CAVITY QED

Photons in single file

A 'single-photon server', producing a steady stream of single-photon pulses for up to half a minute, has been created by confining, cooling and controlling a neutral atom inside a tiny optical cavity.

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In the early days of quantum cryptography, the transmission of single photons was suggested to be the basis of security protocols. But sources producing single photons are expected to play a much broader role in future quantum information systems that require entanglement between distant quantum objects; examples include quantum networks, distributed quantum computing and cryptographic key distribution. One way to realize a single-photon source is to harness spontaneous emission of atoms. This process, however, is — like radioactivity — random, both in direction and time. Directionality can be imposed, for example, by confining one or more atoms inside an optical cavity whose mirrors define the preferred radiation mode and, therefore, a preferred direction of emission. For the atom–cavity system to produce a steady stream of high-quality single-photon pulses, one and only one atom should reside in the cavity. Moreover, this atom must be periodically cooled to prevent its escape from the cavity. Markus Hijlkema and co-workers[1] have now put all required components for an efficient single-photon source together. They have found an ingenious way to use the cavity both to define directionality and to aid the atomic cooling process, resulting in a device they call a 'single-photon server'.

Edward Purcell realized in 1946 that by placing a radiator in a resonant structure, emission into the preferred resonator mode might be enhanced[2]. Originally conceived in the context of NMR, the concept was extended to the optical regime, where the same process imposes directionality of optical emission when the quantum system is placed in a small standing-wave cavity.

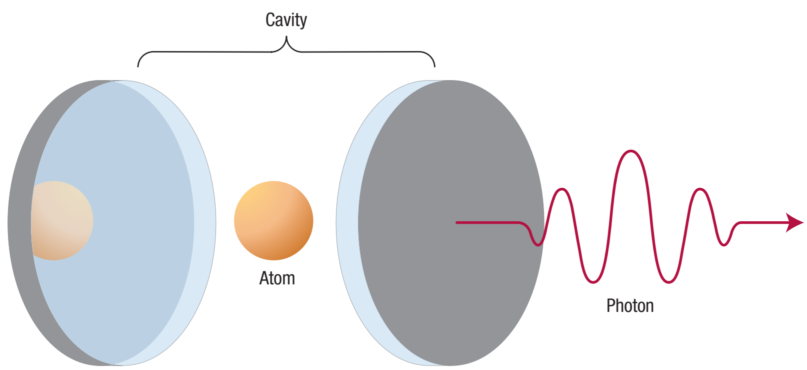

Figure 1 One at a time. To realize a single-photon server, Hijlkema and co-workers[1] trap and hold a single rubidium atom between two mirrors of an optical cavity. A trigger laser induces an atomic Raman transition, causing emission of a photon in the preferred cavity mode. The cavity output is a single-photon pulse. After a cooling cycle to remove the excess kinetic energy of the recoil from the atom, the process is repeated.

The cavity has the additional advantage of defining so-called gaussian field modes, which are well suited for efficient coupling of the output to optical fibres. The Purcell effect formed the basis of a directional single-photon source based on one long-lived ion[3]. By contrast, Hijlkema and colleagues[1] trap a neutral rubidium atom within the submillimetre confines of an optical resonator. To maintain sufficiently strong coupling to the cavity, the atom should be localized close to an antinode. This is achieved using, in addition to the laser that excites the atomic transition, another laser that weakly polarizes the atom and drags it to the required position by the optical tweezer effect[4].

Single photons are produced when a 'trigger laser' excites a Raman transition, causing the emission of a photon into the cavity mode (see Fig. 1). Even if the atom is initially well localized, the photon-production process results in atomic recoil, increasing the atom's kinetic energy until it shakes itself free of the optical tweezers. Until now this has been a major difficulty of one-atom sources of single photons. To circumvent the problem, one option would be to cool the atomic motion after every photon emission event, thus keeping the atom confined long enough for application purposes.

Hijlkema *et al.*[1] have mastered this crucial step, with an approach that allows them to hold a single atom in the cavity for up to a minute. Three-dimensional cooling of neutral atoms to submillikelvin temperatures is now routine in free space. However, it is a substantially more challenging task inside the confines of an optical microcavity. Using a clever technique that uses the cavity standing wave field as part of the cooling process, Hijlkema *et al.*[1] have succeeded in confining an atom and monitoring its presence in real time. Cooling results from forcing the recoiled atom to climb the steep gradient of the trapping potential, thereby dissipating kinetic energy into radiation. By alternating the cooling intervals with the trigger laser pulses, Hijlkema *et al.* stroboscopically cool and monitor the atom, without significantly perturbing the train of single photons (which extend to as many as 300,000 photons[1]).

The single-photon character of a source is verified by observing subpoissonian photoelectron detection statistics. That is, when an excited atom has emitted a photon, it takes some time to excite the atom again, and thus allow it to emit a second photon. As a result, the joint probability for the simultaneous detection of two photons is zero[5]. The presence of two or more radiating atoms suppresses the effect, as was observed — along with the non-classical effect known as photon antibunching — using laser-excited atomic beams in the 1970s (ref. 6). In more recent work, many-atom effects have been essentially excluded by imaging the emission from individually trapped ions and atoms[7,8]. Hijlkema and colleagues[1] perform real-time measurements to ensure the presence of just one atom.

For future applications it will be important to demonstrate the fact that the single photons produced by independent photon servers are indistinguishable[9]. Interference of identical, remotely generated photons is a key element in the entanglement of distant material nodes of a quantum network system. Theoretical protocols often assume the ability to produce indistinguishable single photons on demand at remote node locations. Robust and efficient single-photon sources are therefore thought to be particularly important for the practical success of large-scale quantum information systems. In the shorter term, two distant single-photon servers could be used for photon-mediated entanglement of the server atoms. As atomic states may be detected with near-perfect efficiency, this could enable a test of Bell's inequality[10] (that is, of so-called local realism) in a way that circumvents the loophole of low detection efficiency that has plagued all previous measurements.

References

1. Hijlkema, M. *et al. Nature Phys.* **3,** 253–255 (2007).
2. Purcell, E. M. *Phys. Rev.* **69,** 681 (1946).
3. Keller, M., Lange, B., Hayasaka, K., Lange, W. & Walther, H. *Nature* **431,** 1075–1078 (2004).
4. Ashkin, A. *Phys. Rev. Lett.* **24,** 156–159 (1970).
5. Carmichael, H. J. & Walls, D. F. *J. Phys. B* **9,** L43–L46 (1976).
6. Kimble, H. J., Dagenais, M. & Mandel, L. *Phys. Rev. Lett.* **39,** 691–695 (1977).
7. Diedrich, F. & Walther, H. *Phys. Rev. Lett.* **58,** 203–206 (1987).
8. Darquié, B. *et al. Science* **309,** 454–456 (1987).
9. Hong, C. K., Ou, Z. Y. & Mandel, L. *Phys. Rev. Lett.* **59,** 2044–2047 (2005).
10. Bell, J. S. *Rev. Mod. Phys.* **38,** 447–452 (1966).

QUANTUM COMPUTING

In the 'death zone'?

An event advertised as the first demonstration of a commercial quantum computer raises the question of how far one can go with a 'do not care' attitude towards imperfections, without losing the quantum advantage.

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On 13 February this year, in a widely publicised demonstration[1], the company D-Wave Systems presented an implementation of a quantum adiabatic-optimization algorithm on their version of a 16-bit quantum computer. Unlike the conventional approach to building quantum computers, D-Wave's philosophy sidesteps the issue of having to endow the system with a built-in tolerance against a certain degree of imperfection (an approach known as 'fault-tolerant computing'). In fact, they argue that noise might actually be a good thing, at least when using — as the D-Wave team does — heuristic algorithms such as adiabatic optimization. Allowing noise to enter the system, and stepping back to see how well the quantum algorithm performs despite all imperfections, might indeed be a good idea in view of the enormous experimental challenges posed by maintaining coherence among more than a few interacting quantum bits. The approach, however, can only go so far. Quantum circuits with error rates above a certain threshold enter a regime where everything they do can be simulated on a classical computer. Theoretical studies have recently significantly moved this threshold, thereby making it more difficult for those who want to implement quantum algorithms without worrying too much about the coherence of their systems.

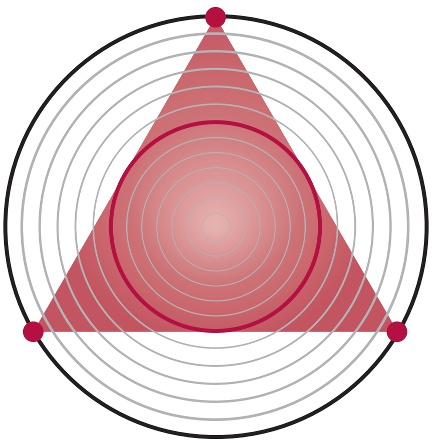

Figure 1 Losing the quantum advantage. In this schematic picture, all operations that quantum mechanics permits are represented by the black circle. A few of these operations — shown as red points — can be easily simulated classically, implying that all operations within the red triangle can be simulated classically as well, without anything 'quantum' happening. Any noisy system 'lives' within a concentric circle of smaller radius, and the noisier the system, the smaller the circle. If the circle of possible operations is smaller than the 'threshold' circle (in red), any computation the system is able to perform can equally well be achieved classically.

Precisely how much noise is too much noise remains an open question. A few months ago, Buhrman and colleagues[2] predicted that an error rate of approximately 45% per gate operation already takes a computation into a 'death zone' where only classical computation can survive. Building too noisy a quantum computer can, therefore, quickly turn into a losing proposition, at least as long as quantum computers are more expensive than traditional computers. The way the transition into a 'bad regime' is proven goes back to earlier work by Virmani *et al.*[3], and uses the notion that very noisy quantum operations can be viewed as probabilistic mixtures of more simple quantum operations that we know how to simulate classically (see Fig. 1). Any circuit made up of such noisy gates can therefore be simulated by a probabilistic, classical computation and hence can have none of the quantum benefits that we might be hoping for.