Quantum optics

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Dissimilar photons can bunch too

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Contrary to intuition, photons do not have to be indistinguishable for maximum photon bunching to occur. Partially indistinguishable photons can exhibit pronounced bunching.

Scientists working in optics are well acquainted with the fundamental phenomenon of interference of light, as described by the classical electromagnetic wave dynamics resulting from Maxwell's equations. In quantum optics, such interference effects find explanation at the level of single photons. Consider a stream of photons injected into one of the input modes of an optical network, where several possible paths are simultaneously available for the photon to reach a given detector. For each single photon exciting the input mode, and scattered across the multiple possible paths, one must sum at the detection point the probability amplitudes of all the paths, amplitudes that in quantum mechanics are complex numbers. The actual probability of detecting the photon is equal to the modulus squared of this sum: a bright fringe of constructive interference is observed when all contributions sum up in phase, whereas a dark fringe corresponds to a vanishing sum, due to contributions with different phases.

Interestingly, in this situation, even when numerous photons are flowing together, each photon can be thought of as interfering only with itself. In fact, classical interference does not arise from the interactions between different photons, but from the indistinguishability of the different possible optical paths, which is the condition for summing their probability amplitudes at the detection point. Interference is only observed if the detector cannot discriminate whether the photon has taken one or the other path to reach it.

Quantum mechanics, however, introduces a further level of indistinguishability that involves the particles themselves. Multiple quantum particles can be genuinely identical, and need to be described by a wavefunction that is symmetrized (for the bosons) or antisymmetrized (for the fermions) with respect to the particle exchange. Basically, all the possible permutations of these particles are to be considered equally likely, and indistinguishable in the description of their quantum state. This feature further enriches the situation and brings about additional interference phenomena – often dubbed quantum interference – that go beyond what can be predicted by the laws of classical physics, and that have raised great interest in recent years.

The simplest and most celebrated example of quantum interference is perhaps the Hong–Ou–Mandel effect[1], which occurs when two indistinguishable photons impinge simultaneously on the separate inputs of a balanced beam-splitter with two inputs and two outputs. To the surprise of those learning of this effect for the first time, quantum interference completely suppresses the possibility of having the photons appear at distinct outputs: rather, the two photons bunch together in either one of the outputs. Increasing the number of photons and optical modes enables the observation of even more spectacular effects. In the presence of specific symmetry conditions, both on the

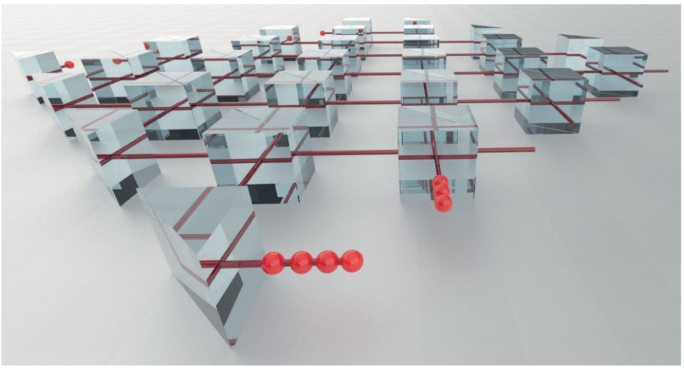

Fig. 1 | A multimode interferometer realized with bulk beam-splitters and prisms, fed with *N* single photons. The probability for the *N* photons to bunch up, in any given subset of the modes at the output, is typically maximal when the photons are perfectly indistinguishable. Seron et al. have now discovered that this is not always the case.

interferometer construction and on the input photon state, quantum interference forbids the observation of a vast class of possible output configurations[2].

For photons injected into a general, randomly constructed, multimode interferometer, quantum interference produces an output photon distribution that is highly non-trivial. The problem of computing or even sampling the output distribution – the 'boson sampling problem' – is conjectured to be intractable for classical computers, if the number of photons and modes is sufficiently large. In fact, a photonic machine that is capable of experimentally performing this quantum interference process and sampling the output photon distribution has recently provided evidence of a 'quantum advantage'[3] – that is, evidence of a quantum machine performing a specific task faster than current classical computers. A further complication rises from the fact that indistinguishability among particles is not just an 'on/off' property and that, in the general case, multiple particles can be only partially (in)distinguishable. If distinguishability is gradually altered and more than two photons are involved, a non-trivial interference landscape is observed with modulations of constructive and destructive interference visibility[4].

Although the fine features of the output photon distribution are laborious to predict and hard to compute, a few general rules can be stated governing the tendency of photons to bunch together[5]. For instance, a simple law valid for any interferometer of any size, injected with N photons simultaneously in distinct modes, guarantees that the probability of detecting the N photons bunched in a given single output mode is $N!$ times larger if these photons are indistinguishable than in the case in which they can be described as distinguishable classical particles (for instance, if they have different polarization or wavelength spectrum). Any partial distinguishability among the photons lowers the bunching probability with respect to the optimum of the perfectly indistinguishable case.

Recently, a generalization of this bunching law was reported as a conjecture, strongly supported by extensive numerical simulations[6]: considering N photons injected in a generic multimode interferometer, the probability of detecting all photons in whichever given subset of K output modes is maximal when the photons are perfectly indistinguishable (see also the pictorial representation in Fig. 1). More precisely, in the case $K < N$ the conjecture is limited to input photons that are only 'classically correlated', namely one should exclude quantum-entangled input states, but this is quite a technical remark. In some sense, we might say that this conjecture condenses the physical intuition about bosonic bunching gained in the latest decades of research.

Writing in *Nature Photonics*, Benoit Seron and colleagues are now disproving this conjecture, by bringing solid counterexamples[7]. They prove that, when injecting one photon per mode in a specifically designed interferometer, the probability of detecting all the photons bunched in the first two output modes is the highest if they belong to a certain partially distinguishable state, rather than in the case of perfect indistinguishability.

The smallest example the authors provide is based on seven photons in seven modes. In this case, the enhancement of the bunching probability of this partially distinguishable case, with respect to the perfect indistinguishable one, is rather tiny. But they also show how to generalize the experiment to an arbitrary number of photons $N > 7$. Notably, the ratio between the bunching probability in the engineered partially distinguishable case and the indistinguishable case is found to increase monotonically with increasing N, thus making this peculiar phenomenon more and more pronounced for larger number of photons.

The importance of this result should not be underestimated. Bosonic bunching is well known in quantum mechanics in its most essential manifestations. Multiphoton bunching, in particular, has been extensively investigated in recent years, and experimental advances have allowed us to observe the quantum interference of identical photons well beyond the elementary two-particle case. As mentioned, boson sampling experiments based on the interference of identical photons have gained much interest in the context of demonstrating a genuine quantum advantage. Thus, quantum interference of identical particles has passed from being a topic of fundamental interest, but of little experimental application, to being the fuel that currently powers experimental photonic quantum technologies.

Gaining a correct picture of the physics of multiparticle interference becomes important not only for researchers specialized in this topic, but for the broader community of physicists, and especially for scientists working in general in the photonics field. The present study shows compelling evidence that quantum interference of partially indistinguishable bosons is a highly non-trivial phenomenon. On the one hand, the knowledge of this counterexample allows us to rectify wrong intuitions on multiparticle interference. On the other hand, this work seems to suggest that partially distinguishable photons could not only be imperfect surrogates of identical particles we cannot afford to produce, but they could, in certain applications, represent a useful resource in themselves.

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Competing interests

The author declares no competing interests.