Experimental Interference of Independent Photons

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Interference of photons emerging from independent sources is essential for modern quantum-information processing schemes, above all quantum repeaters and linear-optics quantum computers. We report an observation of nonclassical interference of two single photons originating from two independent, separated sources, which were actively synchronized with a rms timing jitter of 260 fs. The resulting (two-photon) interference visibility was (83 ± 4)%.

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Is it possible to observe fully destructive interference of photons if they all originate from separate, independent sources? Yes, according to quantum theory [1–3]. The perfect interference of photons emerging from independent sources cannot be understood by the classical concept of the superposition of electromagnetic fields but only by the interference of probability amplitudes of multiparticle detection events. As stressed by Mandel “this prediction has no classical analogue, and its confirmation would represent an interesting test of the quantum theory of the electromagnetic field” [2].

Mastering the techniques involving independent sources of single photons and entangled pairs of photons has become vital for implementations of quantum networks and quantum computing schemes [4,5]. For these devices to work it is often tacitly assumed that stable interference between systems from independent sources is feasible. The generic example is that of quantum repeaters [6], which by definition involve entanglement swapping and distillation between spatially separated, independent nodes requiring independent sources. Despite recent claims [7], however, up to now no experiment has been able to fulfill the strict requirements for the sources to be independent and spatially separable. Teleportation of states of particles emitted by sources completely detached from the sources of the entangled pairs of the quantum channel could become feasible. Other applications are linear-optics quantum computing schemes of the Knill-Laflamme-Milburn-type [8], in which ancilla qubits need to become entangled to other, independent optical qubits during the process of the computation.

To demonstrate that two independently emitted photons do interfere, it is important to assure that there exists no possibility whatsoever for the coherence properties of the light emitted by either source to be influenced by the other. Therefore, the operation of one source must not in any way rely on the working of the other source. Such a configuration addresses exactly the needs for practical quantum communication and computation schemes. In the case of long-distance quantum communication any common optical elements shared by the sources and thus any dependence would impede the working of the scheme over large distances due to dispersion or losses. Our experiment fulfills these requirements for independent quantum sources. At the same time it serves as a prototype solution for a variety of quantum-information processing devices.

First, consider two independent classical sources. Any correlation between intensities at two detectors placed in the joint far field of the sources is a manifestation of standard interference of classical waves and shows at most 50% visibility [3]. This is only observable if the detector integration times are below the coherence times of the two fields. A well-known example is the stellar interferometry method introduced by Hanbury-Brown and Twiss [9].

The situation becomes fundamentally different for quantum states of light, e.g., in the case of two separate spontaneously decaying atoms. While one photon can be detected practically anywhere, there are points for which detection of the second photon is then strictly forbidden. The resulting correlation pattern has 100% visibility, completely unexplainable by interference of classical waves. This is due to destructive interference of two indistinguishable processes: (a) detector 1 registers a photon from source 1 and detector 2 registers a photon from source 2, and (b) the other way around.

Quantum interference of two fully independent photons has thus far never been observed. Since the 1960s, however, interference of light from independent sources has
been addressed in many experiments. In [10] two independent He-Ne lasers were used to observe the beating of their superposed outputs. Later [11], transient spatial interference fringes between beams from independent ruby lasers were reported. In both cases the interference was classically explainable. Partly motivated by the often overinterpreted quotation from Dirac that each photon interferes only with itself [12], follow-up experiments [13,14] investigated the question whether one can observe interference of two photons if each one was generated by a different source. This was done by simply attenuating the laser beams. However, attenuation does not affect the statistical nature of laser light. The only quantum aspect was that the detection involved clicks due to photon registrations. Consequently, the observed effects could “not readily be described in terms of one photon from one source interfering with one from the other” [13].

All following experiments involving the interference between single photons employed the well-known Hong-Ou-Mandel (HOM) interference effect, which utilizes the bosonic nature of photons: two indistinguishable photons that enter a 50:50 beam splitter via different input ports will always be detected in one output port. Such two-photon interference was first reported [15] for photon pairs emerging from a spontaneous parametric down-conversion (SPDC) source.

The first interference of separately generated photons was observed by Rarity et al. [16] (see also [17]). They measured HOM-type interference of an SPDC photon and an attenuated part of the very same laser beam pumping the SPDC process. Further related experiments, provided gradual progress with respect to the independence of the utilized sources. A first step was the interference of two triggered single photons created via SPDC by the same pump pulse passing twice through the very same SPDC crystal [18]. Further contributions used photons generated by two mutually coherent time-separated pulses from the same mode-locked laser in one SPDC crystal [19] and, later, generated in one quantum dot [20]. Another step was to create interfering photons in two separate SPDC crystals pumped by the same laser [21].

In a recent experiment [7], interference of two photons generated by two SPDC sources, pumped by pulsed laser beams, was demonstrated. There, the two lasers were synchronized via interaction in a common Kerr medium. The two lasers cannot be considered to be fully independent, because in the Kerr medium not only interference between the fields occurs, but also an interaction between them, which has been demonstrated [22] to influence the relative phase of the beams, and thus may serve as a mechanism for establishing a certain degree of coherence between the two beams. Therefore, the absence of a time-averaged common phase between the laser beams is not due to their independence but due to detuning of the cavities and drifts [22,23]. Furthermore, spatial separation of the two sources, so essential for long-distance quantum communication, is intrinsically impossible with that scheme because of the necessity of intracavity interaction.

As has been pointed out in one of those prior works, “truly independent sources require the use of independent but synchronized fs laser(s)” [21]. Our experiment employs this technique and realizes a scheme involving two independent quantum sources which can in principle be separated by large distances.

The photons emitted from a quantum source are typically generated by the interaction of an (optical) pump field with a nonlinear medium. The medium and the pump field are integral constituents of the source. In our experiment, each of the two sources consists of an SPDC crystal pumped optically by a pulsed fs laser.

To be able to observe interference we have to make sure that the two photons registered behind the beam splitter cannot be distinguished in any way. We use SPDC to generate pairs of correlated photons. The detection event of one of the photons (trigger) of each pair is used to operationally define the presence of the other one on its way to the beam splitter (in this way we assure that the observed interference is due to two photons only, each from a different source). In such a case without frequency filtering, the initial sharp time correlation of photons of an SPDC pair poses a problem: the times of registration of the trigger photons provide temporal distinguishability of the photon registrations behind the beam splitter. Short pump pulses and spectral filters narrower than the bandwidth of these pulses in the paths of the photons give the desired indistinguishability [24].

Additional timing information is contained in the time difference between the independent pulses pumping the two SPDC crystals. In principle, one could compensate this again by filtering. For pulses without any time correlation this would, however, require extremely narrow filters and eventually result in prohibitively low count rates. Synchronizing the pulses of the two independent pumps increases the probability of joint emission events (see Fig. 1) and hence the count rates. The fact that one needs to actively synchronize the sources is a direct unavoidable consequence of their independence. The active synchronization method we use involves only electronic communication (10 kHz bandwidth) about the relative pulse timing between the independently running femtosecond lasers (see Fig. 1). No optical elements whatsoever are shared by the pumps.

Our two SPDC crystals were pumped by UV pulses with center wavelengths of 394.25 ± 0.20 and 394.25 ± 0.20 nm and rms bandwidths of 0.7 ± 0.1 and 0.9 ± 0.1 nm. These beams were produced via frequency doubling of IR pulses from two independent Ti:sapphire femtosecond lasers (master and slave, see Fig. 2). One of these mode-locked lasers was driven by an Ar-ion gas laser, the other by a solid-state Nd:YAG laser. They produced pulses at ~76 MHz repetition rate with center wavelengths of 788.5 ± 0.4 and 788.5 ± 0.4 nm, rms bandwidths of 2.9 ± 0.1 and 3.2 ± 0.1 nm and rms pulse widths...
The timing jitter between the two generated SPDC pairs is theoretically expected to be 

\[ \frac{0.3 \pm 0.2}{0.0006} \times 350 \quad \text{fs} \]

independently are assumed to be filtered to the same bandwidth. We assume both lasers to have the same bandwidth. Also, the resulting UV beams pumped type-II BBO crystals for SPDC. Reflecting prisms (RP) and mirrors (M) guided the SPDC photons through half-wave plates and BBO crystals (CO) to compensate various walk-off effects. All photons were coupled into single-mode fibers (SMF) to guarantee optimal spatial mode overlap. Polarizers \( P_1 \) and fiber squeezers (SQ) ensured the indistinguishability of the photons at the single-mode fiber beam splitter (FBS). Coincidences \( C \) between the detectors \( D_1 \) and \( D_2 \) could be triggered on detection events in both \( D_3 \) and \( D_4 \).

To additionally demonstrate the role played by distinguishability in this effect we prepared different input states under otherwise equivalent experimental conditions. First, we used perfectly distinguishable orthogonally polarized input states, which as expected, show no interference [Fig. 3(b)]. Next, unpolarized input photons [Fig. 3(c)] were used which are a mixture of orthogonally polarized photons and hence are partially distinguishable. They still have a probability of 1/2 to coincide in their polarization, which results in an expected visibility of ideally 33% or, taking into account the relative timing jitter, 29.6 ± 0.8%. We observed 26 ± 3%. Finally, we demonstrated the interference for photon sources endowed with thermal statistics. Without monitoring the trigger detection events, the emission statistics in each input mode of the beam splitter is equivalent to light emitted by a thermal source. For two such beams of equal average intensity one would expect 20% visibility [3] in the ideal case or 18.0 ± 0.5% when velocity mismatch between UV and IR photons in the second-harmonic generation (SHG) and SPDC crystals. The central wavelengths of the lasers and the filters are all assumed to be equal.

In order to obtain the theoretical expectations for the HOM dip we used standard quantum electrodynamics [25]. We assume both lasers to have the same bandwidth. Also, both interfering photons and both trigger photons, respectively, are assumed to be filtered to the same bandwidth. The timing jitter between the two generated SPDC pairs is 350 ± 30 fs, resulting from the jitter of the laser synchronization (260 ± 30 fs Gaussian jitter) and the group-bandwidth filters (BF_1 and BF_2) to get the fundamental and 9th harmonic signals.

![Image of pump lasers synchronized by a Coherent Synchrolock™ using two phase-locked loops (PLL), each consisting of a phase detector (⊗), a low-pass filter (F) and an amplifier (A) (see e.g. [27]). One PLL operates at the repetition frequency of the lasers (76 MHz) for a coarse time synchronization. Then, a second PLL operating at the lasers’ 9th harmonic (684 MHz) takes over. Both PLLs adjust the “slave” laser’s repetition frequency via cavity mirrors driven by piezoactuators. The PLLs are fed by fast photo diodes (PD_1 and PD_2) filtered by bandwidth filters (BF_1 and BF_2) to get the fundamental and 9th harmonic signals.](image1)

![Image of pulsed IR laser beams, which were electronically synchronized (ES, see Fig. 1), were frequency doubled (one in a lithium triborate (LBO), the other in a β-barium borate (BBO) crystal). The resulting UV beams were used which are a mixture of orthogonally polarized photons and hence are partially distinguishable. They still have a probability of 1/2 to coincide in their polarization, which results in an expected visibility of ideally 33% or, taking into account the relative timing jitter, 29.6 ± 0.8%. We observed 26 ± 3%. Finally, we demonstrated the interference for photon sources endowed with thermal statistics. Without monitoring the trigger detection events, the emission statistics in each input mode of the beam splitter is equivalent to light emitted by a thermal source. For two such beams of equal average intensity one would expect 20% visibility [3] in the ideal case or 18.0 ± 0.5% when velocity mismatch between UV and IR photons in the second-harmonic generation (SHG) and SPDC crystals. The central wavelengths of the lasers and the filters are all assumed to be equal.](image2)
FIG. 3 (color online). Experimental two-photon interference from independent sources. The solid lines represent Gaussian fits to the data points. (a) HOM-type interference of indistinguishable photons from actively synchronized independent sources. The observed visibility was 83 ± 4% and the dip width was 0.79 ± 0.04 ps. (b) Input photons distinguishable by their polarization. No interference occurs. (c) Unpolarized input photons show limited interference due to partial distinguishability. The observed visibility was (26 ± 3%). (d) Classical interference from a thermal source, showing a dip visibility of 15 ± 2%.

bearing in mind the relative timing jitter. Experimentally we achieved a lower visibility of 14.5 ± 2.0% due to differences of the SPDC-pair rates in the two sources (approximately a factor of 2). Note that for specially prepared classical light sources, the visibility can even reach the very maximum of 50% [3].

Our experiment demonstrates the feasibility of interference of two single photons originating from independent, spatially separated sources, which are actively time synchronized. The visibility of the effect is above the threshold for further use in quantum communication processes like quantum teleportation or entanglement swapping. This result is a step toward the realization of quantum repeaters, quantum networks, and certain optical quantum computing schemes. Because of the separability of the utilized sources the presented scheme opens the door for future long-distance applications involving multiphoton interference. Moreover, the use of such independent sources might also provide conceptual advantages for experiments on the foundations of quantum physics [26].

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