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Press Release

Photons under Control

Researchers at the Max-Planck-Institute of Quantum Optics (MPQ) in Garching have achieved unprecedented control over the creation of single photons

By using a tightly trapped single calcium ion, localized between two ultra-high reflectivity mirrors, and subjecting it to an external laser pulse, the scientists could emit photons one by one. The emission time and the pulse shape of each photon were completely user-controlled. Remarkably, the device was operated without interruption over a period limited only by the trapping time of the ion, typically many hours. The achievement has important applications in quantum information processing. A controlled quantum interface between atoms and photons has become feasible. In this way, local ion-based operations on quantum states can be combined with long distance quantum information exchange, a key requirement for the implementation of a secure quantum internet (Nature, October 28, 2004).

Next year marks the 100th anniversary of Einstein's discovery of the photoelectric effect. This discovery was an important conformation of Max Planck's quantum hypothesis proposed at the end of the year 1900. According to this hypothesis, the energy of an electromagnetic wave does not consist of a continuous flow, but of discrete energy packages, the photons. Atoms emit photons in an uncontrolled way. In the past, this has not been a problem, because in the macroscopic world, we only experience the effect of light as the sum over billions of billions of photons each second, so that fluctuations are averaged out. However, new types of light sources have recently been developed in the laboratory, that emit photons one by one. These experiments are motivated by schemes proposing to use the quantum states of photons to process information with unparalleled efficiency, or to realize secure communication. To work reliably, quantum processing schemes require emission and absorption of the photons in a fully controlled way.

One method to create a single photon is to place a single atom between two mirrors, which form a cavity, resonantly supporting the photon to be generated. From a suitable excited state, the atom emits a single photon into the cavity mode. The main problem with using an atom is the lack of control over its position in the cavity due to limitations of trapping technology. This leads to randomly fluctuating conditions for photon generation and hence random properties of the emitted photons.

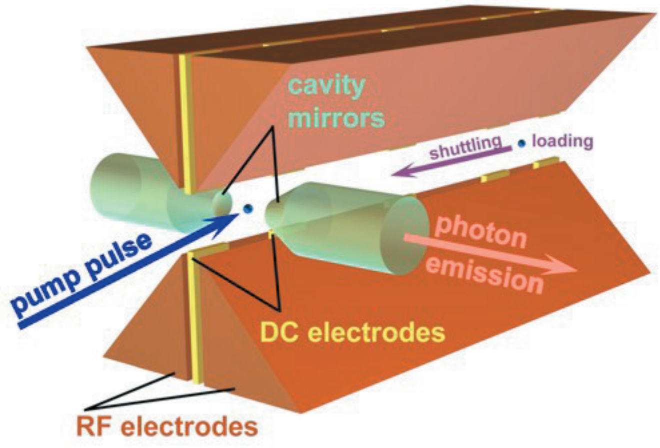

Fig. 1:
Ion trap used in the experiment. The ion is loaded at the rear end and pushed along the trap axis to the centre of the cavity. Photon emission is achieved by means of a pump pulse injected from the side. Single photons are emitted through the output mirror.

Image: Max Planck Institute for Quantum Optics

Matthias Keller, Birgit Lange, Kazuhiro Hayasaka, Wolfgang Lange and Herbert Walther of the Max-Planck-Institute of Quantum Optics have overcome the limitations of trapped atoms in cavities. They used a single calcium ion, confined in a radio frequency trap (Fig. 1). By means of laser cooling, the ion‘s motion was restrained to a region 40 nm in diameter. This is only a fraction of the wavelength of the photons to be generated (866 nm) and provides optimum conditions for controlling the interaction of ion and field.

The ion was placed between two high-reflectivity mirrors (see Fig. 1). The distance between the mirrors is adjusted, so that a standing light wave can form between them, coinciding with a suitable atomic transition. Initially, the cavity contains no light. Energy must be supplied externally by exciting the ion with a laser beam injected from the side of the cavity. If the system parameters are set correctly, the ion absorbs a photon from the external laser. Subsequently, the strong interaction with the cavity mode induces the ion to emit a single photon into the cavity mode. After the emission, the ion is found in a state, in which it does not absorb the exciting laser light anymore. In this way, creation of a second photon is prohibited. In order to deliver the photon to the outside world, one of the mirrors is made partially transparent, causing the photon to leak out of the cavity and completing the process of single-photon generation.

Since the photon emission is triggered by the external laser pulse, the researchers could create the photon at the push of a button. But not only the emission time, the shape of the single-photon pulse is also linked to the shape of the excitation pulse. But how can a single-photon pulse shape be measured? In the experiment, a single photon reveals itself by producing a click in a detector at a certain time. At this moment, all other information about the photon is irretrievably lost. However, at the Max-Planck-Institute, the researchers took advantage of the fact that their control over the initial preparation of the ion is so good, that every photon emitted from the apparatus has identical properties. This allows them to probe the pulse shape by performing repeated measurements on subsequent photons. By statistically evaluating the arrival times of the photons, which are spread out over 2 microseconds, an image of the shape of the photon pulse is obtained. Two examples of measured pulse shapes are shown in Fig. 2. The blue trace represents the measured photon arrival times, to be compared with the superimposed red trace, obtained from a quantum mechanical calculation. The precise coincidence between the two curves illustrates the degree of control that was achieved in the experiment. Note that the pulse shape in Fig. 2b belongs to just a single photon, which was cast in a shape with two maxima by a corresponding pump pulse.

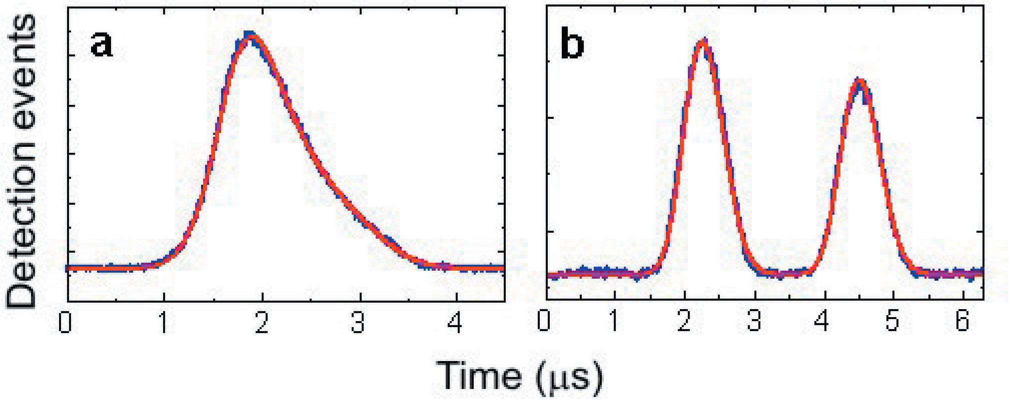

Fig. 2:
Single photon pulse shapes, obtained by statistically evaluating the detection times of identically prepared photon. ***a*** *single-peaked pump-pulse;* ***b*** *twin-peaked pump-pulse.*
Image: Max Planck Institute for Quantum Optics

Another big advantage is the long storage time of ions, usually several hours. This is in contrast to atoms with trapping times below one second. The Max-Planck group has extracted a continuous stream of single photons for an unprecedented 90 minutes, 10.000 times longer than for atoms. This is important for a reliable operation of the device in quantum information processing. The coupling of ions and photons in a controlled way is required in schemes linking optical long-distance quantum communication with ion-trap quantum processors, both of which have been successfully demonstrated in the past. The result could be a quantum version of the internet, in which local processing sites are connected with each other by photonic channels.

Original work:

M. Keller, B. Lange, K. Hayasaka, W. Lange, and H. Walther
Continuous generation of single photons with controlled waveform in an ion-trap cavity system
Nature **431**, 1075; 28 October 2004

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