First quantum teleportation between light and matter

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The concept of quantum teleportation - the disembodied complete transfer of the state of a quantum system to any other place - was first experimentally realised between two different light beams. Later it became also possible to transfer the properties of a stored ion to another object of the same kind. A team of scientist headed by Prof. Ignacio Cirac at MPQ and by Prof. Eugene Polzik at Niels Bohr Institute in Copenhagen has now shown that the quantum states of a light pulse can also be transferred to a macroscopic object, an ensemble of 10 to the power of 12 atoms (*Nature*, 4 October 2006).

This is the first case of successful teleportation between objects of a different nature - the ones representing a "flying" medium (light), the other a "stationary" medium (atoms). The result presented here is of interest not only for fundamental research, but also primarily for practical application in realising quantum computers or transmitting coded data (quantum cryptography).

Since the beginning of the nineties research into quantum teleportation has been booming with theoretical and experimental physicists. Transmission of quantum information involves a fundamental problem: According to Heisenberg's uncertainty principle two complementary properties of a quantum particle, e.g. location and momentum cannot be precisely measured simultaneously. The entire information of the system thus has to be transmitted without being completely known. But the nature of the particles also carries with it the solution to this problem: the possibility of "entangling" two particles in such a way that their properties become perfectly correlated. If a certain property is measured in one of the "twin" particles, this determines the corresponding property of the other automatically and with immediate effect.

With the help of entangled particles, successful teleportation can be achieved roughly as follows: An auxiliary pair of entangled particles is created, the one being transmitted to "Alice" and the other to "Bob". (The names "Alice" and "Bob" have been adopted to describe the transmission of quantum information from A to B.) Alice now entangles the object of teleportation with her auxiliary particle and then measures the joint state (Bell measurement). She sends the result to Bob in the classical manner. He applies it to his auxiliary particle and "conjures up" the teleportation object from it.

Are "such "instructions for use" merely mental games? The great challenge to theoretical physicists is to devise concepts which can also be put into practice. The experiment described here has been conducted by a research team headed by Prof. Eugene Polzik at Niels Bohr Institute in Copenhagen. It follows a proposal made by Prof. Ignacio Cirac, Managing Director at MPQ, and his collaborator Dr. Klemens Hammerer (also at MPQ at that time, now at University of Innsbruck, Austria).

First the twin pair is produced by sending a strong light pulse to a glass tube filled with caesium gas (about 10^{12} atoms). The magnetic moments of the gas atoms are aligned in a homogenous magnetic field. The light also has a preferential direction: It is polarised, i.e. the electric field oscillates in just one direction. Under theses conditions the light and the atoms are made to interact with one another so that the light pulse emerging from the gas that is sent to Alice is "entangled" with the ensemble of 10 to the power of 12 caesium atoms located at Bob's site.

Alice mixes the arriving pulse by means of a beam splitter with the object that she wants to teleport: a weak light pulse containing very few photons. The light pulses issuing at the two outputs of the beam splitter are measured with photo-detectors and the results are sent to Bob.

The measured results tell Bob what has to be done to complete teleportation and transfer the selected quantum states of the light pulse, amplitude and phase, onto the atomic ensemble. For this purpose he applies a low-frequency magnetic field that makes the collective spin (angular momentum) of the system oscillate. This process can be compared with the precession of a spinning top about its major axis: the deflection of the spinning top corresponds to the amplitude of the light, while the zero passage corresponds to the phase.

To prove that quantum teleportation has been successfully performed, a second intense pulse of polarised light is sent to the atomic ensemble after 0.1 milliseconds and, so to speak, "reads out" its state. From these measured values theoretical physicists can calculate the so-called fidelity, a quality-factor specifying how well the state of the teleported object agrees with the original. (A fidelity of 1 is equivalent to a perfect agreement, while the value zero indicates that there has been no transfer at all.) In the present experiment the fidelity is 0.6, this being well above the value of 0.5 that would at best be achieved by classical means, e.g. by communicating measured values by telephone, without the help of entangled particle-pairs.

Unlike the customary conception of "beaming", it is not a matter here of a particle disappearing from one place and re-appearing in another. "Quantum teleportation constitutes methods of communication for application in quantum cryptography, the decoding of data, and not new kinds of transportation", as Dr. Klemens Hammerer emphasizes. "The importance of the experiment is that it is now possible for the first time to achieve teleportation between stationary atoms, which can store quantum states, and light, which is needed to transmit information over great distances. This marks an important step towards accomplishing quantum cryptography, i.e. absolutely safe communication over long distances, such as between Munich and Copenhagen."

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