Slow light in cool atoms

Jon Marangos

An experiment with atoms at nanokelvin temperatures has produced the remarkable observation of light pulses travelling at velocities of only 17 m s^{-1}. The large optical nonlinearities seen in this system may open up new opportunities in quantum optics.

In our usual understanding, the speed of light, c, is the absolute top speed in the Universe at 3×10^8 m s^{-1} in a vacuum. So observation of light pulses propagating at a speed no faster than a swiftly moving bicycle, described by Hau *et al.*[1] on page 594 of this issue, comes as a surprise. We know that light can be slowed to a modest extent in refractive and transparent media, for example water and glass, to velocities typically a factor of 1.5–2.0 times slower than c. But there is a limit to how much light can be slowed in normal optical materials, because the larger refractive index associated with slower propagation is inevitably accompanied by increased light absorption.

Under special circumstances, however, this limit can be overcome — that is, a perfectly transparent medium can be created in which the speed of light is slowed enormously. The systems in question are laser-dressed atomic media that acquire new optical properties because light does not interact directly with atoms but with a system composed of atoms plus laser field. This requires the preparation of laser-dressed atoms (see box for the technical details) to create what is termed electromagnetically induced transparency, in which quantum interference leads to the cancellation of absorption[2]. In this new kind of system, the dispersive (or refractive) properties of the medium — including the velocity of propagation of an optical pulse — become independent of absorption[3]. For example, Steve Harris and colleagues[4] at Stanford have used coherently prepared lead atoms to reduce the propagation velocity of a resonantly tuned light pulse to c/165. To achieve even slower pulse velocities, cold atoms are required because, to maximize the quantum interference effect, the thermal motion must be small.

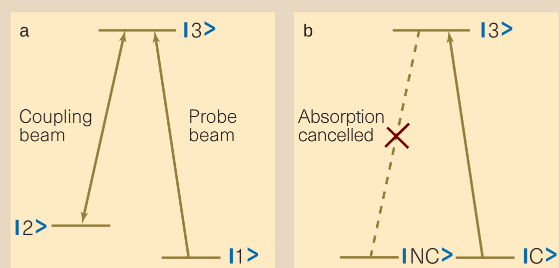
Hau and her co-workers[1] use ultra-cold sodium atoms. They load a magneto-optical trap with sodium atoms, and the gas is cooled briefly with a laser to reach temperatures of 50 μK (ref. 5). With the lasers switched off, only atoms in the ground state with magnetic dipoles directed opposite to the magnetic field are confined by the novel magnetic trap developed by the authors[6]. Hau *et al.* then evaporatively cool the atoms in this trap to reach temperatures in the region of the Bose–Einstein condensation threshold T_c = 435 nK. (Bose–Einstein condensates were first observed in 1995, in a famous experiment by Eric Cornell and Carl Wieman[7], and are a unique state of matter in which all of the atoms exist in the same quantum state.)

In ultra-cold atoms, extremely narrow transparency dips due to quantum interference can be induced using very low powers of the 'coupling' laser beam. Accompanying this low absorption will be a very steep variation, with probe laser frequency, in the refractive index. This steep slope and the high sample density in the trapped cloud of atoms leads to ultra-slow light propagation. The velocity of the probe laser pulse increases with the coupling laser power and decreases with atom density. So the lowest velocities are obtained by Hau *et al.* at low temperatures — for which strong interference can be seen with very low coupling laser power — and high sample density. The atom density shows an abrupt increase below T_c to values of 5×10^{12} cm^{-3}, and although results for temperatures above T_c were obtained from the ultra-cold samples, the lowest velocities were always seen at temperatures below this value.

The coupling laser field and probe pulse used in this experiment (Fig. 1, overleaf) are derived from the same continuous-wave dye laser, with their frequency set by an acousto-optic modulator. The coupling laser is linearly polarized and directed perpendicular to the axis of the 0.2-mm-long cloud of atoms. The circularly polarized probe field is shaped into a 2.5-μs-long pulse by a second acousto-optic modulator. This pulse is propagated along the axis of the atom cloud. It takes the probe pulse about 7 μs to pass through only 0.2 mm of cold atoms. Modest losses due to absorption are observed, although without quantum interference this medium would be completely opaque. The lowest velocity recorded was just 17 m s^{-1} at temperatures below T_c. For temperatures above T_c the velocities were up to a factor of four larger than this.

The reduction of the propagation veloci-

Box 1: Laser-dressed atoms



In the experiment of Hau *et al.*[1], the sodium atoms can be thought of as a three-level atomic system subject to a pair of resonant laser fields. In **a**, the coupling field (linearly polarized) is applied to the unpopulated hyperfine states |2⟩ and |3⟩ and the probe pulse (circularly polarized) is applied to the |1⟩-|3⟩ transition. In the absence of these fields the eigenstates of the system are simply those of the atomic Hamiltonian (that is, |1⟩, |2⟩ and |3⟩). In **b**, in the presence of the fields the system has a new Hamiltonian of the atom plus laser field. Two of the eigenstates of this Hamiltonian (|C⟩ and |NC⟩) are a coherent superposition of |1⟩ and |2⟩. State |C⟩ remains coupled to the fields, but can be ignored in this experiment as it is unpopulated. In the populated eigenstate |NC⟩ the probability amplitudes of each of the component states (|1⟩ and |2⟩) make equal but opposite contributions. This leads to a transition dipole moment from |NC⟩ to |3⟩ which exactly vanishes through destructive interference; this is electromagnetically induced transparency. This non-coupled state |NC⟩ is called a 'dark state' to express how quantum interference has cancelled the interaction with the laser fields[10].

The quantum interference exists over a range of probe frequencies set by the coupling field power. In an ultra-cold sample complete absorption cancellation can be induced for very low coupling powers due to the very small magnitude of the atomic thermal motion. In this case there is a very narrow transparency dip and an abnormally steep dispersion profile that leads to a very slow pulse propagation velocity. J. M.

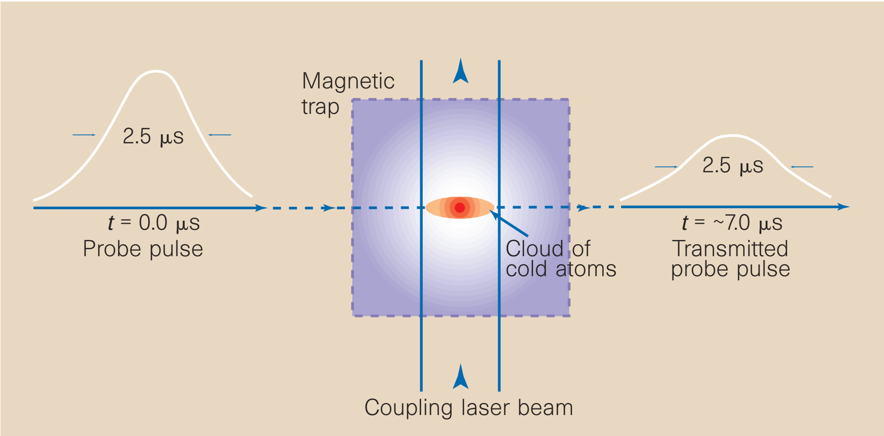


Figure 1 **The experimental set-up of Hau *et al.*[1]. The circularly polarized probe pulse takes about 7 μs to traverse the 0.2-mm cloud of cold atoms — this is 1/10 millionth of the speed of light in a vacuum.**

ty of the probe pulse — which is by a factor of about 20 million compared with the speed of light in a vacuum — is a stunning proof of the dramatic changes that can occur to the optical properties of laser-dressed atoms. In contrast to a normal atomic medium, the atoms here are in the presence of the coupling laser field so the probe pulse should be thought of as interacting with a system composed of the atoms plus the coupling field. The atoms alone could not have stored the energy of the probe pulse for the required time because of the normal dissipative process of spontaneous emission (see box). However, when the probe pulse enters the medium, its energy goes into the combined atom and field system where it is immune from rapid spontaneous decay. At the end of transmission the energy is returned to the probe field from the system. The energy of the probe pulse is, in a sense, kept safe within the non-decaying 'dark state' of the atom created by quantum interference.

Hau *et al.* have not yet found out if the atom cloud remains in the Bose–Einstein condensed state during the interaction with the probe. It may be that the main role the condensate plays in the slow velocity propagation is in providing a high density of cold atoms. The authors propose that with some technical improvements (higher frequency stability, lower coupling powers) still lower velocities can be achieved, perhaps down to a few centimetres per second.

Another important aspect of the work was the observation of large optical nonlinearities, in the form of an intensity-dependent refractive index. This was inferred from measuring the intensity-dependent frequency shift in the position of the transparency peak. Hau *et al.* conclude that, at 0.18 $cm^2 W^{-1}$, the nonlinear refractive index is unprecedentedly large.

Earlier work also considered potential applications of the optical properties of laser-dressed atoms. For instance, there have been detailed proposals to use these systems in highly sensitive magnetometers[8] or as an intracavity element to narrow a laser cavity linewidth. The slow pulse velocities reported by Hau *et al.* have yet to find a specific application, but laser-dressing clearly results in profound modifications of the optical properties of the medium. In the laser-dressed cold atoms, the pulse takes 7 μs to traverse the 0.2-mm sample. Propagating in a vacuum for the same period, by contrast, the pulse would have travelled 2 km! Perhaps this phenomenon could be used in optical delay lines for generating very long delays, or in allowing a shorter reference arm for an interferometer in which the other arm is many kilometres in length. Other applications might use the long time the pulse can be stored in the medium without significant dissipation, for instance in optical data storage.

Finally, the massive nonlinearities observed in this system are of a type that lead to a strong coupling between pairs of photons. Photons are particles that normally cannot interact strongly, so this is an unusual regime. Potentially these interactions may be large enough that it would become possible for a single photon to switch an optical cavity[9]. Nonlinearities of this kind have also been shown to be the key ingredient in experiments in quantum optics such as optical squeezing, quantum non-demolition measurements and studies of non-locality. The increased magnitude in the nonlinearities observed by Hau *et al.* may lead to improvements in these experiments. □

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1. Hau, L. V., Harris, S. E., Dutton, Z. & Behroozi, C. H. *Nature* **397,** 594–598 (1999).
2. Harris, S. E. *Phys. Today* **50,** 36–40 (1997).
3. Scully, M. O. *Phys. Reps* **219,** 191–201 (1992).
4. Kasapi, A. *et al. Phys. Rev. Lett.* **74,** 2447–2450 (1995).
5. Chu, S. *et al. Rev. Mod. Phys.* **70,** 685–741 (1998).
6. Hau, L. V. *et al. Phys. Rev. A* **58,** R54–R57 (1998).
7. Anderson, M. H. *et al. Science* **269,** 198–201 (1995).
8. Scully, M. O. *et al. Phys. Rev. Lett.* **69,** 1360–1363 (1992).
9. Yamamoto, Y. *Nature* **390,** 17–18 (1997).
10. Arimondo, E. *Prog. Opt.* **35,** 257–354 (1996).

Planetary science

Snapshots of an ancient cover-up

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Mars is a superb and arguably unique natural laboratory for the study of climate in the early stage of evolution of the terrestrial planets. As described in four papers in this issue[1–4], beginning on page 584, spectacular images from the Mars Orbiter Camera, an instrument on the Mars Global Surveyor spacecraft currently orbiting Mars, are providing a new view of the processes that shaped the Martian surface.

Shortly after the planets formed 4.5 billion years ago, planetismal impacts on their surfaces, and the differentiation of metal and rock to form planetary cores and mantles, heated the interiors of the terrestrial planets. As these planets rapidly cooled they liberated volatile gases to form atmospheres and, at least on Earth, the oceans. Both Earth and Mars underwent these processes, but the geological record on Earth predominantly preserves surfaces younger than 500 million years old; earlier records have been eradicated by processes such as subduction, continental collision and erosion. On Mars, however, most surfaces have ages greater than three billion years and they retain tantalizing hints that the early heat-loss phase on this planet produced climatic conditions that were much more hospitable than the cold, desert-like environment that exists now[5,6].

Today, Mars is too cold and the atmosphere is too thin for liquid water to be stable at the surface. Most water is currently stored as ice in the polar caps and in 'frozen aquifers' beneath the surface. However near-global images, of moderate resolution (around 200 metres per pixel) that were taken by the Mariner 9 and Viking Orbiter space probes in the 1970s, revealed a planet on which liquid water had flowed on the surface. From the early images, a diversity of early Martian climates were proposed, ranging from warm conditions with hemispheric-scale oceans to near-freezing conditions where water flowed on the surface for only the briefest of periods. Previous data have not been able to distinguish between specific evolutionary schemes, but spectacular new high-resolution images from the Mars Orbiter Camera (MOC) are allowing the range of possibilities to be narrowed considerably. In the four reports[1–4] now published, MOC principal