Single atom stores quantum information

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A data memory can hardly be any smaller: researchers working with Gerhard Rempe at the Max Planck Institute of Quantum Optics in Garching have stored quantum information in a single atom. The researchers wrote the quantum state of single photons, i.e. particles of light, into a rubidium atom and read it out again after a certain storage time. This technique can be used in principle to design powerful quantum computers and to network them with each other across large distances.

Quantum computers will one day be able to cope with computational tasks in no time where current computers would take years. They will take their enormous computing power from their ability to simultaneously process the diverse pieces of information which are stored in the quantum state of microscopic physical systems, such as single atoms and photons. In order to be able to operate, the quantum computers must exchange these pieces of information between their individual components. Photons are particularly suitable for this, as no matter needs to be transported with them. Particles of matter however will be used for the information storage and processing. Researchers are therefore looking for methods whereby quantum information can be exchanged between photons and matter. Although this has already been done with ensembles of many thousands of atoms, physicists at the Max Planck Institute of Quantum Optics in Garching have now proved that quantum information can also be exchanged between single atoms and photons in a controlled way.

Using a single atom as a storage unit has several advantages - the extreme miniaturization being only one, says Holger Specht from the Garching-based Max Planck Institute, who was involved in the experiment. The stored information can be processed by direct manipulation on the atom, which is important for the execution of logical operations in a quantum computer. "In addition, it offers the chance to check whether the quantum information stored in the photon has been successfully written into the atom without destroying the quantum state," says Specht. It is thus possible to ascertain at an early stage that a computing process must be repeated because of a storage error.

The fact that no one had succeeded until very recently in exchanging quantum information between photons and single atoms was because the interaction between the particles of light and the atoms is very weak. Atom and photon do not take much notice of each other, as it were, like two party guests who hardly talk to each other, and can therefore exchange only a little information. The researchers in Garching have enhanced the interaction with a trick. They placed a rubidium atom between the mirrors of an optical resonator, and then used very weak laser pulses to introduce single photons into the resonator. The mirrors of the resonator

reflected the photons to and fro several times, which strongly enhanced the interaction between photons and atom. Figuratively speaking, the party guests thus meet more often and the chance that they talk to each other increases.

The photons carried the quantum information in the form of their polarization. This can be left-handed (the direction of rotation of the electric field is anti-clockwise) or right-handed (clock-wise). The quantum state of the photon can contain both polarizations simultaneously as a so-called superposition state. In the interaction with the photon the rubidium atom is usually excited and then loses the excitation again by means of the probabilistic emission of a further photon. The Garching-based researchers did not want this to happen. On the contrary, the absorption of the photon was to bring the rubidium atom into a definite, stable quantum state. The researchers achieved this with the aid of a further laser beam, the so-called control laser, which they directed onto the rubidium atom at the same time as it interacted with the photon.

The spin orientation of the atom contributes decisively to the stable quantum state generated by control laser and photon. Spin gives the atom a magnetic moment. The stable quantum state, which the researchers use for the storage, is thus determined by the orientation of the magnetic moment. The state is characterized by the fact that it reflects the photon's polarization state: the direction of the magnetic moment corresponds to the rotational direction of the photon's polarization, a mixture of both rotational directions being stored by a corresponding mixture of the magnetic moments.

This state is read out by the reverse process: irradiating the rubidium atom with the control laser again causes it to re-emit the photon which was originally incident. In the vast majority of cases, the quantum information in the read-out photon agrees with the information originally stored, as the physicists in Garching discovered. The quantity that describes this relationship, the so-called fidelity, was more than 90 percent. This is significantly higher than the 67 percent fidelity that can be achieved with classical methods, i.e. those not based on quantum effects. The method developed in Garching is therefore a real quantum memory.

The physicists measured the storage time, i.e. the time the quantum information in the rubidium can be retained, as around 180 microseconds. "This is comparable with the storage times of all previous quantum memories based on ensembles of atoms," says Stephan Ritter, another researcher involved in the experiment. Nevertheless, a significantly longer storage time is necessary for the method to be used in a quantum computer or a quantum network. There is also a further quality characteristic of the single-atom quantum memory from Garching which could be improved: the so-called efficiency. It is a measure of how many of the irradiated photons are stored and then read out again. This was just under 10 percent.

The storage time is mainly limited by magnetic field fluctuations from the laboratory surroundings, says Ritter. "It can therefore be increased by storing the quantum information in quantum states of the atoms which are insensitive to magnetic fields." The efficiency is limited by the fact that the atom does not sit still in the centre of the resonator, but moves. This causes the strength of the interaction

between atom and photon to decrease. The researchers can thus also improve the efficiency: by greater cooling of the atom, i.e. by further reducing its kinetic energy.

The researchers at the Max Planck Institute in Garching now want to work on these two improvements. "If this is successful, the prospects for the single-atom quantum memory would be excellent," says Stephan Ritter. The interface between light and individual atoms would make it possible to network more atoms in a quantum computer with each other than would be possible without such an interface; a fact that would make such a computer more powerful. Moreover, the exchange of photons would make it possible to quantum mechanically entangle atoms across large distances. The entanglement is a kind of quantum mechanical link between particles which is necessary to transport quantum information across large distances. The technique now being developed at the Max Planck Institute of Quantum Optics could some day thus become an essential component of a future "quantum Internet".

SOURCE [2]

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