Scientists demonstrate quantum state exchange between light and matter

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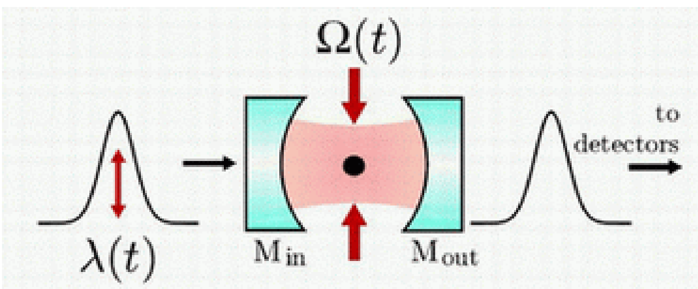

This schematic of the scientists&acute experiment shows a light pulse illuminating a cesium atom in an optical cavity, where the quantum states of the light and atom are mapped onto each other. When the light pulse exits, its interference with the original pulse demonstrates the reversibility of the state transfer. Image credit: Boozer, et al.

Quantum computers offer the promise of processing information much more efficiently than classical computers. But before quantum computers can be built, scientists must confront several challenges, one of which is quantum computers' vulnerability to their surroundings. Interaction with outside forces would immediately damage a quantum computer's information; this problem is known as "decoherence."

One method to coherently process quantum information involves cavity quantum electrodynamics (QED). In this method, scientists use a small cavity to achieve coherent dynamics between an atom and a photon by manipulating an atom's radiation properties with mirrors. Scientists from the California Institute of Technology are among the leaders in cavity QED, and have recently reported an important advance to enable a coherent distribution of quantum information across a network.

In their paper published in *Physical Review Letters*, physicist David Boozer and his colleagues have demonstrated the reversible state transfer of a coherent light pulse to and from the internal state of an atom trapped in an optical cavity. This observation is the first verification of atomic physicist Ignacio Cirac's proposal for the reversible mapping of quantum states between light and matter using cavity QED to provide strong coupling for the atom-photon interaction.

"The most significant result of this work is the demonstration of reversibility (i.e., coherence) for the light emission and absorption processes," Boozer told *PhysOrg.com*. "The fact that this process is coherent means that it preserves superpositions of quantum states, hence it is a way of mapping quantum information between an atom and light."

In quantum networks, qubits (the information states for quantum computers) can be represented by either atoms or photons. Atoms, which have long coherence times, serve as "stationary" qubits, or nodes of a network, where they are stored and locally manipulated. Photons, on the other hand, serve as "flying" qubits, or quantum channels that connect nodes over long distances. While many single-photon sources have been demonstrated in the past decade, none have been experimentally shown to be reversible until now.

"In principle, in a quantum computer there are several logic gates, each of which performs an elementary quantum operation on one or two stationary qubits," Boozer explained. "The gates are connected together in a network, so that the output of one gate can be transported as a flying qubit to the input of the next gate. Hence, one needs a way to turn stationary qubits into flying qubits and vice-versa, which is what our recent work has demonstrated."

In the Caltech scientists' experiment, a cesium atom is localized within the cavity by a far off-resonant optical trap, where it repeatedly undergoes a series of light absorption and reemission cycles, lasting a total of 360 ms. During each such cycle, the cavity is first illuminated by an incident pulse of coherent light. Whenever the atom-cavity system absorbs this pulse, the quantum state of the light is written onto the internal state of the atom.

After a delay of about 300 ns, the atomic state gets mapped back onto an emitted pulse of light, which is allowed to interfere with the source of the original coherent pulse. Observing the resulting interference fringe demonstrates the reversibility of the overall absorption-reemission process.

"Our optical cavity has a very small mode volume (the cavity length is only 42 microns), which ensures that the coherent interaction between the atom and light field occurs on a much faster time scale than the decoherence caused by atomic spontaneous emission or cavity leakage," Boozer explained. "Thus the atom and cavity field can exchange quantum information coherently many times before an incoherent process occurs. This regime is known as strong-coupling in cavity QED."

The scientists explain that the efficiency of the light-to-atom transfer is limited in this scenario by factors such as passive mirror losses, equal transmission coefficients of the cavity mirrors, and the coupling of the atom to both polarization modes of the cavity.

With the ability to reversibly transfer a qubit's state from "flying" to "stationary" and back again, the scientists have taken a step toward coherently transferring quantum information across a network, without disruption with the outside world. Still, Boozer and his colleagues look forward to future improvements.

“In the present work, the qubit is encoded in the photon-number states of light and in the hyperfine levels of the atom,” he said. “A more robust scheme which we may pursue in the future would be to instead use the polarization degree of freedom of the light, and the magnetic sublevels of the atom. Another future goal will be to increase the efficiency of the state transfer process, for instance by using cavity mirrors with unequal transmissivities and/or even higher reflectivities.”

Citation: Boozer, A. D., Boca, A., Miller, R., Northup, T. E., and Kimble, H. J. "Reversible State Transfer between Light and a Single Trapped Atom." *Physical Review Letters* 98, 193601 (2007).