Demonstration of Temporal Distinguishability of Three and Four Photons with Asymmetric Beam Splitter

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By using an asymmetric beam splitter, we observe the generalized Hong-Ou-Mandel effects for three and four photons, respectively. Furthermore, we can use this generalized Hong-Ou-Mandel interferometer to characterize the temporal distinguishability of a multi-photon state.

Indistinguishability is essential in achieving quantum entanglement. As more particles get involved in quantum information sciences [1], their mutual indistinguishability will play an paramount role in some of the quantum information protocols. Thus assessing multi-particle indistinguishability has become an increasingly urgent task.

Mathematically, the temporal indistinguishability of an N-photon state is characterized [2] by the permutation symmetry of its spectral wave function: \( \Phi(\omega_1, \omega_2, ..., \omega_N) = \Phi(\mathcal{P}\{\omega_1, \omega_2, ..., \omega_N\}) \) with \( \mathcal{P} \) as the arbitrary permutation operator. For the two-photon case, the visibility in a Hong-Ou-Mandel interferometer [3] characterizes the degree of permutation symmetry and thus the degree of temporal indistinguishability [4, 5]. Generalization of this scheme to an arbitrary N-photon case is not trivial [2] and involves complicated scheme of projection measurement [6, 7, 8]. In this paper, we will demonstrate a simple scheme using only one adjustable asymmetric beam splitter and multi-photon coincidence measurement to characterize the temporal distinguishability of a multi-photon state.

The idea is that for an input state of \( |m,n\rangle \) to an asymmetric beam splitter (Fig.1a) of transmissivity \( T \) and reflectivity \( R \) \((T \neq R)\), the probability \( P_{\text{out}}(m,n) \) for \( m \) photons coming out in one port and \( n \) photons in the other port is zero with the appropriate values of \( T \) and \( R \), due to multi-photon interference. Since the effect of interference depends on photon distinguishability, we can use the visibility of the above mentioned interference effect to characterize the temporal distinguishability of the input state of \( |m,n\rangle \) (Fig.1b,c).

It can be shown [6] that for the case of \( n = 1, m = N \), we have \( T = NR = N/(N+1) \) for \( P_{N+1}(N,1) = 0 \) in the ideal case. But for the non-ideal case, the visibility is simply \( p/N \), where \( p \) is the number of photons among the \( N \) photons that are indistinguishable from the single photon from the other port. This result is exactly the same as the complicated projection measurement scheme discussed in Ref [2]. So as we scan the delay between the single photon and the \( N \) photons, we will see a number of dips with visibility of \( p/N \), as shown in Fig.1c. The picture in Fig.1c will fully characterize the temporal distinguishability of the \( N \) photons in Fig.1b.

The case of \( m = n = 2 \) can realized with \( T = (3 \pm \sqrt{3})/6, R = (3 \mp \sqrt{3})/6 \). The visibility of different scenarios in this case is exactly the same as the projection scheme in Ref [2]. But the case of other values of \( m,n \) are complicated.

Experimentally, we employ the state \(|1_H, 2_H\rangle\) and \(|2_V, 2_H\rangle\) in an asymmetry beam splitter made of half wave plate (HWP) and polarization beam splitters (PBS) (Fig.2). With proper rotation angle of the HWP, we may achieve \( T = 2/3 \) for three-photon case or \( T = (3 \pm \sqrt{3})/6 \) for the four-photon case. The two different detection schemes for three and four photons are shown in the insets of Fig.2, respectively. The state \(|2_V, 2_H\rangle\) can be easily generated from a type-II parametric down-conversion process. But the state \(|1_H, 2_H\rangle\) is not straightforward. We use a same scheme as in Ref. [10] to produce a three-photon state with adjustable temporal distinguishability.

Fig.1 (a) Scheme for interference of \( N \) photons and a single photon with an asymmetric beam splitter. (b) Temporal distribution of an \( N \)-photon state as related to the single photon state. (c) The result of \( N+1 \)-photon coincidence shows the interference dips of various visibility.
We measure the three-photon coincidence (inset (a) of Fig. 2) as a function of the delay $\Delta$ between the two H-photons and the single V-photon. There are two scenarios in this case: (a) the two H-photons are indistinguishable and in the state of $|2_H, 1_V \rangle$ or (b) the two H-photons are well separated and become distinguishable in the state of $|1_H, 1_H' \rangle$. The results for these two scenarios are shown in Fig. 3(a) and Fig. 3(b), respectively. Similarly, the four-photon result is shown in Fig. 3(c).

Both Fig. 3(a) and Fig. 3(c) show the typical Hong-Ou-Mandel dips for three- and four-photon cases, respectively, with a large visibility (85% and 92%). The double dip feature in Fig. 3(b) is due to temporal separation between the two H-photons with a proper adjustment of their relative delay. The close to 50% visibility reflects the fact that the two H-photons are distinguishable. This is consistent with the theory mentioned earlier. Thus this scheme with an asymmetric beam splitter can characterize the degree of temporal distinguishability of a multi-photon state by the visibility of interference dips.

It should be pointed out that for $n = 1, m = 2$, the scenario of indistinguishable two H-photons in Fig. 3(a) was first discussed by Wang and Kobayashi [11] and later realized experimentally by Sanaka et al. [12].

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**Fig. 2** Experimental Setup. HWP: half wave plate; PBS: polarization beam splitter; IF: interference filter

**Fig. 3** Coincidence counts as a function of delay shows the Hong-Ou-Mandel effect for (a) the state $|1_V, 2_H \rangle$, (b) the state $|1_V, 1_H, 1_H' \rangle$, and (c) the state $|2_V, 2_H \rangle$.

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