DISSIMILAR PHOTONS CAN BUNCH, TOO

Andrea Crespi
Dipartimento di Fisica – Politecnico di Milano
and Istituto di Fotonica e Nanotecnologie – Consiglio Nazionale delle Ricerche (IFN-CNR),
piazza Leonardo da Vinci 32, 20133 Milano (Italy)

Identical photons scattered across a multimode optical network show an increased probability to cluster in a subset of the output modes than classical particles would do. This so-called 'bunching' tendency, rooted in the bosonic nature of the photons, is typically most pronounced when they are perfectly indistinguishable, and is unavoidably degraded by introducing particle distinguishability. It is now found that, in specific interferometers, bunching is instead maximal when photons are prepared in an engineered state with only partial indistinguishability. This surprising result shines new light on the role of particle distinguishability in quantum interference processes.

Scientists working in optics are well acquainted with the fundamental phenomenon of interference of light, as it is described by the classical electromagnetic wave dynamics resulting from the Maxwell's equation. In quantum optics, classical interference may be explained at the level of single photons. In fact, let us consider a stream of photons injected in one of the input modes of an optical network, where several possible paths are simultaneously available for the photon to reach a given detector starting from a given input. For each single photon exciting the input mode, and scattered across the multiple possible paths, one has to sum at the detection point the probability amplitudes of all the paths, amplitudes that in quantum mechanics are complex numbers. The actual probability to detect 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, while a dark fringe correspond to a vanishing sum, due to contributions with different phases.

Interestingly, in this situation, even when multitudes of photons are flowing together, each photon can be thought 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. Namely, 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 which involves the particles themselves. Indeed, multiple quantum particles can be genuinely and deeply identical, and need to be described by a wavefunction which 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 scenario 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 the 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. To the surprise of who learns of this effect for the first time, quantum interference suppresses completely the possibility to have again the two photons at distinct outputs: rather, the two photons bunch together in either one of the two 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 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 in a general, randomly constructed, multi-mode interferometer, quantum interference produces an output photon distribution that is highly nontrivial. The problem of computing or even sampling such output distribution - the so-called *BosonSampling* 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 performs experimentally this quantum interference process and samples such output photon distribution has recently provided evidence of a *quantum advantage* [3], i.e. 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].

Anyway, while 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 to detect the N photons bunched in a given single output mode is $N!$ times larger if these photons are indistinguishable, with respect to the case in which they can be described as distinguishable classical particles (e.g. 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 to detect 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 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, as gained in the latest decades of research.

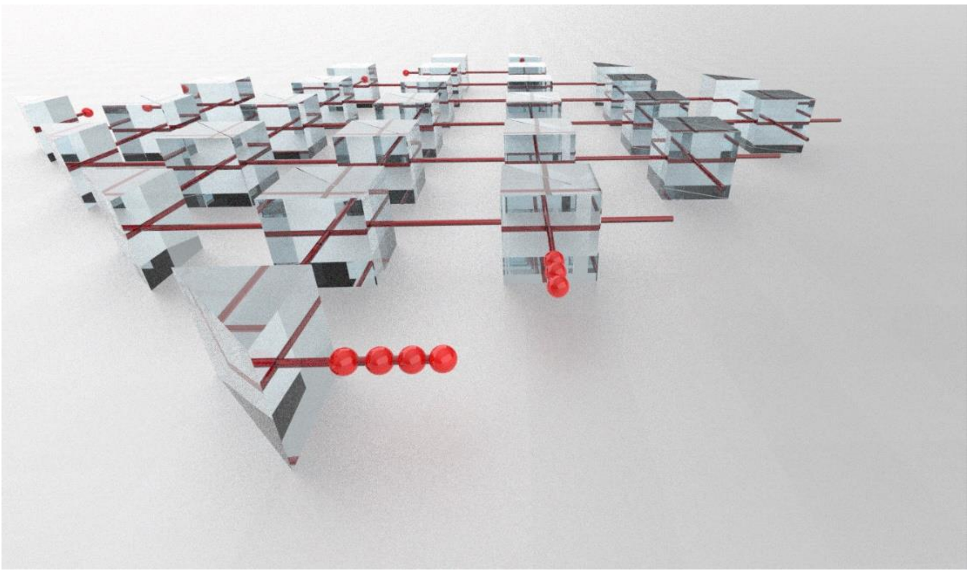

Figure 1 Multimode interferometer realized with bulk beam-splitters and prisms, fed with *N* single photons. The probability for the *N* photons to bunch up, in any given subset of the modes at the output, is typically maximal when the photons are perfectly indistinguishable. Seron et al. have now discovered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

Writing in Nature Photonics, Benoit Seron and colleagues are now disproving this conjecture, by bringing solid counterexamples. They prove indeed that, when injecting one photon per mode in a specifically designed interferometer, the probability to detect 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 7 photons in 7 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. However, in this work it is also shown 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. Multi-photon bunching, in particular, has been extensively investigated in the recent years, and experimental advances have allowed to observe the quantum interference of identical photons quite beyond the elementary two-particle case. As mentioned, *BosonSampling* 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 multi-particle 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 is showing an unprecedently compelling and peculiar evidence that quantum interference of partially indistinguishable bosons is a highly non-trivial phenomenon. On the one hand, the knowledge of this counterexample allows to purify wrong intuitions on multi-particle interference. On the other hand, this work seems to suggest that partially distinguishable photons could be not only imperfect surrogates of identical particles we cannot afford to get, but they could perhaps represent a useful resource by themselves, in certain applications.

[1] C.-K. Hong, Z.-Y. Ou, and L. Mandel. "Measurement of subpicosecond time intervals between two photons by interference." *Phys. Rev. Lett.* **59**, 2044 (1987).

[2] C. Dittel, G. Dufour, M. Walschaers, G. Weihs, A. Buchleitner, and R. Keil. "Totally destructive many-particle interference." *Phys. Rev. Lett.* **120**, 240404 (2018).

[3] H.-S. Zhong, et al. "Quantum computational advantage using photons." *Science* **370**, 1460-1463 (2020).

[4] M. Tillmann, et al. "Generalized multiphoton quantum interference." *Phys. Rev. X* **5**, 041015 (2015).

[5] N. Spagnolo, et al. "General rules for bosonic bunching in multimode interferometers." *Phys. Rev. Lett.* **111**, 130503 (2013).

[6] V.S. Shchesnovich "Universality of generalized bunching and efficient assessment of boson sampling." *Phys. Rev. Lett.* **116**, 123601 (2016).