QUANTUM NETWORKS

When superatoms talk photons

Quantum networks could permit secure communication over large distances and, eventually, quantum computing with photons. One of the basic building blocks has now been put in place.

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A quantum network consists of quantum storage devices that communicate with each other by means of single photons that carry bits of quantum information. The nodes of such a network are matter–light interfaces: that is, devices for faithfully mapping quantum states between photons and, for instance, ions, atoms or molecules. Teaching two nodes to talk to each other is — in practice — a formidable challenge. Daniel Felinto and co-workers, reporting on page 844 of this issue[1], have now taken this important step towards practical quantum networks. They store a quantum state in each of two superatoms, and convert those states on demand simultaneously into a pair of 'nearly identical' photons. Their method uses a feedback technique whereby the measurement of photons alters the sequence of laser pulses that are applied to steer the quantum evolution in each of the superatoms.

The matter–light interface is difficult to implement because the quantum state of the material system must be transformed into a photon travelling in a well-defined direction at a well-defined time. This is close to impossible with a single microscopic quantum system, such as an atom, which will emit into a random direction. Instead, Felinto *et al.*[1] resort to a trick known from classical antennas: if the phases of many antennas are appropriately locked together, the emitted field interferes constructively in a well-defined direction. In the case at hand, where a high-directionality emitter of single photons is needed, the antennas are replaced with caesium atoms — around one million of them — which share a single excitation between them, but are locked in phase. The result is a 'superatom' that emits a single photon of the same frequency that each of its atomic constituents would do. The emission, however, is 50,000 times more directional.

It may seem a daunting task to lock the phases of a million atoms together, but this can be accomplished surprisingly simply. All that is required is to measure a photon previously emitted by the same sample[2]. This prepares a collective state of the ensemble such that it is, even in principle, impossible to tell which atom emits the next photon. The first measurement locks all atomic phases together, into a state that Robert Dicke first termed 'optical bomb', and that became later known[3] as a 'super-radiant state'. If the atoms conspire to share a photon without giving away who is the 'excited one', the resulting superatom can emit much more strongly than a collection of independent atoms.

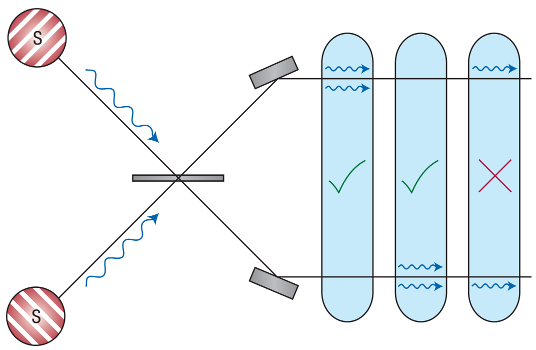

Figure 1 Identity check. The photons emitted, on demand, by two superatoms (S) interfere on a partially reflecting mirror. If the photons are identical, they always emerge together.

To avoid excitations of several atoms inside the superatom, the experiment must be done in a regime of low incident laser power. As a consequence, in most trials the superatom remains in its ground state. Fortunately, it is possible to know when the excitation process was successful: a single photon created in the excitation process is detected. If the excitation failed, the system is reset to start over, until the process is successful.

Such feedback was demonstrated by two other groups for one superatom[4,5]. However, even the simplest quantum network requires two nodes. Felinto and colleagues[1] now demonstrate that the conditional evolution can be applied to two superatoms independently. This feat is crucial with a view to practical quantum networks, because it significantly increases the chance of simultaneously exciting the two spatially separated superatoms, in the present experiment[1] by a factor of 28 — thus reducing the measurement time from roughly a month to a day.

Although the two superatoms now can talk photons, they cannot really exchange quantum states by emitting and absorbing photons unless they speak the same language: that is, unless their photons are identical. Given that the two superatoms are composed of the same constituent atoms, their photons should be similar. But 'similar' is not good enough. External fields can influence the photon frequency and temporal wavepacket shape. What, then, does it mean for two photons to be identical? This question was answered by Hong, Ou and Mandel[6], who investigated what happens when pairs of photons are incident from two different sides on a mirror that reflects 50% of the incoming light. When two single photons are different, each exits on either side with 50% probability, choosing its exit direction independently from the other. But if the photons are identical, something very strange happens. They still leave the mirror in one direction or the other, but now the two photons coalesce, and always emerge together on the same side of the mirror.

Felinto *et al.* use this effect to determine 'how identical' the photons emitted by the two superatoms are. They measure how often the two photons emerge together rather than exiting on opposite sides of a partially reflecting mirror (see Fig. 1) — in the present experiment[1], the photons are 90% identical. Therefore, the superatoms speak slightly different dialects of the same language, but the overlap is sufficient for quantum communication.

What, then, remains to be done to realize secure quantum communication over long distances[2]? First, longer communication chains consisting of pair-wise connected superatoms are required. It will also be necessary to increase the quantum storage time beyond the current 30 μs. Alternatively, one could try to refresh the quantum memory periodically without reading it out (this process is known as quantum error correction). It might then become possible to connect two superatoms, one in Pasadena and the other, perhaps, in Paris.

REFERENCES

1. Felinto, D. *et al. Nature Phys.* **2,** 844–848 (2006).
2. Duan, L.-M., Lukin, M. D., Cirac, J. I. & Zoller, P. *Nature* **414,** 413–418 (2001).
3. Dicke, R. H. *Phys. Rev.* **93,** 99–110 (1954).
4. Matsukevich, D. N. *et al. Phys. Rev. Lett.* **97,** 013601 (2006).
5. Chen, S. *et al. Phys. Rev. Lett.* **97,** 173004 (2006).
6. Hong, C. K., Ou, Z. Y. & Mandel, L. *Phys. Rev. Lett.* **59,** 2044–2046 (1987).