

Exchange symmetry in multiphoton quantum interference

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Photons are bosons, and yet, when prepared in specific entangled states, they can exhibit nonbosonic behavior. While this phenomenon has so far been studied in two-photon systems, exchange symmetries and interference effects in multiphoton scenarios remain largely unexplored. In this work, we show that multiphoton states uncover a rich landscape of exchange symmetries. With three photons already, multiple pairwise combinations are possible, where each pair of photons can exhibit bosonic, fermionic, or anyonic exchange symmetry. This gives rise to *mixed* symmetry systems that are not possible to achieve with two photons alone. We experimentally investigate how these symmetry configurations manifest in the observed interference of three photons, whereby tuning the exchange symmetry with respect to a specific photon pair controls the complete three-photon interference behavior. We show that multiphoton interference can be effectively turned on and off by tuning the symmetry of the constituent pairs. The possibility of accessing and tuning new quantum statistics in a scalable photonic platform not only deepens our understanding of quantum systems but is also highly relevant for quantum technologies that rely on quantum interference.

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I. INTRODUCTION

Particles in nature are either bosons or fermions and have wave functions that are symmetric or antisymmetric, respectively, under the exchange of two identical particles [1–3]. This exchange symmetry directly influences quantum interference: identical bosons bunch together, while identical fermions, constrained by the Pauli exclusion principle, exhibit antibunching [4–7]. Nevertheless, theoretical models of particles with more exotic exchange statistics—such as those of anyons and Majorana fermions—provide foundational insights in topics like quantum error correction and quantum computing [8–10].

The overall symmetry of the wave function of bosons or fermions must be preserved. However, given access to multiple degrees of freedom, this symmetry may be distributed in a manner that emulates dynamics distinct from those of the fundamental particle symmetry. This means that, for example, with the right preparation, bosonic particles can manifest fermionic or anyonic statistics [11,12].

Photons are a particularly appealing testbed for exploring particle symmetries in this way. First, they do not interact, and

so, in contrast to charged particles such as ions, their dynamics are governed solely by symmetries and interference. Second, they possess multiple distinct degrees of freedom—such as polarization and arrival time—that are relatively straightforward to prepare, control, and measure [13–15]. Third, recent technological advances have enabled the preparation of high-quality entangled states of photons, which is necessary to distribute the bosonic symmetry in a way that unlocks other particle statistics [16,17]. For instance, polarization-entangled photon pairs with different symmetries in their spatial modes have been used to explore particle statistics going beyond those of bosons [18]. This is important, for example, in the context of quantum interference and quantum walks [11,19–21].

Scaling to the interference of larger numbers of photons leads to rich interference phenomena [22–31]. Recent studies have investigated the roles of properties such as photon distinguishability and state purity in interference [32–36] and have shown that multiphoton interference can be harnessed to generate entangled states [37–42]. Furthermore, various quantum technologies, ranging from quantum communication and metrology to quantum simulation, benefit from multiphoton interference [43–45].

In this work, we investigate how exchange symmetry influences the dynamics of three particles. Having states with more than two particles enables different pairings and, consequently, various combinations of pairwise symmetries. We experimentally probe three-photon interference involving quantum states with *mixed*-exchange symmetries—multipartite states in which some components are symmetric under exchange, while others are antisymmetric. By varying

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the symmetry of the constituent pairs of photons, we can tune the contribution of the purely bosonic components to the interference. We observe that signatures of multiphoton interference appear only when both pairings are symmetric and disappear in the case of mixed symmetries. We demonstrate that the exchange symmetry associated with a particular photon pair uniquely determines the entire three-photon interference behavior, while the exchange symmetry of the remaining photon pair does not influence the interference. This asymmetry implies that the three photons do not play equivalent roles within the experimental configuration. Our work shows that photons are an ideal platform for exploring fundamental particle statistics and underlines how the symmetry of states can influence quantum interference.

II. THEORY

Photonic states can be described in the context of interference experiments by their *internal* states, i.e., the degrees of freedom that are not resolved by the detection scheme, and *external* states, the degrees of freedom that are resolved [46]. In this work, we use two internal states, $|0\rangle$ and $|1\rangle$, and two external states, $|a\rangle$ and $|b\rangle$. Our goal is to describe the exchange symmetry of photonic states that contain internal and external degrees of freedom.

For two photons, a possible basis for describing an arbitrary internal state is given by the Bell basis [47]:

$$|\psi^\pm\rangle_{\text{int}} = \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle), \quad (1)$$

$$|\phi^\pm\rangle_{\text{int}} = \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle). \quad (2)$$

This case is well known in the context of quantum information: the Bell basis is complete, and the discrimination of Bell states is of central importance in photonic quantum information [48–52].

For the external degree of freedom, consider two photons that occupy two spatial modes a and b . The corresponding bases for pairs of external states are given by

$$|\psi^\pm\rangle_{\text{ext}} = \frac{1}{\sqrt{2}}(|ab\rangle \pm |ba\rangle), \quad (3)$$

$$|\phi^\pm\rangle_{\text{ext}} = \frac{1}{\sqrt{2}}(|aa\rangle \pm |bb\rangle). \quad (4)$$

In this work, we impose the condition that the two photons occupy distinct spatial modes, which makes their exchange symmetry easily accessible, leaving us with the external states $|\psi^\pm\rangle_{\text{ext}}$ as in Eq. (3).

Note that for the internal and external degrees of freedom, the state $|\psi^\pm\rangle_{\text{int/ext}}$ is antisymmetric under pairwise exchange, whereas all others are symmetric. Additionally, the state $|\psi^\pm\rangle_{\text{ext}}$ is an eigenstate of the transformation of a beam splitter and, therefore, remains unchanged upon passing through it.

Photons are bosons, and as such, their overall wave function exhibits symmetric behavior. This results in four possible combinations of internal and external states, as introduced by

Zeilinger in Ref. [53], given by

$$|\Phi^+\rangle \sim |\phi^+\rangle_{\text{int}} |\psi^+\rangle_{\text{ext}}, \quad (5)$$

$$|\Phi^-\rangle \sim |\phi^-\rangle_{\text{int}} |\psi^+\rangle_{\text{ext}}, \quad (6)$$

$$|\Psi^+\rangle \sim |\psi^+\rangle_{\text{int}} |\psi^+\rangle_{\text{ext}}, \quad (7)$$

$$|\Psi^-\rangle \sim |\psi^-\rangle_{\text{int}} |\psi^-\rangle_{\text{ext}}, \quad (8)$$

which are equivalent to the four canonical Bell states (see Appendix B in the Supplemental Material [54] for derivation). We can also interpret this as the distribution of the exchange symmetry over the internal and external degrees of freedom, respectively. The first three states are expressed as products of states that are symmetric under the exchange of internal and external degrees of freedom. The overall bosonic symmetry of the last state $|\Psi^-\rangle$ factorizes into states that are antisymmetric over the internal and external degrees of freedom.

Extending to more than two photons allows for interesting combinations of pairwise symmetries among them, leading to a richer interference landscape and enabling finer control over the symmetry properties of the resulting states. For N photons, the overall state must exhibit bosonic exchange symmetry, and the exchange symmetry can again be distributed over the internal and external degrees of freedom. We can define a symmetric N -photon wave function $|\Psi^{(N)}(\vec{\phi})\rangle$, which describes the overall state of N photons, and a set of parameters $\vec{\phi}$, which captures how the exchange symmetry is partitioned across the internal and external states [see Fig. 1(a)]. In general, we can decompose the symmetric wave function into a superposition of states that are overall symmetric but possess different symmetry types for constituent degrees of freedom. That is, $|\Psi^{(N)}(\vec{\phi})\rangle = \sum C_{\mu\mu'} |\psi^\mu\rangle_{\text{int}} |\psi^{\mu'}\rangle_{\text{ext}}$, where $C_{\mu\mu'}$ is the weight of specific combinations of internal and external states, $|\psi^\mu\rangle_{\text{int}}$ and $|\psi^{\mu'}\rangle_{\text{ext}}$, respectively [55–57].

We investigate such symmetries with a state of three photons occupying two polarization (internal) and two spatial (external) modes. Let us define a set of states with specific pairwise exchange symmetry:

$$|\Psi\rangle_{a,a,b}^{\text{sym}} = \frac{1}{\sqrt{3}}(a_0^\dagger a_0^\dagger b_1^\dagger + a_0^\dagger a_1^\dagger b_0^\dagger) |\text{vac}\rangle, \quad (9)$$

$$|\Psi\rangle_{a,a,b}^{\text{mix}} = \frac{1}{\sqrt{3}}(a_0^\dagger a_0^\dagger b_1^\dagger - a_0^\dagger a_1^\dagger b_0^\dagger) |\text{vac}\rangle, \quad (10)$$

where the subscript a, a, b indicates two photons in mode a and one photon in mode b , and the indices 0 and 1 refer to the internal states of the photons. Note that the normalization is absorbed into the creation operators acting on the same mode(s). We now consider the symmetries under the exchange of the two photons in the spatial mode a with each other, and the second photon in mode a with the photon in mode b . The state $|\Psi\rangle_{a,a,b}^{\text{sym}}$ is symmetric under the exchange of either pair of photons in their internal and external degrees of freedom. However, the state $|\Psi\rangle_{a,a,b}^{\text{mix}}$ exhibits symmetric behavior under the exchange of the two photons in the same mode and antisymmetric behavior when the internal or external states of the second photon in mode a and the photon in mode b are exchanged. The resulting state, therefore, exhibits a so-called *mixed symmetry* (see Table I). Exchanging the first

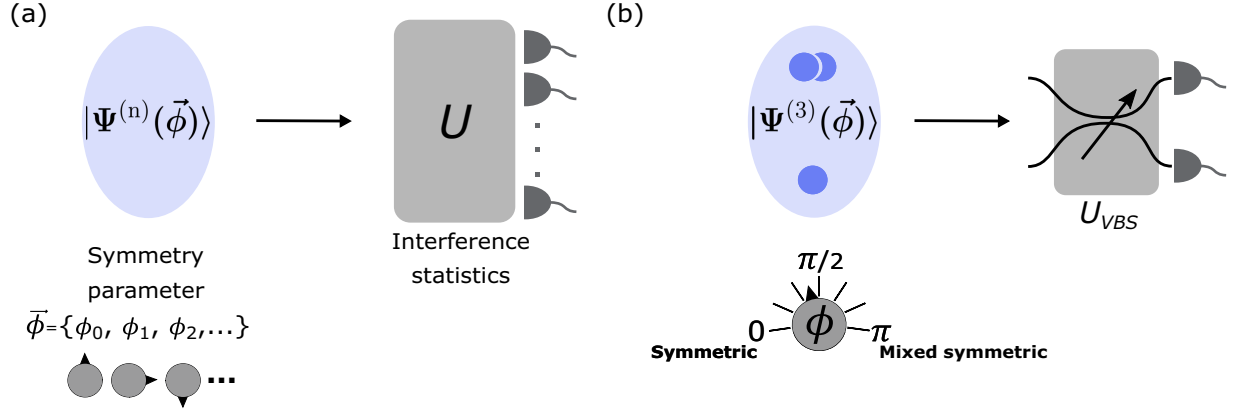


FIG. 1. Probing exchange symmetry in photon interference. (a) The bosonic symmetry of the wave function $|\Psi^{(n)}(\vec{\phi})\rangle$ for N photons can be distributed over different degrees of freedom using a set of parameters $\vec{\phi}$. This allows access to nonbosonic pairwise exchange statistics when the state is evolved under some unitary U and then measured. (b) A state of three photons, $|\Psi^{(3)}(\vec{\phi})\rangle$, with a relative phase, ϕ , to directly adjust the exchange symmetry and probe different particle statistics using a variable beam splitter described by the unitary U_{VBS} [see Eq. (13)].

photon in mode a with the photon in mode b yields a product state for the symmetric state, while the state vanishes for the mixed symmetry state (see Appendix D in the Supplemental Material [54]). Note that in all cases the overall symmetry of the three-photon state always remains symmetric, regardless of the symmetries of the subsystems.

We can now tune between the states $|\Psi\rangle_{a,a,b}^{\text{sym}}$ and $|\Psi\rangle_{a,a,b}^{\text{mix}}$ by introducing a phase parameter ϕ :

$$|\Psi^\phi\rangle_{a,a,b} = \frac{1}{\sqrt{3}}(a_0^\dagger a_0^\dagger b_1^\dagger + e^{i\phi} a_0^\dagger a_1^\dagger b_0^\dagger)|\text{vac}\rangle, \quad (11)$$

as depicted in Fig. 1(b).

The state in Eq. (11) can be rewritten as

$$|\Psi^\phi\rangle_{a,a,b} = \cos(\phi/2)|\Psi\rangle_{a,a,b}^{\text{sym}} - i \sin(\phi/2)|\Psi\rangle_{a,a,b}^{\text{mix}}, \quad (12)$$

which reveals that the state is indeed a superposition of the symmetric state $|\Psi\rangle_{a,a,b}^{\text{sym}}$ and the mixed-symmetry state $|\Psi\rangle_{a,a,b}^{\text{mix}}$, with $|\cos(\phi/2)|^2 = \cos^2(\phi/2)$ and $|-i \sin(\phi/2)|^2 = \sin^2(\phi/2)$ being their respective contributions to the state. The contribution of each component to the different scattering probabilities, or photon-number

distribution, is determined by the absolute square of the corresponding amplitude.

The effect of the state's symmetry is revealed through the scattering probabilities, in particular, by observing the scattering distributions of the photons at a beam splitter. Here we employ a variable beam splitter (VBS), described by the transformation

$$U_{\text{VBS}} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ \sin(\theta) & -\cos(\theta) \end{pmatrix}, \quad (13)$$

where the parameter θ describes the splitting ratio.

The scattering probabilities $P(x, y)$ denote the probability of detecting y photons in mode a and y photons in mode b . Below we give the expressions for the output configurations (3,0) and (1,2):

$$P(3, 0) = \cos^2(\phi/2)p_{3,0}(\theta), \quad (14)$$

$$P(1, 2) = \cos^2(\phi/2)p_{1,2}(\theta) + \sin^2(\phi/2)p'_{1,2}(\theta), \quad (15)$$

where the quantities $p_{3,0}$, $p_{1,2}$, and $p'_{1,2}$ depend only on the splitting ratio of the VBS θ (refer to Appendix F in the Supplemental Material [54] for detailed calculations and

TABLE I. Exchange symmetry of the different degrees of freedom for the symmetric state $|\Psi\rangle_{a,a,b}^{\text{sym}} = \frac{1}{\sqrt{3}}(a_0^\dagger a_0^\dagger b_1^\dagger + a_0^\dagger a_1^\dagger b_0^\dagger)|\text{vac}\rangle$ and the mixed-symmetry state $|\Psi\rangle_{a,a,b}^{\text{mix}} = \frac{1}{\sqrt{3}}(a_0^\dagger a_0^\dagger b_1^\dagger - a_0^\dagger a_1^\dagger b_0^\dagger)|\text{vac}\rangle$, corresponding to the symmetry parameter $\phi = 0$ and $\phi = \pi$, respectively. The indices a, a, b indicate two photons in the spatial mode a and a third photon in mode b . Note that a symmetric exchange leaves the state unchanged, whilst an antisymmetric exchange introduces a global factor of -1 . However, the overall bosonic symmetry of the state is preserved in all cases.

State	Photon pair exchanged	Exchange symmetry of degree of freedom		Overall symmetry	Phase parameter ϕ
		Polarization	Spatial mode		
$ \Psi\rangle_{a,a,b}^{\text{sym}}$	$ \Psi\rangle_{a,a,b}^{\text{sym}}$	Symmetric	Symmetric	Symmetric	0
	$ \Psi\rangle_{a,a,b}^{\text{sym}}$	Symmetric	Symmetric	Symmetric	
$ \Psi\rangle_{a,a,b}^{\text{mix}}$	$ \Psi\rangle_{a,a,b}^{\text{mix}}$	Symmetric	Symmetric	Symmetric	π
	$ \Psi\rangle_{a,a,b}^{\text{mix}}$	Antisymmetric	Antisymmetric	Antisymmetric	

definitions). As before in Eq. (12), the factors $\cos^2(\phi/2)$ and $\sin^2(\phi/2)$ are the contributions of the symmetric and mixed-symmetry components of the input state, respectively. By isolating θ dependence and ϕ dependence in the expressions, we make explicit the contributions of the beam-splitter scattering and the intrinsic symmetry of the state to the scattering probabilities.

We see that the fully bunched output (3, 0) only results from the symmetric component of the state and vanishes when $\phi = \pi$. The partially bunched distributions have contributions from the symmetric and mixed-symmetry components of the state and never vanish. The complete set of probabilities, including analogous cases, can be found in Appendix F of the Supplemental Material [54].

We aim to study three-photon interference and the influence of symmetry on the scattering probabilities. Note that the state in Eq. (11) can be constructed by combining a single photon with a $|\Psi\rangle$ -type Bell state with a generalized phase. That is,

$$|\Psi^\phi\rangle'_{a,a,b} = a_0^\dagger \frac{1}{\sqrt{2}} (a_0^\dagger b_1^\dagger + e^{i\phi} a_1^\dagger b_0^\dagger) |\text{vac}\rangle. \quad (16)$$

Therefore, we compare the scattering probabilities of the three-photon state to those of a Bell state and a single photon that do not interfere. We calculate the scattering probabilities of the Bell state and the single photon separately, and then we obtain the product of the statistics $\xi(x, y)$ by multiplying them. The single photon scatters probabilistically with

$$P_s(1, 0) = \cos^2(\theta), \quad (17)$$

$$P_s(0, 1) = \sin^2(\theta), \quad (18)$$

depending only on the setting of the VBS.

A $|\Psi\rangle$ -type Bell state with a general phase, ϕ , is defined as

$$|\Psi^\phi\rangle = \frac{1}{\sqrt{2}} (a_0^\dagger b_1^\dagger + e^{i\phi} a_1^\dagger b_0^\dagger) |\text{vac}\rangle, \quad (19)$$

which can be written as a superposition of the symmetric and antisymmetric Bell states as

$$|\Psi^\phi\rangle = \cos(\phi/2) |\Psi^+\rangle - i \sin(\phi/2) |\Psi^-\rangle, \quad (20)$$

where the phase ϕ sets the symmetry of the state. The output statistics for the scattering of such a state at a VBS are as follows:

$$P_{\text{Bell}}(2, 0) = \frac{1}{2} \cos^2(\phi/2) \sin^2(2\theta) = P_{\text{Bell}}(0, 2), \quad (21)$$

$$P_{\text{Bell}}(1, 1) = \cos^2(\phi/2) \cos^2(2\theta) + \sin^2(\phi/2). \quad (22)$$

For $\phi = \pi$, we obtain the antisymmetric Bell state, and the bunching probabilities $P_{\text{Bell}}(2, 0)$ and $P_{\text{Bell}}(0, 2)$ vanish, while $P_{\text{Bell}}(1, 1)$ remains constant. The antisymmetry of the state prevents the two photons from occupying the same mode. For $\phi = 0$, we obtain the symmetric Bell state $|\Psi^+\rangle$, and the scattering probabilities depend on the splitting ratio of the VBS (refer to Appendix A in the Supplemental Material [54]).

Now we can calculate the three-photon statistics (i.e., the product of statistics), $\xi(x, y)$, from the statistics of the single photon and the Bell state. Here we present the probabilities

for $\xi(3, 0)$ and $\xi(1, 2)$:

$$\begin{aligned} \xi(3, 0) &= P_s(1, 0) P_{\text{Bell}}(2, 0) \\ &= \cos^2(\phi/2) \tilde{p}_{3,0}(\theta), \end{aligned} \quad (23)$$

$$\begin{aligned} \xi(1, 2) &= P_s(1, 0) P_{\text{Bell}}(0, 2) + P_s(0, 1) P_{\text{Bell}}(1, 1) \\ &= \cos^2(\phi/2) \tilde{p}_{1,2}(\theta) + \sin^2(\phi/2) \tilde{p}'_{1,2}(\theta), \end{aligned} \quad (24)$$

where, as before, $n(m)$ denotes photons in mode 1(2). We see that the product of the statistics can be written in the same form as Eqs. (14) and (15), however, with different quantities: $\tilde{p}_{3,0}$, $\tilde{p}_{1,2}$, and $\tilde{p}'_{1,2}$. Refer to Appendix G of the Supplemental Material [54] for the complete probability distribution, including the cases $\xi(0, 3)$ and $\xi(2, 1)$, which have similar expressions. Only in the antisymmetric case do we find that the product of the statistics is the same as the joint statistics for the partially bunched distributions (2, 1) and (1, 2) and therefore exhibits identical behavior. That is,

$$\left. \begin{aligned} P(1, 2) &= \xi(1, 2) \\ P(2, 1) &= \xi(2, 1) \end{aligned} \right\} \quad \text{for } \phi = \pi.$$

For all other cases, the scattering probabilities differ, and thus we observe three-photon interference signatures that are different from the product of the statistics of a Bell state along with a single photon.

III. EXPERIMENT AND RESULTS

We study the interference behavior of symmetric and mixed-symmetry states experimentally. In our experiment, the internal states are encoded in polarization with $|0\rangle \equiv |H\rangle$ and $|1\rangle \equiv |V\rangle$. We prepare the three-photon input state by adding a single photon to one of the modes of a generalized Bell state [see Fig. 1(b)].

The Bell state is generated using a photon source based on spontaneous parametric down-conversion (SPDC) in a Sagnac interferometer, and the single photon is generated from a heralded linear SPDC source.

The phase of the Bell state can be tuned using a combination of wave plates (see Fig. 2 and Appendix H in the Supplemental Material [54] for more details). The single photon is combined with one of the photons of the Bell state by using a balanced beam splitter and postselecting cases where both photons end up in the same spatial mode, leading to the VBS. This results in the desired three-photon state of Eq. (11). The VBS is then employed to tune the coupling between the two modes, and the photon statistics are measured at the output. Each mode of the VBS is demultiplexed to four superconducting nanowire single-photon detectors using multiport splitters to achieve pseudo-photon-number resolution.

Figure 3 presents the measured three-photon scattering probabilities, which we use to identify signatures of three-photon interference. Our approach is to compare the joint statistics of the three-photon state with the product of the individual scattering probabilities of a two-photon Bell state, along with that of a single photon. Deviations between the two statistics indicate signatures of three-photon interference.

We first measure the scattering probabilities of the Bell state and the single photon, separately [Figs. 3(a) and 3(b)], and compute the product of the individual probabilities $\xi(x, y)$

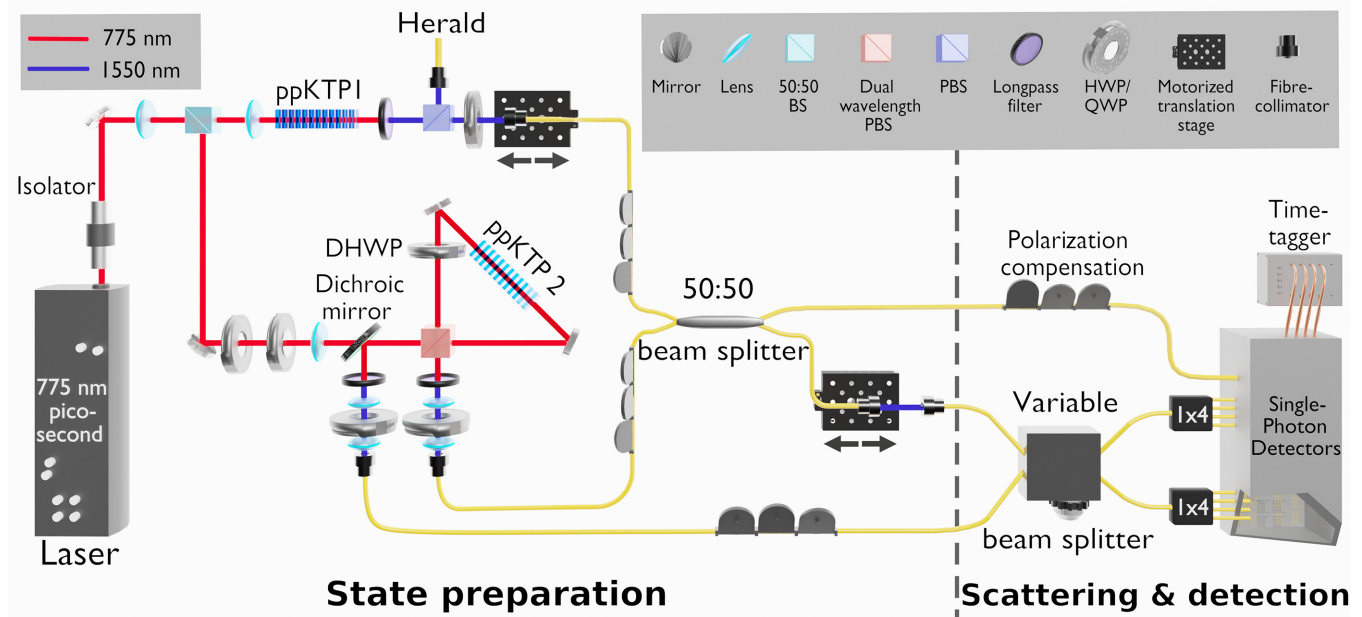


FIG. 2. Overview of the experimental setup. A picosecond pulsed laser at $\lambda_p = 775$ nm is used to pump two spontaneous parametric down-conversion sources consisting of periodically poled potassium titanyl phosphate (ppKTP 1, ppKTP 2) crystals. The resulting down-converted signal and idler photons are at $\lambda_{s/i} = 1550$ nm. The first source (ppKTP 1) is in a linear configuration and is used to generate the heralded single photon, while the other source (ppKTP 2) is a Sagnac-type source, which results in the generation of a Bell state. The heralded single photon and one-half of the Bell state are sent to the two input ports of a fiber-based 50:50 beam splitter. One of the outputs of the 50:50 beam splitter is directed to one of the inputs of the VBS. Only the cases where both photons are directed to the VBS and no photons are detected at the other output are considered to be successful measurement runs. The other half of the Bell state is directed to the other input of the VBS. Each VBS output is demultiplexed to four superconducting nanowire single-photon detectors to achieve pseudo-photon-number resolution.

[Fig. 3(c)]. We then measure the scattering probabilities of the three-photon state $P(x, y)$ for different settings of the VBS [Fig. 3(d)].

Plotting the difference, $\Delta P = P(x, y) - \xi(x, y)$, between these two sets of statistics [Fig. 3(e)] provides a direct visualization of evident *three-photon interference*. Genuine three-photon interference refers to correlations in the output photon-number distribution that cannot be decomposed into contributions from pairwise (two-photon) interference alone. This can be clearly understood by examining the three cases of ϕ separately.

For $\phi = 0$, we have the state $|\Psi\rangle_{a,a,b}^{\text{sym}}$, where we observe a clear difference between the product of the statistics of the Bell state and the single photon, and the measured joint three-photon probabilities. The pronounced deviations indicate strong three-photon interference, demonstrating that the symmetry of the state can enhance multiphoton correlations.

As for $\phi = \pi/2$, the behavior is intermediate: three-photon interference is still present, but deviations from the product of statistics of the individual components are less pronounced than for $\phi = 0$, reflecting that the state possessing intermediate symmetry exhibits reduced three-photon interference signatures.

For $\phi = \pi$, as discussed before, the three-photon state $|\Psi\rangle_{a,a,b}^{\text{mix}}$ contains symmetric and antisymmetric pairs. The antisymmetric pair always ends up antibunching, resulting in the vanishing of the scattering probabilities $P(3, 0)$ and $P(0, 3)$. Comparing our result with the product of the individual two-photon and single-photon scattering probabilities shows that the behavior is identical in both cases, indicating

the absence of genuine three-photon interference present in the three-photon scattering probabilities.

We see close agreement between experiment and theory across all datasets, with well-resolved details in the measured scattering probabilities. This agreement attests to the high photon quality and precise control of the quantum state achieved in our setup. The small deviations of the measured data from theoretical predictions can be attributed to imperfect Bell state generation and errors that accumulate through the experimental setup. Imperfections in the photon sources, such as a slight spectral mismatch, could introduce distinguishability. To check this, we performed Hong-Ou-Mandel interference using the VBS and estimated a visibility of $99.3^{+0.5}_{-0.6}\%$ for the interference of photons generated at the Sagnac source and of $95.4^{+3.1}_{-4.5}\%$ for photons generated from two different sources (see Fig. 4 and refer to Appendix H in the Supplemental Material [54] for more details on the experimental setup). The reduced visibility in the two-source case is due to photons from the two independent sources being slightly different from one another in their generation processes. Furthermore, higher-order photon pair generation could result in accidental coincidences that reduce the quality of interference. It was also observed that the VBS exhibited some hysteresis and that it took some time for the splitting ratio to stabilize after being set. Small drifts during the course of the measurements may have contributed to some discrepancies. Combined with Poissonian errors at the detection stage, these effects account for the residual differences between the experimental results and the predicted theory.

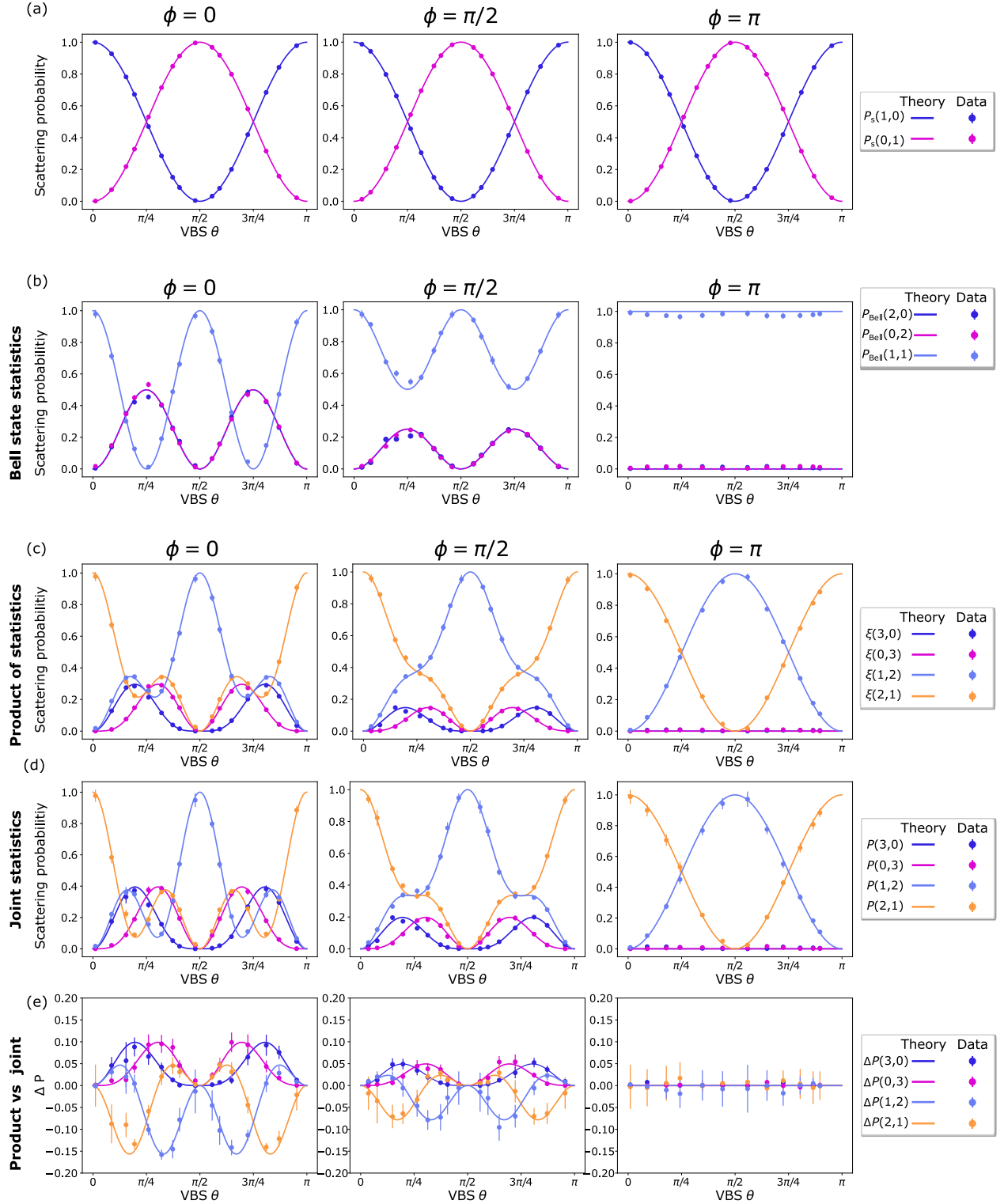


FIG. 3. Scattering statistics at the variable beam splitter (VBS). $P(x, y)$ denotes the probability of detecting x photons in the first output mode and y photons in the second. The VBS can be tuned from full transmission ($\theta = 0$ and $\theta = \pi$) over a balanced beam splitter ($\theta = \pi/4$ and $\theta = 3\pi/4$) to full reflection ($\theta = \pi/2$). (a) Scattering probabilities for a heralded single photon. (b) Scattering probabilities for a generalized $|\Psi\rangle$ -type Bell state, $|\Psi\rangle_{a,b}^\phi = \frac{1}{\sqrt{2}}(a_0^\dagger b_1^\dagger + e^{i\phi} a_1^\dagger b_0^\dagger)|\text{vac}\rangle$, for phases $\phi = \pi$, $\pi/2$, and 0. (c) The product of the independent scattering probabilities from panels (a) and (b), denoted $\xi(x, y)$, shown for each value of ϕ . (d) Joint scattering probabilities for the three-photon entangled state $|\Psi\rangle_{a,a,b}^\phi = \frac{1}{\sqrt{3}}(a_0^\dagger a_0^\dagger b_1^\dagger + e^{i\phi} a_0^\dagger a_1^\dagger b_0^\dagger)|\text{vac}\rangle$, also for $\phi = \pi$, $\pi/2$, and 0. (e) The difference $\Delta P = P(x, y) - \xi(x, y)$, highlighting minimal deviation for $\phi = \pi$ and maximal deviation for $\phi = 0$. Error bars indicate Poissonian uncertainties arising from photon-counting statistics.

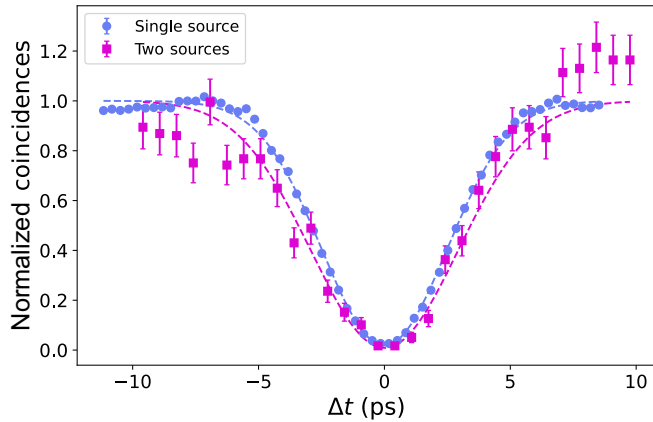


FIG. 4. Hong-Ou-Mandel (HOM) interference between photons from a single Sagnac source, and heralded HOM interference between photons from two independent sources (heralded linear and Sagnac source).

IV. CONCLUSION

In this work, we experimentally demonstrated the influence of the symmetry of the constituent states on multiphoton (multiparticle) interference. Using three photons, we were able to access a complex symmetry space that is not possible with smaller systems—one with *mixed-symmetry*, where one pair of photons is symmetric under exchange, while the other is antisymmetric. By tuning the phase ϕ , which acts as a direct control parameter over the state's symmetry, we were able to switch on and off genuine three-photon interference. This was evident from the absence of three-photon interference signatures when ϕ was set to π and the presence of clear deviations between the joint statistics and the product of the statistics for $\phi = 0$.

From the investigated three-photon state, we found that the roles of the photons are not identical. Varying the symmetry of the photon pair that occupies different external states tunes the three-photon interference behavior, whilst the exchange symmetry of the photons sharing the same external state is fixed and cannot be used to control the interference. Investigating a state with three spatial modes and one photon in each mode using a tritter would give access to immanonic statistics, which are characterized by the mixed-symmetry immanent of the unitary matrix instead of the bosonic permanent or the fermionic determinant [26,27]. In this configuration, each of the three photons is placed in a different spatial mode, which eliminates the structural asymmetry arising from having two photons occupying the same mode.

This ability to control the interference by tuning the symmetry of photonic states suggests a scalable approach to probing and emulating particle statistics beyond the bosonic

regime. With just two photons, we can already emulate non-bosonic statistics by observing the evolution of their external state. Furthermore, scaling up to three photons allows us to access generalized immanonic statistics that lie between bosonic permanents and fermionic determinants. Extensions to four-photon states or qutrits could facilitate the emulation of even more complex quantum systems governed by non-trivial exchange statistics. Four-photon experiments could be implemented, for example, by adding a second heralded single photon to the current setup or by interfering two independent Bell states at a four-port splitter. Experiments with three qutrits could be realized by using time-bin encoding and a three-port splitter, for instance. Both the required numbers of photons and the required interference devices are available in current experiments [58–61].

Our experiment, therefore, proves to be a promising platform for exploring the fundamental role of symmetry in quantum interference. With the advent of more advanced hardware, the preparation of different types of photonic entangled states will be increasingly versatile, making the investigated symmetries of wave functions ever more accessible.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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