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Fundamental statistics phase of bosons directly measured via indistinguishable photons

A simple yet effective optical setup, employing two controllable indistinguishable photons, is proven to allow a direct observation of the exchange phase due to the bosonic particle statistics.

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When two identical tennis balls are hit simultaneously by a racquet, we are always capable to distinguish them by following their spatial trajectories, however close they are to one another. Quantum identical particles, that is particles of the same species like electrons, atoms or photons, behave in a profoundly different way. In fact, when their wavefunctions become spatially overlapping, the particles are indistinguishable from one another and therefore individually unaddressable [1]. This genuinely quantum property comes with two other fundamental traits fulfilled by these building blocks of the universe: the symmetrization postulate and the spin-statistics theorem [2]. The symmetrization postulate claims that the global state, or wavefunction, of a system of identical particles can only be either symmetric (unchanged) or antisymmetric (sign-changing) when single states of any two particles are swapped. Particles of the first type are named bosons and obey the Bose-Einstein statistics, while particles of the second type are named fermions and obey the Fermi-Dirac statistics. Consequently, bosons can possess the very same single-particle state, while fermions cannot occupy the same quantum state due to the Pauli exclusion principle. The spin-statistics theorem, originally proven by W. Pauli, then establishes a connection between the intrinsic spin s of quantum identical particles and their statistical behavior: particles with integer spin must be bosons (such as photons, $s = 1$), while particles with odd-half-integer spin are fermions (such as electrons, $s = 1/2$). The exchange symmetry associated to the symmetrization postulate rules the way identical particles aggregate in Nature to form compound structures of matter and light, being responsible for phenomena like electron orbital occupation and photon bunching. The reason why, in a three-dimensional world, exclusively symmetric and antisymmetric states appear to occur in connection with the particle spins has been one of the main conundrums of quantum mechanics [2].

Beyond these fundamental aspects, systems of indistinguishable particles also have a technological impact. As a matter of fact, identical particles are the typical basic constituents of compound quantum networks assembled for quantum information and computation tasks [3]. Nonetheless, the physical nature of identical particle entanglement has been debated, essentially due to the standard textbook description of the (anti)symmetric states of the overall system by means of fictitious labels assigned to the particles [1]. To mention Asher Peres's words: "Two particles of the same type are always entangled even if they are prepared independently far away from each other in different laboratories […]. We must now convince ourselves that this entanglement is not matter of concern" [1]. More recently, thanks to an approach with no fictitious labels [4], it has been shown that the controllable spatial indistinguishability of identical particles, associated to the degree of wavefunction spatial overlap, directly generates useful quantum entanglement enabling teleportation [5], even when the particles are prepared independently and never interact with one another. Experiments employing photonic setups have then confirmed the theoretical predictions [6]. These findings have contributed to settle the debate about the role of identical particle entanglement, which can thus be actual and exploited as a direct quantum resource.

All the features above make the characterization of identical particle systems of

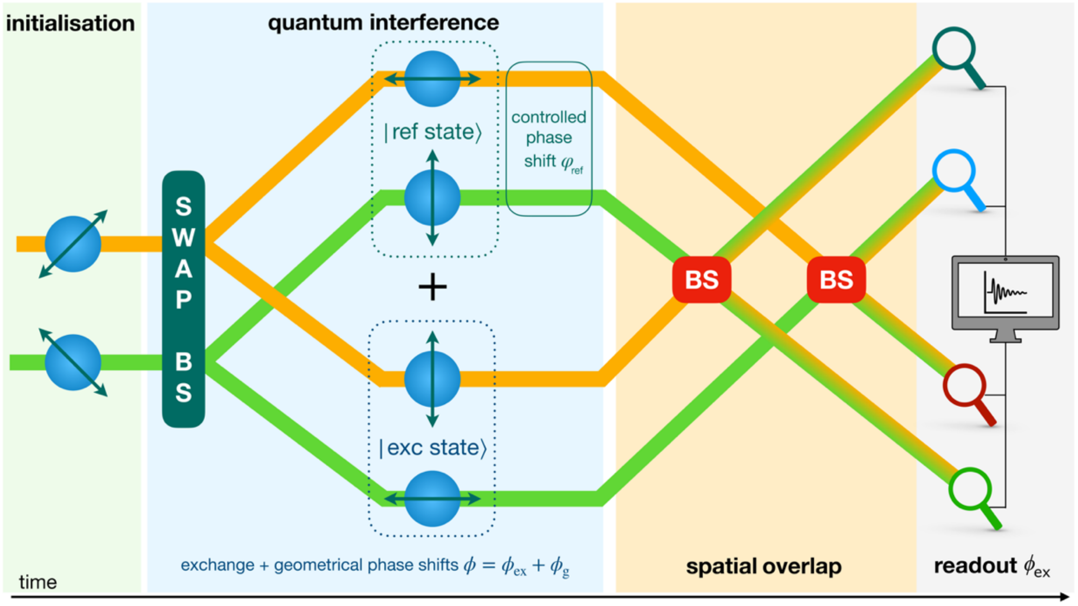

Figure 1 | The photonic state-dependent transport protocol. A state of two diagonally polarized photons is initially prepared and then sent through a swapping beamsplitter (SWAP BS) which creates a superposition of a reference state (|ref state⟩), with one photon horizontally polarized and one photon vertically polarized, with an exchanged state (|exc state⟩), where the states of the two photons have been physically swapped. For the exchanged state both a particle exchange (statistics) phase ϕ_{ex} and a geometric phase ϕ_g show up ($\phi = \phi_{ex} + \phi_g$), due to the intrinsic physical process. To detect the statistics phase of the photons, a spatial overlap between the reference state and the exchanged state is then created. This is done by adjusting a further phase shift φ_{ref}, controlled by the photon path lengths, and by combining the states via two beamsplitters (BSs). A final readout is performed by photon counting at four detectors to obtain joint probabilities which are directly linked to the particle statistics phase ϕ_{ex}.

central importance. From experimental evidence, including the famous 1987 quantum optical experiment performed by Hong-Ou-Mandel which provided the first observation of quantum interference with two identical particles [7], theorists have postulated that the observed statistics for bosons and fermions can be produced if and only if the associated global wavefunctions are symmetric and antisymmetric, respectively. Physically, the symmetrization of the wavefunctions implies the existence of a definite phase between the original multiparticle state and the one where two single-particle states are swapped: the so-called particle exchange (or statistics) phase ϕ_{ex}. For a two-particle system one has $|\chi_1, \chi_2\rangle = e^{\phi_{ex}}|\chi_2, \chi_1\rangle$, where χ_1, χ_2 are two single-particle states expressing the degrees of freedom of each particle, with $\phi_{ex} = 0$ (π) for bosons (fermions). Over the years, several investigations have indirectly corroborated the validity of the symmetrization postulate by verifying the absence of particular states which are forbidden by the postulate [8-11]. Its direct confirmation has remarkably remained elusive, essentially due to the difficulty to perform an interferometric measurement of the exchange phase.

Now, in their work on *Nature Photonics*, Tschernig and co-authors report the first direct experimental observation of the particle exchange phase of photons by interferometry [12], realizing a photonic version of a theoretical proposal known as state-dependent transport protocol [13], depicted in Fig. 1. It is worth to notice that the particle statistics phase cannot be directly measured without superposing a reference state with its swapped version, which creates a quantum interference where ϕ_{ex} becomes a relative phase amenable to interferometric detection. The most natural scenario where this can be achieved is in quantum photonics, via control of traveling photons as bosonic identical particles. In their experiments, Tschernig and co-authors implemented two coupled Mach-Zehnder interferometers to superpose a reference state $|\text{ref state}\rangle = |\leftrightarrow_a, \updownarrow_b\rangle$ of two indistinguishable photons, horizontally and vertically polarized occupying two spatial modes *a* and *b*, with its physically permuted version $|\text{exc state}\rangle = |\updownarrow_c, \leftrightarrow_d\rangle$, where the photons travel along two different spatial modes *c* and *d*. The quantum interference part of the setup especially creates the quantum superposition $|\Psi\rangle = |\text{ref state}\rangle + |\text{exc state}\rangle = e^{i\varphi_{\text{ref}}}|\leftrightarrow_{\text{a}}, \updownarrow_{\text{b}}\rangle + e^{i\phi}|\leftrightarrow_{\text{d}}, \updownarrow_{\text{c}}\rangle$, where φ_{ref} is an adjustable phase acquired during the process while $\phi = \phi_{\text{ex}} + \phi_{\text{g}}$ is a fundamental phase containing both the particle exchange phase ϕ_{ex} and the geometric phase ϕ_{g}. In fact, interestingly, their observations concurrently yield a geometric phase of $\phi_{\text{g}} = \pi$ radians, which is expected from the physical swap operation applied to identical particles. The final readout is realized by making the reference and exchanged states spatially overlap along the same modes (paths) and counting photons at four detectors (see Fig. 1). Ruling out the geometric phase, the measurements revealed an exchange phase $\phi_{\text{ex}} = (-0.04 \pm 0.07)$ radians, which unequivocally demonstrates the symmetric nature of the two-photon (bosonic) wavefunctions.

On many occasions, the concept of exchange symmetry of identical particles tends to be used without any analysis of the experimental implications. The reason is because such a concept is sometimes poorly formulated in relation to experimental observations which originated its postulation. However, as shown in the experiment [12], the geometric phase is an intrinsic, and therefore unavoidable, property arising from the physical exchange of any degree of freedom of identical particles [1]. In this respect, these results may serve as a reference to clarify the definition of the symmetrization postulate from a physical point of view.

Besides the fundamental implications, the work by Tschernig *et al.* brings some advances from a technological perspective: (i) it introduces an experimental technique to generate and certify spatially symmetrized two-photon states, which are states whose inherent quantum coherence is known to overcome the detrimental impact of environmental noise [14-16]; (ii) due to their genuine exchange symmetry, the generated states exhibit polarization entanglement [6], which is another unique quantum feature with far-reaching practical implications [3, 4]; (iii) these results can find direct applications to transfer noise-free information via symmetrized two-photon states, and to test entanglement of identical particles, as recently suggested [3]; (iv) finally, the work comes with a complete error budget including dark count rates, photon losses, drifts in the setup, incomplete beam overlap, source stability and so on. This error budget clearly points the way to higher accuracies so that the experiment plus associated analysis may be considered to break ground for precision measurement with photon pairs.

As a prospect, this work motivates further theoretical and experimental studies devoted to design direct methods to detect the particle statistics phase using alternative approaches and different platforms. For instance, it will be of interest to find techniques for directly measuring the fermionic exchange phase, possibly through harnessing ions or electrons in Coulomb crystals or Paul trap. Also, procedures to analyze the statistics of exotic particles like anyons (quasiparticles) in two-dimensional structures are to be developed. The physics route run by quantum identical particles is going to be quite busy.

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References

[1] Peres, A. *Quantum Theory: Concepts and Methods* (Springer, 2002).
[2] Pauli, W. *General Principles of Quantum Mechanics* (Springer-Verlag, 1980).
[3] Morris, B., Yadin, B., Fadel, M., Zibold, T., Treutlein, P. & Adesso, G. *Phys. Rev. X* **10**, 041012 (2020).
[4] Lo Franco, R. & Compagno G. *Sci. Rep.* **6**, 20603 (2016).
[5] Lo Franco, R. & Compagno, G. *Phys. Rev. Lett.* **120**, 240403 (2018).
[6] Sun, K. et al. *Opt. Lett.* **45**, 6410–6413 (2020).
[7] Hong, C. K., Ou, Z. Y. & Mandel, L. *Phys. Rev. Lett.* **59**, 2044 (1987).
[8] Kekez, D., Ljubičić, A. & Logan, B. A. *Nature* **348**, 224 (1990).
[9] de Angelis, M., Gagliardi, G., Gianfrani, L. & Tino, G. M. *Phys. Rev. Lett.* **76**, 2840 (1996).
[10] Hilborn, R. C. & Yuca, C. L. *Phys. Rev. Lett.* **76**, 2844 (1996).
[11] Modugno, G., Inguscio, M. & Tino, G. M. *Phys. Rev. Lett.* **81**, 4790 (1998).
[12] Tschernig, K. et al. *Nat. Photon.* https://doi.org/10.1038/s41566-021-00818-7 (2021).
[13] Roos, C. F., Alberti, A., Meschede, D., Hauke, P. & Häffner, H. *Phys. Rev. Lett.* **119**, 160401 (2017).
[14] Zanardi, P. & Rasetti, M. *Phys. Rev. Lett.* **79**, 3306 (1997).
[15] Perez-Leija, A. et al. *npj Quant. Info.* **4**, 45 (2018).
[16] Nosrati, F., Castellini, A., Compagno, G. & Lo Franco, R. *npj Quant. Info.* **6**, 39 (2020).

Competing interests

The author declares no competing interests.