Physics

VIEWPOINT

Optical Quantum Logic at the Ultimate Limit

Microscopic clouds of cold atoms can mediate interactions between weak pulses of light at the level required for quantum logic with single photons.

by Scott Parkins†

Photons—individual quanta of light—are painfully shy when it comes to interacting with each other in free space; for a start, their extreme speed doesn't help matters. This shyness, and speed, is good from the point of view of faithfully and rapidly transmitting quantum information, but it poses a major challenge to the realization of optical quantum logic gates that use single photons as inputs and outputs. However, what if the photons could be slowed down or even stopped for a while in a special medium through which they could be forced to "talk" to each other? This is the approach taken in three exciting recent experiments [1–3], which used an ensemble of trapped, laser-cooled atoms as the special medium. The researchers showed that in this medium, a pulse of light containing, on average, as little as one photon can interact with, and produce a phase shift of up to 180° on, another, similarly weak pulse (Fig. 1). This result fulfils the requirements of a deterministic (that is, nonprobabilistic) and universal quantum logic gate.

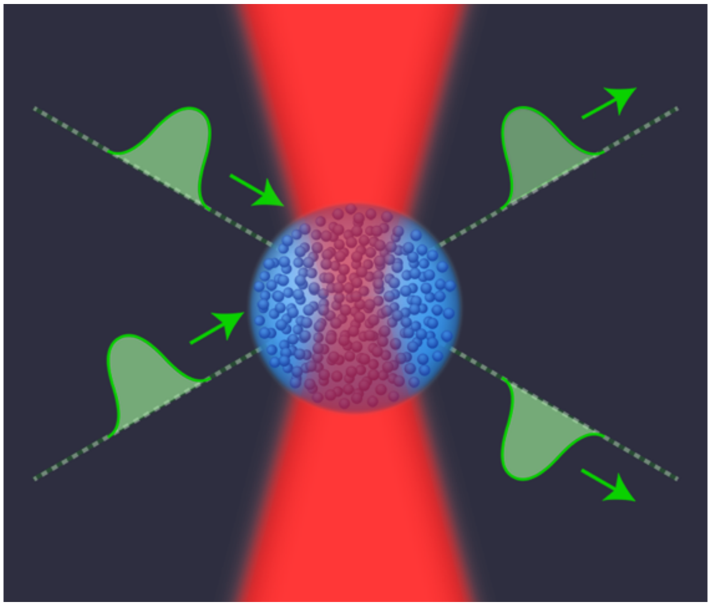

Figure 1: Experimentalists from three groups have used small clouds of cold atoms to mediate strong interactions between pulses of light containing as little as one photon. Auxiliary lasers (red) help to make the atomic medium (blue) largely transparent to the pulses (green), but to also slow or even stop the pulses temporarily, so that, through their common interaction with the atomic medium, one pulse can induce a phase shift of up to 180° on the other. This is a requirement for the realization of a deterministic and universal quantum logic gate with single photons. (APS/Joan Tycko)

The polarization of a single photon (horizontal, vertical, or any quantum superposition of the two) serves nicely as a quantum bit, or qubit. A two-qubit quantum logic gate requires that the output state of the qubits depends in a conditional, nonlinear way on each of their input states—for example, that the photons interact only for one particular combination of polarizations. But for the most part, photons in free space just plain ignore each other. The potential to use atomic media to create the necessary interactions between photons has been known for some time. It was highlighted by a seminal experiment performed by the group of Jeff Kimble at Caltech in 1995 [4]. In that experiment, two continuous-wave weak laser beams, differing slightly in frequency, were passed simultaneously through a small optical resonator containing, on average, just a single cesium atom from an atomic beam. Through the strong coupling of the atom to the laser light confined inside the resonator, it was possible for one beam to impart a nonlinear, polarization-dependent phase shift on the other of up to 16° per photon.

However, the step from continuous, albeit weak, laser beams to few- or single-photon light pulses, as was demonstrated in the new experiments [1–3], is a nontrivial one. Whereas the light in a continuous laser beam has essentially a single frequency, a pulse of light has a spread of frequency components, that is, a finite bandwidth. In particular, the longer the pulse, the smaller the bandwidth, and vice versa. The medium through which simultaneously propagating

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photons interact must also, in practice, have a finite working bandwidth; in the case of the Caltech experiment, this was the inverse of the lifetime of a photon inside the resonator, or the resonator linewidth. For all frequency components of the pulse to experience the same phase shift, the pulse bandwidth must fit within this linewidth. Equivalently, the pulse duration must be much longer than the duration of the interaction. But then, on average, only a small "fraction" of each photon pulse can ever be participating in the interaction, effectively reducing the interaction strength. In fact, it was shown [5, 6] that this trade-off between interaction time and strength, or between bandwidths, leads to a fundamental limit on the achievable phase shift in experiments such as that of Kimble and colleagues [4].

But here enters the fascinating world of "slow light" and the phenomenon of electromagnetically induced transparency (EIT) [7, 8]. EIT occurs when the absorption of "probe" light by an atomic medium is eliminated because of destructive interference between two alternative pathways for a transition from a ground state to an excited atomic state. The different pathways are achieved by involving a third atomic state, which is coupled to the excited state via an auxiliary laser field. The strength of this field determines the bandwidth of the transparency. Significantly, a change in absorption over a sufficiently narrow bandwidth is accompanied by a sharp change in the medium's refractive index and thus a dramatic slowing of the probe light. And this is precisely the effect that the authors of the recent studies [1–3] have employed to force the interaction between weak light pulses propagating through a cold-atom medium, and thereby circumvent the fundamental limit on phase shifts.

Stephan Dürr and colleagues [1] at the Max Planck Institute for Quantum Optics, Germany, slowed an initial "control" pulse—containing, on average, less than one photon—to a standstill for a few microseconds in a microscopic cloud of approximately ten thousand rubidium atoms. The researchers attained this by switching off the auxiliary laser during the passage of the control pulse through the cloud. This effectively reduced the group velocity of the pulse to zero, allowing a single control photon to be stored as an excitation of the third atomic state—in this instance, a high-lying Rydberg state of one atom in the cloud. In keeping with a theoretical proposal [9], the presence of this Rydberg atom and, in particular, its strong influence on other atoms within the cloud, produced a substantial phase shift—up to 180°—on a "target" pulse that subsequently propagated through the cloud. Finally, the authors switched back on the control photon's auxiliary laser, retrieving the photon and completing an "AND gate" operation. This is the essence of a two-qubit controlled-phase gate, and any operation on a quantum computer—universal quantum computation—can be reduced to sequences of this gate and simple one-qubit (or single-photon) gates.

Similarly, Vladan Vuletić and co-workers [2] at the Massachusetts Institute of Technology, Cambridge, stored a photon from a weak pulse through EIT in an ensemble of cold cesium atoms. However, the authors used a hyperfine ground state as the third atomic state and stored the photon as a collective (or spin) excitation of the ensemble. In addition, as in Kimble and colleagues' experiment [4], they placed the ensemble inside an optical resonator, through which a subsequent, propagating pulse could couple strongly to the third atomic state and impart a differential phase shift of up to 60° between the two atomic states involved in the collective excitation. Then, by reapplying the auxiliary laser, they retrieved the stored and phase-shifted photon pulse to complete the gate operation.

Finally, Ite Yu from the National Tsing Hua University, Taiwan, and colleagues [3] made two pulses—each containing, on average, eight photons—propagate slowly and simultaneously through a cold-atom cloud in which two EIT configurations overlapped. This double-EIT system involved four atomic levels (two excited and two ground atomic states) and two auxiliary lasers, similar in spirit to an original proposal [10]. By sharing atomic ground states, the overlapping EIT configurations enabled strong interaction between the pulses and a phase shift to be induced on one pulse by the other. The shift is equivalent to 26° per photon, with the prospect of further improvement.

As impressive as these schemes are, challenges remain in optimizing their performance. For example, the storage and subsequent recovery of photons is currently far from perfect, with efficiency of around 10–20%, due to several imperfections, such as uncontrolled photon scattering and nonuniform atom-light coupling across the clouds. The schemes should also be implemented using actual single-photon pulses, rather than weak pulses that have one or a few photons on average, and the photon polarization should be brought into play explicitly to implement a qubit with each photon. Nonetheless, together these experiments provide a compelling demonstration of the potential of slow light in atomic media and, in particular, the exquisite degree of control that experimentalists can now exert over the interactions of single photons with one another.

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