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2014 New J. Phys. 16 083011

(http://iopscience.iop.org/1367-2630/16/8/083011)

New Journal of Physics
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Experimental observation of entanglement duality for identical particles

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Received 26 March 2014, revised 30 June 2014
Accepted for publication 14 July 2014
Published 5 August 2014
New Journal of Physics **16** (2014) 083011
doi:10.1088/1367-2630/16/8/083011

Abstract

It was shown recently that entanglement of identical particles has a feature called dualism (Bose and Home 2013 *Phys. Rev. Lett.* **110** 140404), which is fundamentally connected with quantum indistinguishability. Here we report an experiment that observes the entanglement duality for the first time with two identical photons, which manifest polarization entanglement when labeled by different paths or path entanglement when labeled by polarization states. By adjusting the mismatch in frequency or arrival time of the entangled photons, we tune the photon indistinguishability from the quantum to the classical limit and observe that the entanglement duality disappears under the emergence of classical distinguishability, confirming it as a characteristic feature of quantum indistinguishable particles.

Keywords: entanglement duality, quantum indistinguishability, quantum mechanics

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1. Introduction

Indistinguishability of identical particles is a fundamental feature of quantum mechanics which has deep consequences for quantum statistics and many-body physics. Quantum indistinguishability has been confirmed for various microscopic particles, ranging from the fundamental, such as photons [1–3] or electrons [4], to more complex composite objects such as atoms [5]. The test of quantum indistinguishability is usually based on the Hanbury-Brown–Twiss (HBT) type of experiment, which requires one to bring particles together for high-order interference [1–5]. If the particles have mutual interaction with each other, which may become unavoidable for increasingly massive objects, the interaction effect could complicate the test of quantum indistinguishability. It was pointed out in a very recent work that entanglement of identical particles shows a unique property called duality, which is fundamentally connected with quantum indistinguishability [6]. This connection opens up a conceptually new way to test quantum indistinguishability without the need to bring the particles together, thereby avoiding the interaction effect. The entanglement duality means that if two identical particles are entangled in a variable A when labeled by another variable B, they will also be entangled in the variable B when labeled by the variable A. This feature is uniquely associated with quantum indistinguishable particles and disappears when the particles become distinguishable.

In this paper, we report the first experimental observation of the entanglement duality with two identical photons and its fundamental connection with quantum indistinguishability. The complementary variables A and B are taken as the photon polarization and path. Through spontaneous parametric down conversion in a nonlinear periodically-poled potassium titanyl phosphate (PPKTP) crystal [7, 8], we generate frequency-degenerate photon pairs along two different paths labeled as signal (S) and idler (I), which are entangled in polarization with an entanglement fidelity of (98.5 ± 0.1) %. We then separate the photons according to their polarization label (horizontal or vertical) and demonstrate their entanglement in the path variable (where the different paths S and I are taken as the qubit basis states) with an entanglement fidelity of (93.8 ± 0.3) %, thereby confirming the entanglement duality for indistinguishable photons. To show that this feature is uniquely associated with quantum indistinguishability, we make the two photons distinguishable by adjusting the mismatch in their frequency or arrival time. The mismatched frequency (or arrival time) is only correlated with the path variable, so the initial symmetry between the two degrees of freedom (path and polarization) is broken when we distinguish the photons by the new label of frequency (or arrival time). As a result, in this case although we still observe a large amount of entanglement in the polarization variable, we see no entanglement in the path variable when the photons are separated according to their polarization.

2. Theoretical background

The concept of entanglement is defined for a composite system which can be divided into two or more subsystems. Identical quantum particles are indistinguishable when they are in the same state, so they can only be labeled and separated through different states of certain variables (modes). For instance, a photon can be labeled by different paths called signal (S) or idler (I) or by different polarizations called horizontal (H) or vertical (V), as illustrated in figure 1(a). To be concrete, let us consider a polarization entangled state $|\Psi\rangle$ for two photons between the signal

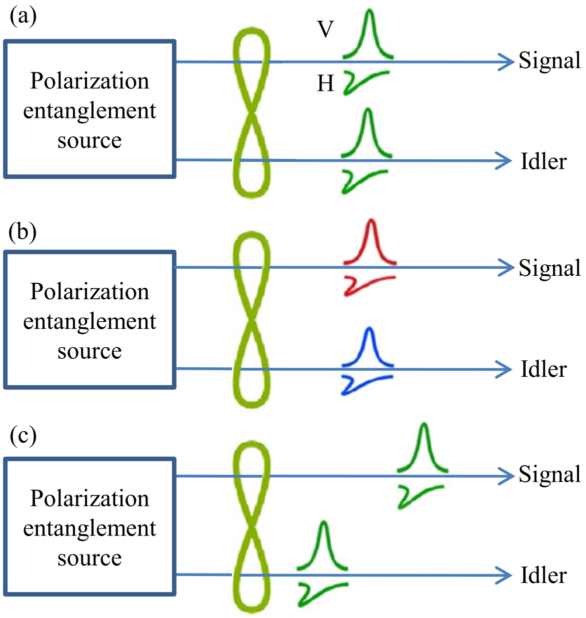

Figure 1. Illustration of test of the entanglement duality through photons with tunable quantum indistinguishability. (a) Entanglement for indistinguishable photons which shows entanglement dualism in the polarization (*H* and *V*) and the path (signal and idler) variables. (b, c) Photons are distinguished through color (frequency, b) or arrival time at the detector (c) and the entanglement dualism breaks down.

and the idler modes with the following form

$$|\Psi\rangle = \left(|H\rangle_S |V\rangle_I + |V\rangle_S |H\rangle_I\right)/\sqrt{2}. \quad (1)$$

Here, different states S and I of the path variable are used to label and separate the two identical photons and different polarization states *H* and *V* are taken as the qubit basis-vectors. The state $|\Psi\rangle$ can be equally written into a dual form

$$|\Psi\rangle = \left(|S\rangle_H |I\rangle_V + |I\rangle_H |S\rangle_V\right)/\sqrt{2}, \quad (2)$$

where we have switched the role of the path and the polarization variables, with the photons entangled in the path variable while labeled by the polarization variable. This is the entanglement duality first noticed in [6], which holds only for identical particles. The dualism breaks down when the particles along the paths S and I become distinguishable, e.g., through difference in some other degrees of freedom such as frequency or arrival time as illustrated in figure 1(b) and (c). In this case, the polarization entanglement remains the same and is still described by equation (1). However, if we separate the photons according to their polarization, the photons from the paths S and I are distinguishable in frequency (or arrival time) and we therefore cannot observe any coherence or entanglement in the path variable. Note that the concept of entanglement duality is different from that of the hyper-entanglement [9] although both of them involve polarization and path entanglement. The hyper-entanglement is not related to quantum indistinguishability and involves simultaneous entanglement in polarization and path variables. Instead, the entanglement duality is an intrinsic property of indistinguishable particles, where the entanglement in polarization and path variables are complementary to each other but not present simultaneously by the same measurement.

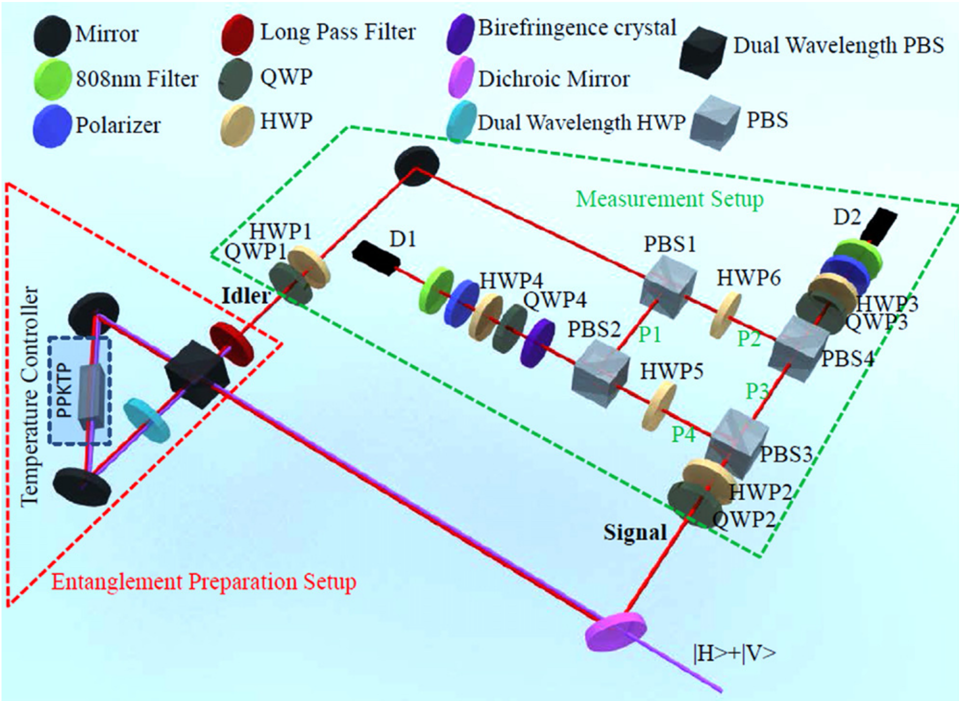

Figure 2. Illustration of the experimental setup for testing of the entanglement duality. A continuous wave (cw) laser beam at the wavelength of 404 nm and with polarization $|H\rangle + |V\rangle$ from a diode laser enters a Sagnac interferometer to pump a PPKTP crystal (15 mm long with a cross-section $2 \times 1\,\text{mm}^2$), generating down-converted photon pairs at the wavelength 808 nm through the type-II phase matching. The interferometer is composed of a dual-wavelength (at both 404 and 808 nm) PBS (polarization beam splitter) and HWP (half wave plate, which flips polarization between H and V). The setup inside the red triangle generates a polarization maximally entangled state between the signal and the idler photons [7, 8]. The setup inside the green box is for measurement of the entanglement duality. By setting the angles of the HWPs and QWPs at appropriate angles (see the text for details), the setup can be used to measure either polarization (or path) entanglement when the photon is labeled by path (polarization). A birefringent crystal is inserted after PBS2 to compensate the optical length difference between the paths P1+P3 and P2+P4. An interference filter of 3 nm width centered at 808 nm wavelength is inserted before the single photon detectors D1 and D2, and the photon counts of these detectors are registered through a home-made coincidence circuit. This setup uses only single-photon interference to verify entanglement in the path variable and never brings the two photons together for the Hong–Ou–Mandel type of interference.

3. Experimental facts

To experimentally observe the entanglement duality, we first generate frequency-degenerate photon pairs through spontaneous parametric down conversion in a nonlinear PPKTP crystal. With the type-II phase matching in the nonlinear crystal, the down converted photons have orthogonal linear polarizations, denoted by H and V, respectively. The entanglement is produced through a Sagnac interferometer as shown in figure 2 [7, 8]. When the polarization of the pump beam is in a coherent superposition $\left(|H\rangle_P + |V\rangle_P\right)/\sqrt{2}$, the down-converted photons go out of the interferometer along two paths denoted as the signal and the idler modes, and the polarization of the signal and the idler photons are described exactly by the entangled state (1) in the ideal case.

In our experiment, we tune the photon distinguishability by adjusting the mismatch in the frequency or the arrival time of the two photons. The frequency mismatch between the two down-converted photons can be tuned through adjustment of the temperature of the nonlinear crystal. At a given temperature, the phase matching condition is satisfied only for certain frequencies of the signal and the idler photons, and by tuning the temperature, we can vary the frequency mismatch between the signal and the idler photons. If this mismatch is larger than the bandwidth of the down-converted photons (which is about 0.78 nm measured in terms of the FWHM (full width at the half maximum) of the wavelength spectrum, as illustrated in figure 1(b), the photons in the signal and the idler modes are completely distinguishable through the frequency. Alternatively, we can also distinguish the signal and the idler photons through their different arrival times at the photon detector. The down-converted photons have a large bandwidth and thus a small coherence time about 2.8 ps, which determines the effective width of the temporal profile of the correlated photon pair. If we tune the mismatch in the arrival time of the signal and the idler photons to make it larger than the width of this temporal profile, the photons are distinguishable through their different arrival times at the detector, as illustrated in figure 1(c).

To confirm the entanglement duality for indistinguishable quantum particles, we need to have a setup to measure the photon polarization entanglement when they are labeled by the path and their path entanglement when the photons are labeled by the polarization. The measurement setup shown in figure 2 achieves these two goals with the same apparatus. The setup consists of a Mach–Zehnder interferometer composed by four polarization beam splitters (PBSs) and a number of half-wave plates (HWPs) and quarter-wave plates (QWPs). The detection of the polarization entanglement is straightforward. We simply set the angles of HWP3, HWP4, HWP5, HWP6 and QWP3, QWP4 all at zero so that they have no effect. In this case, PBS1 and PBS2 (PBS3 and PBS4) work as polarizers to select out the vertical (horizontal) polarization component for the idler (signal) photons, respectively. By tuning the angles of HWP1 and QWP1 (HWP2 and QWP2) for the idler (signal) photons, we can measure their polarization in arbitrary bases and then reconstruct their polarization state through standard quantum state tomography [10].

The main purpose of the measurement setup shown in figure 2 is for detection of the path entanglement when the photons are labeled by their polarization states. In this case, we set the angles of HWP1, HWP2, QWP1, QWP2 all at zero. The PBS1 and PBS3 separate the idler and the signal photons according to their polarization. Now we discuss the entanglement between the horizontal and the vertical photons. For the horizontal photon, the qubit basis-states are denoted by the paths P2 and P3 (corresponding to the idler and the signal modes, respectively). We need to measure the horizontal photon in P2, P3, and their arbitrary superposition bases. For this purpose, we superpose these two components at the PBS4 after the HWP6 set at angle 45^o (which flips polarization from H to V). Then, through rotation of the angles of HWP3, QWP3 and the polarizer before the detector D2, we can measure the horizontal photon in arbitrary superposition bases of the paths P2 and P3. Similarly, through a combination of PBS2, HWP5 (set at angle 45^o), and rotation of HWP4, QWP4, we can measure the vertical photon in arbitrary superposition bases of the paths P1 and P4. Note that for this measurement, the two photons are never brought together for the HBT type of interference. We detect each photon separately in their individual (superposition) bases. From this measurement, we can reconstruct

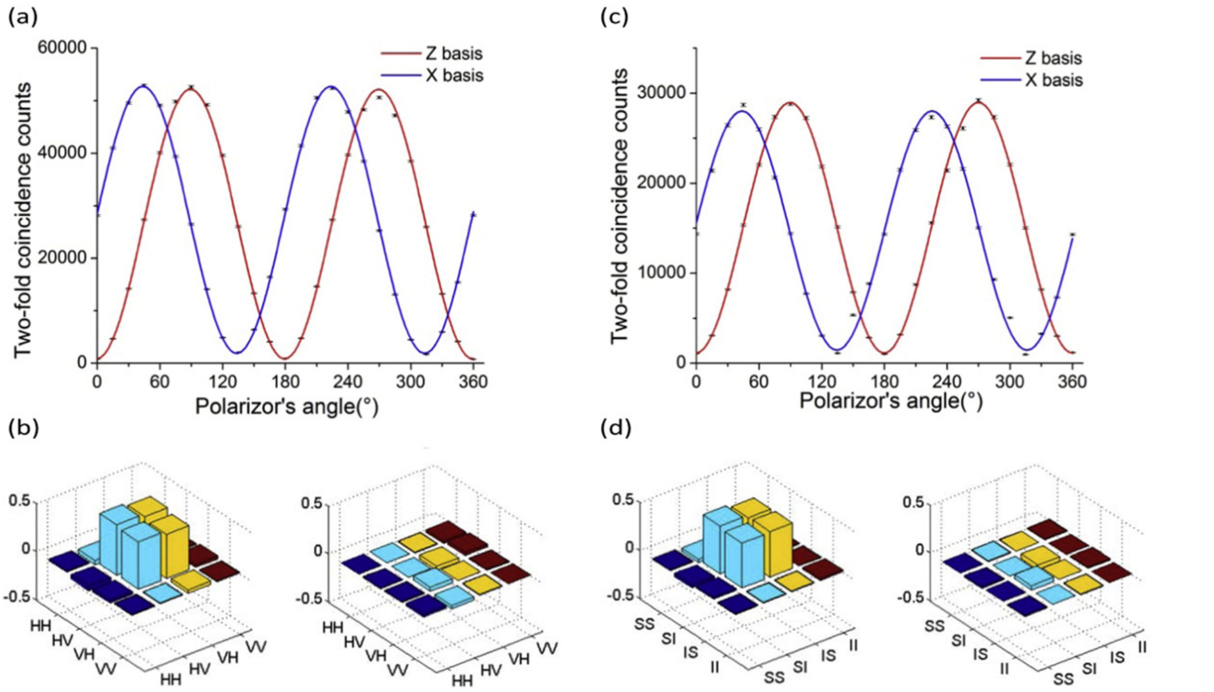

Figure 3. Data for test of the entanglement duality with indistinguishable photons, where figures a, b (c, d) show polarization (path) entanglement when the photon is labeled by path (polarization). (a) The measured polarization correlation in the complementary Z and X bases. (b) The reconstructed density matrix for the polarization qubits, where the left (right) figure shows the real (imaginary) parts of the matrix elements. (c) The path correlation and (d) the density matrix of the path qubits for the horizontal and the vertical photons.

the path state through quantum state tomography and derive its entanglement between the horizontal and the vertical photons.

The data from the entanglement duality measurement is shown in figure 3. In figures 3(a) and (b), we show the data from measurement in the polarization basis for the signal and the idler photons. First, by rotating the polarizer's angle θ for the signal photon while fixing it to zero for the idler photon, we measure their polarization correlation in the Z-basis (projection to $\left[\cos(2\theta)\ |H\rangle_S + \sin(2\theta)\ |V\rangle_S\right]\ |H\rangle_I$) and the X-basis (projection to $\left[\cos(2\theta)\ |H\rangle_S + \sin(2\theta)\ |V\rangle_S\right]\ |+\rangle_I$ with $|\pm\rangle \equiv [\pm|H\rangle + |V\rangle]/\sqrt{2}$), and the oscillation shown in figure 3(a) clearly demonstrates coherence of the input state in the polarization basis. The full density matrix ρ of these two polarization qubits is reconstructed through quantum state tomography by measurement of correlations in 16 complementary bases [10] and shown in figure 3(b). From the measured density matrix, we calculate the entanglement fidelity, defined as $F \equiv \langle \Psi |\ \rho\, |\Psi\rangle$ ($|\Psi\rangle$ is given by equation (1)) [11], and the concurrence C defined in [12] as a measure of its entanglement. We find $F = (98.5\ \pm\ 0.1)\ \%$ and $C = 0.901\ \pm\ 0.002$, where the error bar accounts for the statistical error associated with the photon detection assuming a Poissonian distribution for the photon counts and the error bar is propagated through exact numerical simulation. Similarly, in figure 3(c), we show the path correlation in the Z-basis and the X-basis when the photons are labeled by their polarization, and in figure 3(d), we show the measured density matrix of the path qubits for the horizontal

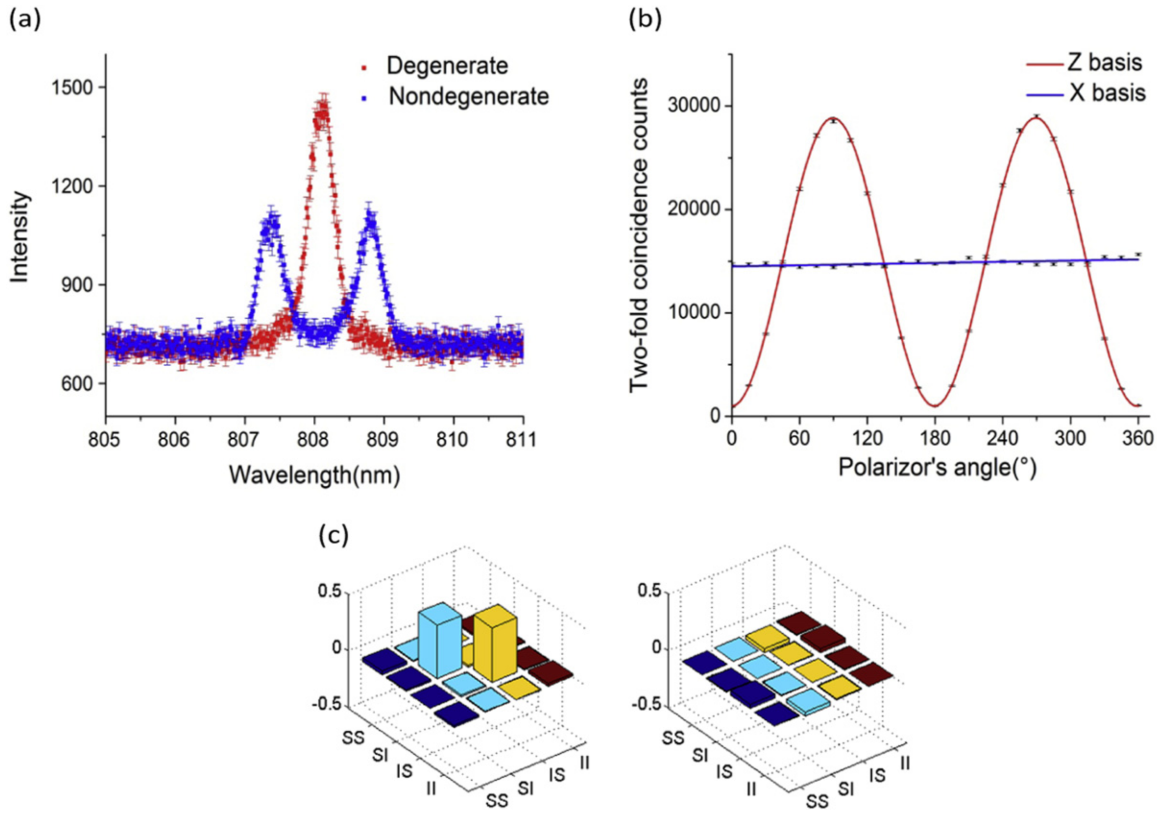

Figure 4. (a) The spectrum of the down-converted photons measured through a spectrometer, where the central peak shows the degenerate case with the temperature of the PPKTP crystal set at 53.7° and the two edge peaks correspond to the nondegenerate case with the crystal temperature at 50.0°. The photons are clearly distinguishable by frequency at the non-degenerate case. (b, c) The measured path correlation (b) and the reconstructed density matrix for the path qubits (c) when the photons are distinguishable through either frequency or arrival time.

and the vertical photons. From the measurement, we find $F = (93.8 \pm 0.3)\,\%$ and $C = 0.896 \pm 0.003$ for the path qubits. We therefore observe a large amount of entanglement for the photons in the polarization variable when labeled by the path and in the path variable when labeled by the polarization, which unambiguously confirms the entanglement duality for two indistinguishable photons.

To demonstrate that the entanglement duality is connected with quantum indistinguishability, we make the photons distinguishable in our experiment by tuning up the mismatch in frequency or arrival time and observe the corresponding change to quantum entanglement. As an example, in figure 4(a) we show the measured frequency spectrum of the down-converted photons by adjusting the temperature of the PPKTP crystal. Clearly, we can tune the photon distinguishability through this control knob. When the photons are distinguished by color or arrival time, we observe a similarly large amount of entanglement in the polarization variable. For instance, with mismatched frequencies as shown in figure 4(a), we find the concurrence $C = 0.903 \pm 0.004$ measured through the quantum state tomography. However, when we label the photons by their polarization and measure their entanglement in the path variable, we find no entanglement. As an example, we show in figures 4(b) and (c) the typical correlation curves and the density matrix elements for the path variable when the photons become distinguishable by either color or arrival time. The coherence is gone as indicated by the flat correlation curve in the X-basis and the vanishing off-diagonal terms in the reconstructed density matrix. From the measured density matrix, we find the concurrence $C = 0$, confirming no entanglement in the path variable. We therefore demonstrate that the entanglement duality is a characteristic property of indistinguishable particles and breaks down when particles become distinguishable. Note that the entanglement (measured by the concurrence C) in the dual basis is monotonically connected with quantum indistinguishability and can be used as a quantitate indicator of the latter, which attains the maximum value 1 under perfect quantum indistinguishability and the minimum 0 for completely distinguishable particles. In our experiment, the value of this quantity C is 0.896 ± 0.003 (0) for the indistinguishable (distinguishable) particles.

4. Conclusion

In summary, we have reported the first experimental demonstration of entanglement duality with two identical photons and its fundamental connection with quantum indistinguishability. The experimental observation of the entanglement duality offers a conceptually new way to test quantum indistinguishability without the need to bring the particles together for the HBT type of interference.

Acknowledgments

This work was supported by the National Basic Research Program of China (973 Program) 2011CBA00300 (2011CBA00302) and the NSFC Grants 61033001, 61361136003. LMD acknowledges additional support from the IARPA MUSIQC program, the ARO and the AFOSR MURI program.

References

[1] Brown R H and Twiss R Q 1956 *Nature* **177** 27
[2] Hong C K, Ou Z Y and Mandel L 1987 *Phys. Rev. Lett.* **59** 2044
Shih Y H and Alley C O 1988 *Phys. Rev. Lett.* **61** 2921
[3] Kaltenbaek R, Blauensteiner B, Zukowski M, Aspelmeyer M and Zeilinger Z 2006 *Phys. Rev. Lett.* **96** 240502
[4] Liu R C, Liu R C, Odom B and Tarucha S 1998 *Nature* **391** 263
Kiesel H, Renz A and Hasselbach F 2002 *Nature* **418** 392
[5] Foling S, Gerbier F, Widera A, Mandel O, Gericke T and Bloch I 2005 *Nature* **434** 481
Jeltes T *et al* 2007 *Nature* **445** 402
[6] Bose S and Home D 2013 *Phys. Rev. Lett.* **110** 140404
[7] Kim T, Fiorentino M and Wong F N C 2006 *Phys. Rev.* A **73** 012316
Fedrizzi A, Herbst T, Poppe A, Jennewein T and Zeilinger A 2007 *Opt. Express* **15** 15377
[8] Giustina M *et al* 2013 *Nature* **497** 227
[9] Barreiro J T, Langford N K, Peters N A and Kwiat P G 2005 *Phys. Rev. Lett.* **95** 260501
[10] James D F V, Kwiat P G, Munro W J and White A G 2001 *Phys. Rev.* A **64** 052312
[11] Blinov B B *et al* 2004 *Nature* **428** 153
[12] Wootters W K 1998 *Phys. Rev. Lett.* **80** 2245