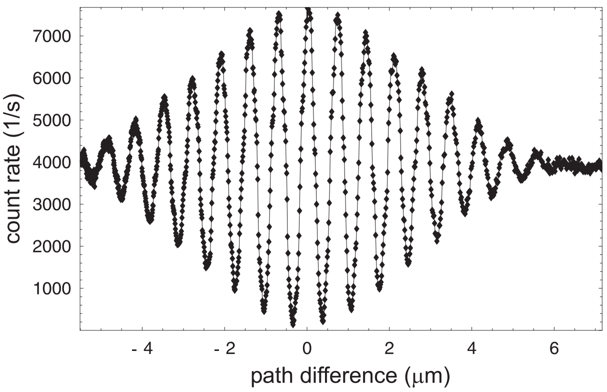

Fig. 6 Interference pattern obtained when overlapping the two arms on a second beamsplitter. The solid line is a guide to the eye.

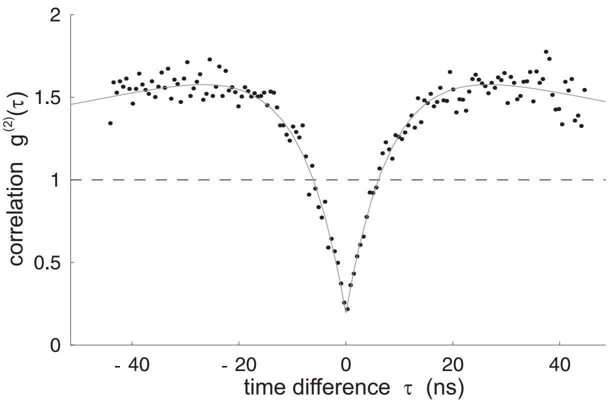

Fig. 7 Second order correlation function $g^{(2)}(\tau)$, measured between the two interferometer outputs. The dip for $\tau = 0$ below 0.5 shows the single photon character of the interfering light.

The visibility $V = (I_{max} - I_{min})/(I_{max} + I_{min})$ is a measure of the indistinguishability of the photon-paths through an interferometer. For zero path-length difference we observe a value of $V = 96.2 \pm 0.5\%$ indicating nearly perfect overlap at the second beamsplitter, with the residual distinguishability mainly caused by imperfections of the beamsplitter and prisms, like unwanted birefringence or non equal splitting. Due to the broad spectral distribution of about 80 nm and the resulting short coherence length of about 6 μm, already a path-length difference of this order allows one to distinguish, in principle, the path of the photon - but only with the simultaneous rapid decrease of visibility and indistinguishability.

The stabilization of the interferometer allowed us to lock the phase of the interferometer over hours and thus enabled us to measure the correlation function also behind the interferometer. The observed correlation function (Fig. 7) again shows anticorrelation of detection events for a time difference $\tau = 0$, and thus proves that only single photons are present inside the interferometer and that the interference pattern is made up only from true single photon events. The particle character of the interfering photons becomes observable again *outside* the interferometer.

4 Conclusion

In this contribution, the principle of complementarity has been experimentally demonstrated in a quite suggestive and straightforward way. The experiment first shows that a photon is detected in only one of the two output arms of a beamsplitter. However, if one combines the two arms on a second beamsplitter, thereby erasing any possibility to infer along which of the arms the photon has evolved, one can observe an interference pattern which depends on the path-length difference of both arms. Whereas the first measurement revealed a particle property, the path of the photon, the second part demonstrates the wave nature of the photon.

As one often takes the quantized nature of light for granted, a strongly attenuated laser misleadingly seems to be sufficient to demonstrate "single-photon" interference. The point is, however, that the particular quantum state of the laser light is perfectly described in a wave model and thus never can be used for Welcher-Weg measurements illustrating particle properties and the principle of complementarity — fully independent from the attenuation of a laser intensity.

The source of single photons used in the present experiment operates at ambient conditions, standard components allow stable and easy handling at affordable prices. We are convinced that, provided a further integration step of the source, this simple but instructive demonstration experiment could give a first hands-on experience on the fundamental principles of quantum mechanics in student labs.

This work was supported by the Deutsche Forschungsgemeinschaft.

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