Switching with single photons

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The idea to perform data processing with light, without relying on any electronic components, has been around for quite some time. In fact, necessary components such as optical transistors are available. However, up to now they have not gained a lot of attention from computer companies. This could change in the near future as packing densities of electronic devices as well as clock frequencies of electronic computers are about to reach their limits. Optical techniques promise a high bandwidth and low dissipation power, in particular, if only faint light pulses are needed to achieve the effect of switching. The ultimate limit is a gate-pulse that contains one photon only. A team of scientists around Professor Gerhard Rempe, director of the Quantum Dynamics Division at the Max-Planck-Institute of Quantum Optics, has now managed to bring this almost utopian task into reality (PRL, DOI: 10.1103/PhysRevLett. 112.073901, 18 February 2014). The scientists succeeded in switching a medium - a cloud of about 200 000 ultracold atoms - from being transparent to being opaque for light pulses. This "single-photon-switch could be the first step in the development of a quantum logic gate, an essential component in the field of quantum information processing.
The experiment starts with cooling a cloud of about 200 000 rubidium atoms down to a temperature of 0.43 micro-Kelvin (this is just above absolute zero, which corresponds to minus 273 degree Celsius). The atoms are held in an optical dipole trap created by the crosswise superposition of two laser beams. The cloud is irradiated by two light pulses separated by 0.15 micro-seconds. The pulses are extremely weak, they contain on average one or even less photons. The first pulse - the so-called gate-pulse - gets absorbed inside the cloud. To be precise, it is stored as an atomic excitation, as it brings one of the atoms into a highly excited Rydberg state. The mere presence of the Rydberg atom leads to a shift of the corresponding energy levels of the other atoms in the cloud. Hence, the wavelength of the second pulse - the target pulse -no longer meets the requirements for excitation and gets blocked. In other words, the cloud of atoms acts as a medium which, on capturing one single photon, switches from being transparent to opaque. The storage of the photon can be maintained as long as the Rydberg state survives, i.e. for about 60 micro-seconds.
The whole procedure is based on a sophisticated combination of a number of experimental measures. For example, the transparency of the cloud is achieved by the application of a control laser. "In order to trap the gate-photon we use the so-called slow-light technique, Dr Stephan Dürr, leader of the experiment, explains. "When the photon is traversing the cloud it polarizes the surrounding medium and is slowed down to a velocity of 1000 km/h. As a consequence, the pulse length shrinks to a couple of tens of micrometres, such that it is completely contained inside the cloud during a certain time window. If the control laser is switch off exactly in this time period, the pulse comes to a halt and is completely converted into an atomic excitation.
The second pulse is prepared with a polarization that cannot couple to the atomic excitation that has been stored before. This prevents the target pulse from reading out the stored photon. "Subsequently, we switch the control laser back on. A photon with the right polarization can retrieve the gate-photon from the cloud. We repeat this cycle every 100 micro-seconds, says Simon Baur, who works at the experiment as a doctoral candidate.
In a series of measurements the scientists were able to prove that the number of transmitted target photons was reduced by a factor of 20 if a gate-photon had been stored in the cloud before. "Our experiment opens new perspectives in the field of quantum information, Professor Rempe resumes. "A single-photon switch could herald the successful storage of quantum information. That way, storage times could be improved. Last but not least, the new device could be the first step in the development of a quantum logic gate, a key element in quantum information processing. Olivia Meyer-Streng
Fig. 1: Illustration of the experimental set-up: an atomic cloud (green) is held in an optical dipole trap and irradiated with light pulses from a control (blue) and a signal beam (red). Graphic: MPQ, Quantum Dynamics Division.
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Im Fokus der wissenschaftlichen Aktivitäten des Max-Planck-Instituts für Quantenoptik steht die Wechselwirkung von Licht und Materie unter extremen Bedingungen. Dabei ist ein Schwerpunkt die hochpräzise Messung der Spektrallinien des Wasserstoffatoms. Hierfür wurde die Frequenzkammtechnik entwickelt, für die Prof. T.W. Hänsch 2005 den Nobelpreis für Physik erhielt. Andere Experimente zielen darauf, einzelne Photonen und einzelne Atome einzufangen und ihre Wechselwirkung miteinander zu kontrollieren und legen damit den Grundstein für zukünftige Quantencomputer. Gleichzeitig entwickeln Theoretiker am MPQ Konzepte, die auf Quantenbits gespeicherten Informationen möglichst effektiv zu übertragen. Mit den dabei entwickelten Algorithmen lassen sich geheime Nachrichten sicher verschlüsseln. Ferner werden am MPQ die bizarren Eigenschaften untersucht, die quantenmechanische Vielteilchensysteme bei extrem tiefen Temperaturen (etwa ein Millionstel Kelvin über dem absoluten Nullpunkt) annehmen können. Und schließlich werden Lichtblitze mit der unvorstellbar kurzen Dauer von einigen hundert Attosekunden (ein Milliardstel von einer Milliardstel Sekunde) erzeugt, die es z. B. ermöglichen, quantenmechanische Prozesse wie das ?Tunneln von Elektronen oder atomare Übergänge in Echtzeit zu beobachten.