Phase and amplitude controlled heralding of N00N states

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Abstract: Entangled photons, an essential resource in quantum technology, are mostly generated in spontaneous processes, making it impossible to know if the quantum state is available for use; giving only *a posteriori* knowledge of the quantum state via destructive photon detection processes. There are schemes for heralding the generation of entangled photons but the heralding schemes developed to date only inform the generation of a predetermined quantum state with no capability of state control. Here, we report the phase and (probability-) amplitude controlled heralding, i.e., complete quantum state heralding, of multiphoton entangled states or N00N states. Since the phase and amplitude controls are inseparably integrated into the heralding mechanism, our scheme enables generation of N00N states with arbitrary phases and amplitudes. Such a flexible heralding scheme is expected to play important roles in various photonic quantum information applications.

OCIS codes: (270.0270) Quantum optics; (270.5585) Quantum information and processing; (270.4180) Multiphoton processes.

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1. Introduction

Entangled photons are a key resource in quantum communication, quantum computing, and quantum metrology. Especially, multiphoton entanglement in the form of N00N states ($|N,0\rangle + |0,N\rangle$) enables Heisenberg-limited measurement, beating the standard quantum limit [1–4]. Currently, the most efficient and versatile schemes for generating entangled photons are based on nonlinear optical processes, such as, spontaneous parametric down conversion (SPDC) [5–9] and spontaneous four-wave mixing (SFWM) [10–13]. However, due to the stochastic nature of such processes, successful generation of the photons remains unknown – so does the quantum state encoded on the photons – until the photons are detected, giving only *a posteriori* knowledge of the quantum state via destructive photon detection processes.

It is nevertheless possible to herald the generation of entangled photons by using the detection of ancillary photons [14, 15]. For instance, heralding of Bell states [16, 17] and N00N states [18–20] has been demonstrated. However, the heralding schemes developed to date are limited in that they only herald the generation of a predetermined quantum state with no control over the state being heralded.

In this paper we report a heralding scheme for N00N states in which the phase and (probability-) amplitude of the entangled state can be arbitrarily chosen. In other words, rather than simply heralding the presence of a predetermined quantum state, our scheme enables heralding of a complete quantum state, both phase and amplitude, of N00N states, which is made possible by inseparably integrating the phase and amplitude controls into the heralding mechanism itself. We experimentally demonstrate phase-controlled heralding of a two-photon N00N state and generalize the result to herald N-photon N00N states with different amplitudes and phases.

2. Experiment

We start by presenting the experimental demonstration of phase-controlled heralding of a two-photon N00N state,

$$|\Phi\rangle = |2_H, 0_V\rangle - e^{2i\theta}|0_H, 2_V\rangle, \tag{1}$$

for horizontal (H) and vertical (V) polarization modes. For convenience, we will omit the normalization constant. In contrast to conventional heralding schemes [14–20], the phase factor θ can be chosen arbitrarily, hence phase-controlled heralding. Note that such variation of the phase is essential for achieving optimal sensitivity in quantum metrology [3,4].

The experimental setup is shown in Fig. 1. The photon source produces the separable four-photon state $|2_H, 2_V\rangle$ by means of SPDC (The SPDC setup is not shown in Fig. 1). A 2 mm-thick type-I β-BaB_2O_4 crystal is pumped by a 390 nm femtosecond pulsed laser having the duration of 100 fs, repetition rate of 95 MHz, and the average power of 150 mW. The quantum state of the SPDC photons is, in the Fock basis, $\sum_{n=0}^{\infty} \eta^n |n_s, n_i\rangle$, in which an equal number of 780 nm photons are generated at signal (s) and idler (i) modes, and $|\eta|^2 - |\eta|^4$ is a probability of a single-pair generation. To eliminate spectral and spatial distinguishabilities between the photons, each of the signal and idler modes is filtered by a narrow bandpass filter (3 nm bandwidth centered at 780 nm) and coupled into a single-mode fiber. The phase-controlled heralding of a two-photon N00N state requires detection of two ancillary photons at the trigger. Thus, to maximize the probability of the four-photon term $|2_s, 2_i\rangle$ while minimizing the contributions from higher number of photons $|n_s, n_i\rangle$ for $n > 2$, we set $|\eta|^2 = 0.018$ in the experiment. The signal and idler photons are adjusted to be horizontally and vertically polarized, respectively, and they arrive at the polarizing beam splitter (PBS) in Fig. 1 simultaneously, producing the two-photon Fock state $|2_H, 2_V\rangle$ at mode a.

The four-photon state $|2_H, 2_V\rangle$ at mode a is then split into two modes c and d with a beam splitter BS. The BS transmittance is set at 79 % to direct only a small fraction of photons to the heralding trigger in mode d. The two-photon N00N state $|2_H, 0_V\rangle - e^{2i\theta}|0_H, 2_V\rangle$ is heralded at mode c if the trigger setup implements the heralding projection $(\hat{d}_H)^2 - e^{-2i\theta}(\hat{d}_V)^2$, where $\hat{d}_H$ and $\hat{d}_V$ are the annihilation operators, respectively, for a horizontally-polarized and a vertically-polarized photon in mode d. At the trigger, the phase shifting operation $R_z(\theta)$, introducing the phase shift $\theta = 4\alpha + \pi$ between the horizontal and vertical polarizations, is implemented with a set of two QWPs (oriented at 45°) and a HWP (oriented at α). The HWP oriented at 22.5° is placed just before the PBS to rotate the measurement basis: $(\hat{d}_H, \hat{d}_V) \to (\hat{d}_H + \hat{d}_V, \hat{d}_H - \hat{d}_V)$. Then, single-photon detections on D_1 and on D_2 (Perkin-Elmer SPCM-AQRH-13) correspond to annihilation operations $\hat{d}_H + e^{-i\theta}\hat{d}_V$ and $\hat{d}_H - e^{-i\theta}\hat{d}_V$, respectively. Simultaneous clicks on both detectors correspond to the annihilation operation $(\hat{d}_H)^2 - e^{-2i\theta}(\hat{d}_V)^2$, hence implementing the projection measurement $|\psi_{\mathrm{trig}}\rangle\langle\psi_{\mathrm{trig}}|$ with $|\psi_{\mathrm{trig}}\rangle = |2_H, 0_V\rangle - e^{2i\theta}|0_H, 2_V\rangle$. Note that the trigger does not generate any heralding signal from the single-pair state $|1_H, 1_V\rangle$ because it

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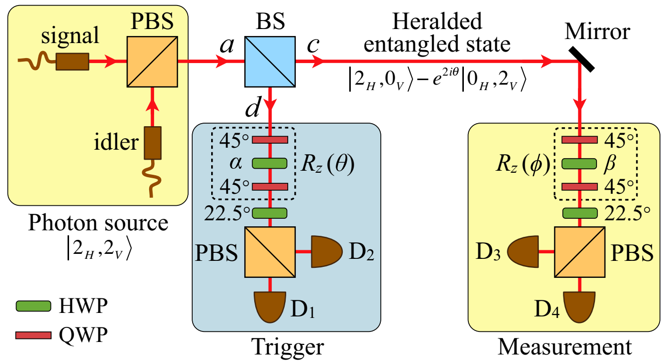

Fig. 1. Experimental setup. The photon source produces the four-photon state $|2_H,2_V\rangle$. PBS and BS are the polarizing and non-polarizing beam splitters, respectively. At the trigger, a set of two quarter-wave plates (QWP) and a half-wave plate (HWP) implements $R_z(\theta)$ where $\theta = 4\alpha + \pi$. If detectors D1 and D2 click simultaneously, the two-photon N00N state $|2_H,0_V\rangle - e^{2i\theta}|0_H,2_V\rangle$ is heralded with θ set by $R_z(\theta)$. At the measurement setup, the heralded N00N state is projected onto the two-photon measurement basis defined by $R_z(\phi)$ and detectors D3 and D4. The phase-controlled heralding of the entangled state is demonstrated by observing four-fold coincidences as a function of the projection angle $\phi = 4\beta + \pi$.

is orthogonal to the projection state $|\psi_{\text{trig}}\rangle$. Therefore, the trigger heralds the two-photon N00N state $|2_H,0_V\rangle - e^{2i\theta}|0_H,2_V\rangle$ at mode c, where the phase 2θ in the heralded state can be chosen arbitrarily at the heralding stage by setting the HWP angle α.

To verify the heralded state, projection measurement shown in Fig. 1 is performed. The heralded entangled state is projected onto the two-photon measurement basis defined by $R_z(\phi)$ with $\phi = 4\beta + \pi$ and two detectors D3 and D4. The coincidence detection at D3 and D4 results in an annihilation operator $(\hat{c}_H)^2 - e^{-2i\phi}(\hat{c}_V)^2$, implementing the projection measurement $|\psi_{\text{mea}}\rangle\langle\psi_{\text{mea}}|$, where $|\psi_{\text{mea}}\rangle = |2_H,0_V\rangle - e^{2i\phi}|0_H,2_V\rangle$. Therefore, given the heralded entangled state $|\Phi\rangle = |2_H,0_V\rangle - e^{2i\theta}|0_H,2_V\rangle$, the projection measurement will lead to the four-photon detection probability

$$P = \frac{1}{2}\left(1 + \cos\left(2\phi - 2\theta\right)\right). \tag{2}$$

Thus, phase-controlled heralding of the two-photon N00N state can be demonstrated by observing four-fold coincidences among the four detectors as a function of the projection angle $\phi = 4\beta + \pi$.

The experimental data are shown in Fig. 2. Four-fold coincidence measurements clearly reveal sinusoidal modulations predicted in Eq. (2) as a function of the projection phase ϕ. The modulations have a period of π due to the $\lambda/2$ photonic de Broglie wavelength of a two-photon $N00N$ state. The high visibility quantum interference, together with the phase shifts observed in Fig. 2, clearly demonstrate phase-controlled heralding of the two-photon N00N state.

3. Generalization

We now generalize the experiment to herald N-photon N00N states with different amplitudes and phases. As shown schematically in Fig. 3, a separable input state $|N_H,N_V\rangle_a$, consisting of N horizontally polarized and N vertically polarized photons, is incident on the BS at random times. The input state is transformed by the BS, whose transmission and reflection coefficients

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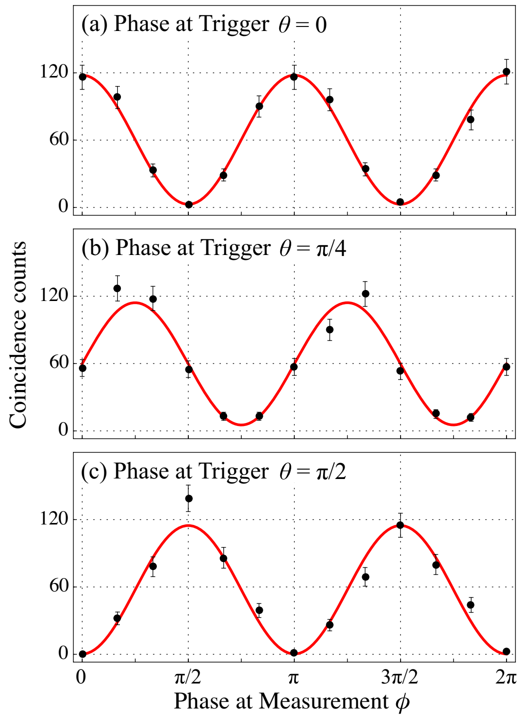

Fig. 2. Projection measurement of the heralded two-photon N00N state $|2_H, 0_V\rangle - e^{2i\theta}|0_H, 2_V\rangle$ for different heralding phases θ. The phase shifts observed here clearly demonstrate phase-controlled heralding of the two-photon N00N state. The coincidence counts are accumulated during (a) 4,800 s, (b) 6,900 s, and (c) 6,300 s at each data point. Solid circles are experimental data and solid lines are sinusoidal fittings to the experimental data. The visibility values calculated from the fitting curves are (a) $95.4 \pm 1.3\%$, (b) $91.2 \pm 3.4\%$, and (c) $99.5 \pm 0.7\%$. Error bars represent one standard deviation.

are t and r, respectively. The photonic quantum state at the output modes c and d of the BS is calculated to be

$$\begin{aligned} |\Phi^{(N)}\rangle_{cd} &= \sum_{k=0}^{2N} t^{2N-k} r^k \sum_{s=\max(0,k-N)}^{\min(N,k)} \sqrt{\binom{N}{s}\binom{N}{k-s}} \\ &\times \ |(N-s)_H, (N-k+s)_V\rangle_c |s_H, (k-s)_V\rangle_d, \end{aligned} \tag{3}$$

where s is the number of horizontally polarized photons at mode d and k is the total number of photons at mode d. Similarly to the experiment, the trigger at mode d performs N-photon projection measurement onto the basis

$$|\psi_{\text{trig}}^{(N)}\rangle_d = (\cos\gamma)^N |N_H, 0_V\rangle_d - (e^{i\theta}\sin\gamma)^N |0_H, N_V\rangle_d, \tag{4}$$

where θ and γ can be arbitrarily chosen.

Upon the N-photon projection measurement (with θ and γ arbitrarily chosen) at the trigger, the photonic quantum state at mode c is heralded to be

$$|\Phi^{(N)}\rangle_c = (\sin\gamma)^N |N_H, 0_V\rangle_c - \left(e^{i\theta}\cos\gamma\right)^N |0_H, N_V\rangle_c. \tag{5}$$

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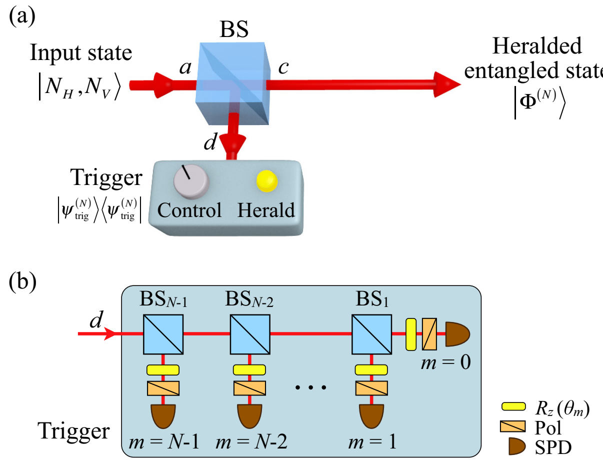

Fig. 3. Scheme for heralding N-photon N00N states with arbitrary amplitudes and phases. (a) The input state $|N_H, N_V\rangle$, consisting of N horizontally polarized and N vertically polarized photons, is prepared at random times. BS is a non-polarizing beam splitter, which can have arbitrary transmittance. The trigger, performing projection measurement $|\psi^{(N)}_{\rm trig}\rangle\langle\psi^{(N)}_{\rm trig}|$, heralds the photon-number entangled state $|\Phi^{(N)}\rangle$ at mode c. (b) Schematic of the trigger. BS$_m$ ($m = 0 \sim N-1$) is a non-polarizing beam splitter, which branches mode d into N output modes. $R_z(\theta_m)$ introduces phase difference θ_m between horizontal and vertical polarizations. Pol is a a polarizer oriented at $-\gamma$ from the horizontal direction and SPD is a single-photon detector. Successful heralding occurs only when all the SPDs click simultaneously. Reflectance of BS$_m$ that maximizes the probability of the simultaneous clicks is $1/(m+1)$ [21, 22].

Note that the scheme does not simply herald the existence or preparation of a predetermined quantum state. The amplitude and phase, both of which can be chosen arbitrarily by the trigger settings, of a quantum state can be heralded, making complete quantum state heralding of N00N states possible.

The projection measurement in Eq. (4) can be implemented by using linear optics and single-photon detectors, as shown in Fig. 3(b). For N-photon detection, mode d is branched into N modes by a series of beam splitters (BS$_1 \sim$ BS$_{N-1}$). The single-photon detection event at m-th mode can be described by the annihilation operator $\cos\gamma\, \hat{d}_H - e^{-i\theta_m}\sin\gamma\, \hat{d}_V$. Then, the N-photon detection event due to simultaneous clicks of all the N single-photon detectors can be described by the annihilation operator

$$\prod_{m=0}^{N-1}\left(\cos\gamma\, \hat{d}_H - e^{-i\theta_m}\sin\gamma\, \hat{d}_V\right) = (\cos\gamma)^N(\hat{d}_H)^N - (e^{-i\theta}\sin\gamma)^N(\hat{d}_V)^N, \tag{6}$$

where $\theta_m = \theta + 2m\pi/N$ [21, 22]. Since the Hermitian conjugate of Eq. (6) operated on the vacuum state is $|\psi^{(N)}_{\rm trig}\rangle_d$ in Eq. (4), the trigger scheme in Fig. 3(b) indeed heralds $|\Phi^{(N)}\rangle_c$ in Eq. (5).

In practice, however, simultaneous clicks at the N detectors can also take place if more than N photons are reflected at the BS in Fig. 3(a), which results in faulty heralding. This is because some of the reflected photons can be lost before arriving at the detectors and/or a conventional single-photon detector cannot resolve photon numbers and has less-than-unity detection efficiency. Such faulty heralding can, of course, be prevented by using photon-number resolving detectors [23] and by monitoring any photon losses, but it can also be circumvented by using a

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highly transmitting BS ($|t|^2 \gg |r|^2$) [14,16,17,24,25]: the probability that more than N photons (i.e. $N+l$ photons) are reflected at the BS is suppressed by a factor of $|r/t|^{2l}\binom{2N}{N+l}/\binom{2N}{N} \ll 1$ compared with the probability that N photons are reflected at the BS. Then, the triggering probability, i.e., all N detectors at the trigger in Fig. 3(b) click simultaneously by N photons in mode d, is calculated to be $|tr|^{2N}(e/N)^N N!((\cos\gamma)^{2N}+(\sin\gamma)^{2N})$, where e is the detection efficiency of each single-photon detector.

So far, we have considered an ideal input state, $|N_H,N_V\rangle_a$, but photon sources may contain additional states $|n_H,n_V\rangle_a$ with $n \neq N$. For example, a quantum state generated via SPDC [6–8,18–20] or SFWM [11–13] is $\sum_{n=0}^{\infty}\eta^n|n_H,n_V\rangle_a$. The generalized heralding scheme described here can exclusively exploit $|N_H,N_V\rangle_a$ out of $\sum_{n=0}^{\infty}\eta^n|n_H,n_V\rangle_a$. First, $|n_H,n_V\rangle_a$ with $n>N$ can be suppressed by choosing a small value of $|\eta|^2$ ($\ll 1$) as the generation probability of $|n_H,n_V\rangle_a$ decreases with increasing n and is quantified by $|\eta|^{2n}$ [6–8]. The other terms $|n_H,n_V\rangle_a$ with $n<N$ are not triggered because the output state after the BS $|\Phi^{(n)}\rangle_{cd}$ does not overlap with the projection state of the trigger $|\psi^{(N)}_{\mathrm{trig}}\rangle_d$, i.e., ${}_d\langle\psi^{(N)}_{\mathrm{trig}}|\Phi^{(n)}\rangle_{cd}=0$ when $n<N$. Then, generation rate of $|N_H,N_V\rangle_a$ per a second is $f(1-|\eta|^2)|\eta|^{2N}$, where repetition rate of pump laser f can change the generation rate [26]. Therefore, our scheme can perform phase and amplitude controlled heralding of N00N states within the current technology.

4. Discussion

Our scheme for amplitude and phase controlled heralding, i.e., complete quantum state heralding, is not limited to N00N states, but can also be applied to other types of entanglement. For instance, in conventional heralding schemes in [14, 16, 17], two static triggers are used, heralding a single Bell state $|\Phi^{(+)}_{\mathrm{Bell}}\rangle = 1/\sqrt{2}(|H\rangle_a|H\rangle_b+|V\rangle_a|V\rangle_b)$ at two paths a and b. There, one of the triggers performs projection measurement $|\psi^{(2)}_{\mathrm{trig}}\rangle\langle\psi^{(2)}_{\mathrm{trig}}|$ in Eq. (4), where θ and γ are fixed to be 0 and $\pi/4$, respectively. By replacing this static trigger with a variable trigger in Fig. 3(b) and Eq. (4), one can herald a non-maximally entangled state, $|\Phi\rangle = \sin^2\gamma|H\rangle_a|H\rangle_b + e^{2i\theta}\cos^2\gamma|V\rangle_a|V\rangle_b$, where θ and γ are varied at the trigger.

Note that, in our scheme for phase and amplitude controlled heralding – complete quantum state heralding – of N00N states, the heralded state is remotely controlled by detecting ancillary photons. The remote control feature is particularly useful when direct access to the heralded state is physically difficult. Furthermore, it allows us to delay the choice of determining the specific form of a heralded entangled state, i.e., delayed-choice heralding, by storing the ancillary photons before measuring them [27]. Finally, our complete quantum state heralding scheme should be distinguished from remote state preparation [28,29]: the former aims to herald an entangled state generated via stochastic processes, while the latter aims to transmit a quantum state to a remote place using prior entanglement.

5. Conclusion

We have introduced and demonstrated complete quantum state heralding in which heralding not only notifies the existence or preparation of a predetermined quantum state, but can also controls the amplitude and phase. Since the phase and amplitude controls are inseparably integrated into the heralding mechanism, our scheme enables generation of N-photon N00N states with arbitrary phases and amplitudes. Such a flexible heralding scheme is expected to play important roles in various photonic quantum information applications.

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