Quantum physics

Single photons stick together

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In the right circumstances, two photons can meet and ‘coalesce’. This effect has now been observed for photons emitted independently from a single-photon source, and has implications for quantum computing.

Can two photons that have never met know something about each other? The question bothered Einstein, and, reporting on page 594 of this issue, Santori *et al.*[1] demonstrate in a new context that the answer is ‘yes’. They have found that consecutive photons emitted from a single-photon source may indeed know each other sufficiently well to be able to interfere in a very peculiar way.

From the perspective of quantum physics, the answer to the above question is ‘yes indeed, provided that the photons are in the same, single mode’. Photons are characterized by several physical properties, such as their frequency and polarization, and together these properties define the ‘mode’ of the electromagnetic field with which the photon is associated. In the simplest approach, a mode can be regarded as a polarized, monochromatic, plane wave, but it can also be defined in a much more flexible way: the photon can be spread coherently over several modes, defining a new single mode.

If two photons are in the same mode, quantum mechanics predicts that a bunching, or coalescence, effect occurs. Let’s consider two photons sent into a beam splitter where each has a 50–50 chance of being reflected or transmitted. Let’s also assume that one photon that is being transmitted ends up in exactly the same mode as the other photon being reflected — in other words, all the properties of the two photons are identical at the beam-splitter output, so that they become essentially indistinguishable. In that case, there are four possible configurations for the two photons being transmitted or reflected, as depicted in Fig. 1.

As is usual in quantum mechanics, there is a probability amplitude for each of these configurations, and the transmission and reflection probabilities are given by the square of the modulus of the sum of these amplitudes. According to this simple calculation, two amplitudes (Fig. 1b, c) have opposite signs, and so cancel each other — they interfere destructively. The result is that the two photons must go to the same output beam (Fig. 1a, d): it is as though they coalesce as they meet at the beam splitter.

This surprising quantum-interference effect, which can be attributed to the ‘bosonic’ character of photons, was first predicted and observed by Hong, Ou and Mandel[2] in 1987. They used pairs of ‘twin photons’, produced simultaneously in a process called parametric down-conversion, which can be induced by shining laser light into a crystal. An optical delay was added to the path of one of the two photons. If this delay is not zero, each one of the twin photons is randomly transmitted or reflected — they miss each other. But if the delay is exactly zero, the photons overlap and the coalescence effect occurs.

Experimentally, it is easy to count the number of times that one photon is transmitted and the other is reflected. As the value of the optical delay is scanned through zero, the number of transmitted–reflected photon pairs vanishes, creating the so-called Mandel dip that is striking evidence of the coalescence effect. It could be argued that the two photons knew about each other before entering the beam splitter because they were twins emitted in a single fluorescence event. But Santori *et al.*[1] have demonstrated that the same effect occurs for truly independent photons, emitted one at a time from a semiconductor quantum dot.

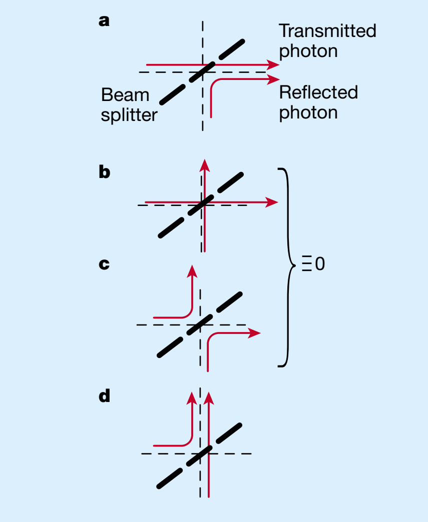

Figure 1 **Two of a kind. When two single-mode, but otherwise independent, photons enter a 50–50 beam splitter, they may be transmitted or reflected in various ways: one may be reflected and the other transmitted** (a and d)**; both photons may be transmitted** (b)**, or both may be reflected** (c)**. By quantum interference, the probabilities for ‘both transmitted’ and ‘both reflected’ cancel out. Only outcomes** a and d **are possible, and the two photons emerge from the beam splitter along the same output, as though they had coalesced. Santori *et al.*[1] show that this quantum effect holds for independent photons emitted from a single-photon source.**

Emission of indistinguishable single photons from quantum dots[3] (or single atoms[4]) can be engineered using cavity quantum-electrodynamic effects[5]. Santori *et al.*[1] sandwiched semiconductor quantum dots between mirrors to form a microcavity and then varied the delay between consecutive emitted photons arriving at a beam splitter. When the photons arrived at the beam splitter together, Santori and colleagues saw the distinctive Mandel dip caused by coalescence of the photons.

This coalescence is not just a curious quantum effect, but has fundamental implications in the field of quantum information processing. Proposed all-optical quantum-photonic networks[6,7] are based on indistinguishable single photons carrying information from node to node and interacting with one another. For such schemes to work, these photons should be in a single mode, exactly in the sense explained above.

Spectacular progress has been made with single-photon sources, and it is now possible to produce single photons on demand, and to use them in quantum-cryptography systems[8]. But most sources produce photons that are spread incoherently over many modes, preventing adequate single-mode behaviour. Parametrically generated photon pairs can be used in some circumstances, such as for teleportation[9], but these are also not ideal as they are not emitted on demand, and thus require an extra unwanted step of conditional preparation.

Santori and colleagues’ experiment, demonstrating the indistinguishability of photons from a single-photon source, can be seen as a first step towards making quantum logic gates for photon-based quantum computing[6]. But the difficulties should not be underestimated: the error rates generated using the present set-up would be too large (by orders of magnitude) compared with the range over which quantum error-correcting codes could be effective. Also, the number of interfering photons required to implement a useful computation is huge, and the integration of the devices would have to be pushed far beyond present technological abilities. Nevertheless, this experiment is a remarkable demonstration of the very peculiar properties of the ‘purest’ states of light that can be imagined — single photons in single modes. ■

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1. Santori, C., Fattal, D., Vučković, J., Solomon, G. S. & Yamamoto, Y. *Nature* **419,** 594–597 (2002).
2. Hong, C. K., Ou, Z. Y. & Mandel, L. *Phys. Rev. Lett.* **59,** 2044–2047 (1987).
3. Moreau, E. *et al. Appl. Phys. Lett.* **79,** 2865–2867 (2001).
4. Kuhn, A., Hennrich, M. & Rempe, G. *Phys. Rev. Lett.* **89,** 067901 (2002).
5. Gérard, J. M. *et al. Phys. Rev. Lett.* **81,** 1110–1113 (1998).
6. Knill, E., Laflamme, R. & Milburn, G. J. *Nature* **409,** 46–52 (2001).
7. Cirac, J. I., Zoller, P., Kimble, H. J. & Mabuchi, H. *Phys. Rev. Lett.* **78,** 3221–3224 (1997).
8. Beveratos, A. *et al.* Preprint quant-ph/0206136 (2002); http://arXiv.org
9. Bouwmeester, D. *et al. Nature* **390,** 575–579 (1997).