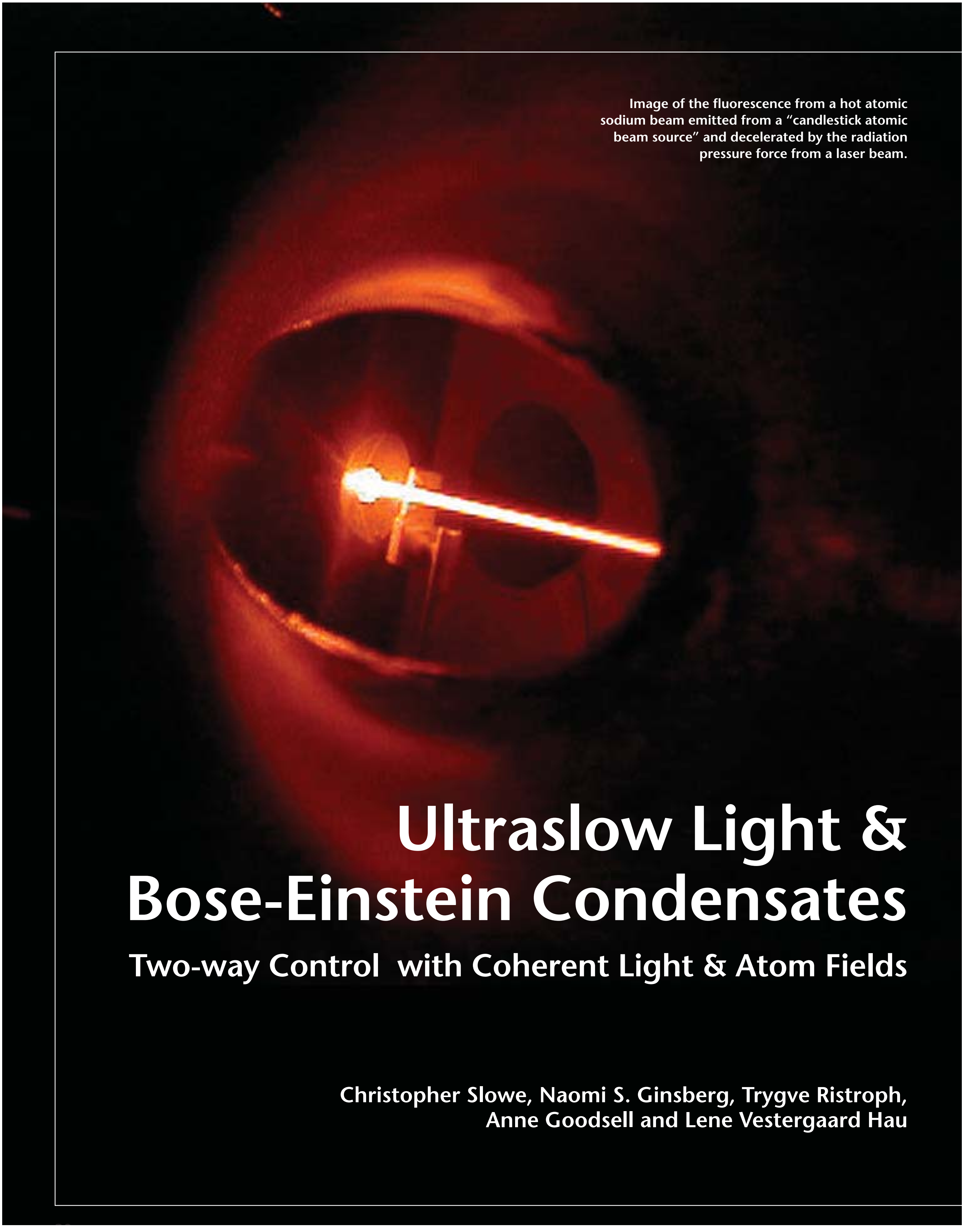

Image of the fluorescence from a hot atomic sodium beam emitted from a "candlestick atomic beam source" and decelerated by the radiation pressure force from a laser beam.

Ultraslow Light & Bose-Einstein Condensates

Two-way Control with Coherent Light & Atom Fields

Christopher Slowe, Naomi S. Ginsberg, Trygve Ristroph,
Anne Goodsell and Lene Vestergaard Hau

Ultraslow light has been used to form dramatic new nonlinear excitations in superfluid Bose-Einstein condensates of laser-cooled alkali atoms, and to create pulsed coherent matter waves. We describe these phenomena and a novel single-atom detector for use in studying the waves' coherence properties.

Alkali atoms (Li, Na, K, Rb, Cs) have one valence electron, which makes them spectrally similar to hydrogen and ideal for laser cooling experiments. The interaction of the outermost electron with a resonant light field can cause excitation of an atom that will subsequently decay back to its ground state. Due to absorption of a single photon, the atom recoils with a velocity of a few mm/s in the direction of the illuminating light beam, as each photon carries momentum $h\nu/c$ (here, ν is the laser frequency and h is Planck's constant). Within nanoseconds, the atom decays and emits a photon in a random direction via spontaneous emission, and receives a second momentum recoil.

If this cycle of absorption and spontaneous emission is repeated many times by illuminating atoms with a laser beam, all of the tiny absorption recoils add up, whereas the spontaneous emission events produce random recoils with no net contribution to the atom's motion. The result is a powerful net force on the atom, commonly referred to as the radiation pressure force; this is the basis of laser cooling. Atoms constantly exchange momentum with the laser field, which, as a result, can be used to dramatically cool an atomic sample from hundreds of K to milli-K in a matter of milliseconds.

Creation of Bose-Einstein condensates

Preparation of cold samples of atomic gases begins with creation of a magneto-optical trap (MOT). An optical molasses, which cools the atoms, consists of three counter-propagating pairs of orthogonal laser beams tuned slightly below an atomic resonance. A MOT is generated by superimposing on the optical molasses a quadrupolar magnetic field to create a confining—or trapping—potential, allowing for the collection of billions to trillions of milli-K atoms in a few seconds. At this point, laser cooling reaches its limit because the randomness of spontaneous emission combined with the corpuscular nature of the photon becomes a hindrance to achieving lower temperatures.

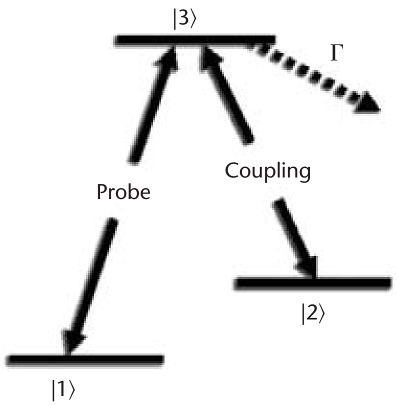

Figure 1. Energy level diagram for ultraslow light.

At this stage in the cooling process, a second technique known as evaporative cooling is employed. In much the same way as a cup of coffee cools, the faster, higher-energy atoms are preferentially forced to leave a confining electromagnetic trap while the remaining atoms are allowed to collide and rethermalize. By successively removing only the hottest atoms, the remaining atoms have, on average, less energy, and the temperature of the sample will drop. Housed in an ultrahigh-vacuum chamber, these ultracold gases can remain trapped for minutes at a time.

The development of tools for atom cooling enabled the examination of the properties of these cold gases—which constitute a new realm of physics. Though individual atoms are typically thought of as classical point particles with well defined positions and momenta, the wave nature of matter becomes obvious at very low temperatures where the deBroglie wavelength associated with each atom is macroscopically large. When the deBroglie wavelength becomes comparable to the inter-atomic spacing, atoms lose their individuality, forming a Bose-Einstein condensate (BEC). In this state, a collection of millions of atoms can then be described as a single entity: a coherent matter field.

BECs have intriguing properties similar to those of superfluids and superconductors, and we can draw a strong analogy between an atom field and the coherent electromagnetic field of a laser. Using ultraslow light in a BEC, we have created a pulsed atom laser and exotic nonlinear excitations in Bose condensates.

Ultraslow light with coherent atoms

Ultraslow light is a consequence of a destructive quantum interference between the probability amplitudes for two separate absorption-emission paths to and from the excited state, $|3\rangle$, of the three-level system of internal atomic energy levels (Fig. 1). This destructive interference prevents absorption and causes the atoms to remain in a "dark state," a coherent superposition of the two ground states, $|1\rangle$ and $|2\rangle$. A coupling laser, resonant with the $|2\rangle$ to $|3\rangle$ transition, illuminates the atom cloud. As a result, when a pulse of probe light resonant with the $|1\rangle$ to $|3\rangle$ transition enters the cloud of atoms, it is transmitted with minimal loss and can be detected on the other side after a significant temporal delay.

The superposition state is governed by the relation $\Psi_2/\Psi_1=-\Omega_p/\Omega_c$, where Ψ_2 and Ψ_1 represent the population amplitudes of atoms in states $|2\rangle$ and $|1\rangle$, and Ω_p and Ω_c are proportional to the probe and coupling electric fields amplitudes. As a probe pulse propagates through the BEC of atoms prepared in $|1\rangle$ and illuminated by the coupling laser, the dark state ensures that a coherent shadow pulse of atoms partly in $|2\rangle$ follows along, like a moving hologram imprinted in the atomic medium. This phenomenon is demonstrated visually in Fig. 2(a). Our applications of ultraslow light take full advantage of this property.

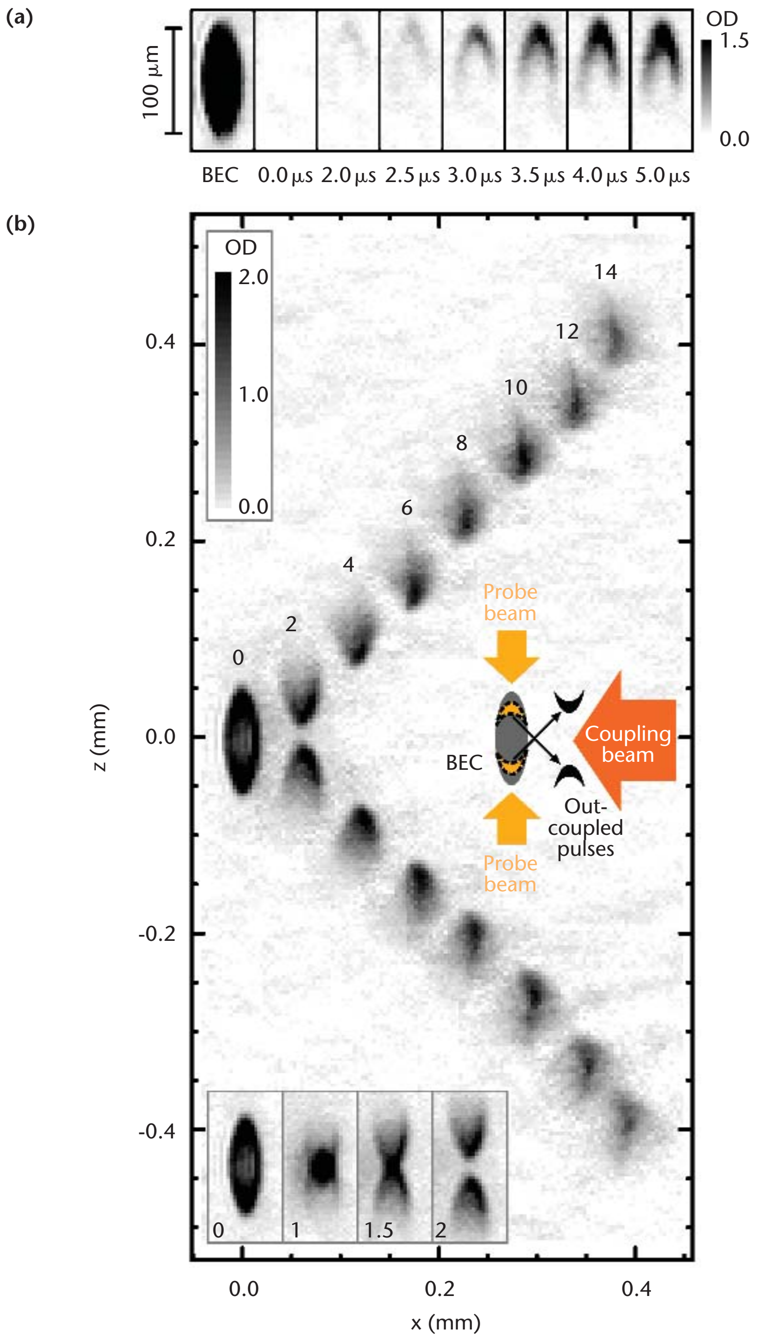

Figure 2. (a) Direct observation of the slowing and spatial compression of a light pulse in a BEC. The figure shows the accumulation of atoms in $|2\rangle$ as a probe light pulse enters a BEC of $|1\rangle$ atoms illuminated by a coupling laser. The atomic imprint, left as a hologram in the cloud, is imaged with a resonant laser beam. A complete absorption image of an undisturbed BEC is shown on the left, as a reference. (b) Pulsed atom laser. Outcoupled condensates of $|2\rangle$ atoms are resonantly imaged at the times indicated (in milliseconds). The diagram on the right shows the orientation of the probe and coupling laser beams as well as the imprints of the probe pulses and the direction in which they are outcoupled. The top inset is the optical density scale bar. In the bottom inset we show some close-up frames in the time interval from t=0 to t=2 ms in which the two pulses cross through one another.

The dispersion curve experienced by the probe light as a result of the coupling beam illumination of the atom cloud has an incredibly steep slope around resonance. This leads to a dramatic reduction of the group velocity for the light pulse, by factors of tens of millions.[1] The group velocity can be controlled by—and is in fact proportional to—the intensity of the coupling beam. As the light pulse enters the atom cloud, the front edge slows while the back edge—still in free space—catches up. Ultimately, the probe pulse is spatially compressed by the same factor by which it is slowed—from a length of several kilometers to tens of microns—and fits entirely inside the cloud. By abruptly turning off the coupling laser, the slowly moving light pulse stops and turns off, but leaves the holographic imprint frozen in the cloud.[2]

If the atom cloud is a fully coherent BEC, we can use it to manipulate the stored light pulse. When we stop the light pulse, we can use electric- and magnetic-field controlled interactions among atoms in the condensate to process the imprinted optical information during the storage time. By subsequent revival of the light pulse, we can read back the processed information into the light field.[3] For this process, we use a geometry in which the probe and coupling beams co-propagate, introducing a negligible two-photon recoil due to absorption of one laser field and emission into the other.

On the other hand, we use the coherent laser fields to manipulate coherent samples of atoms. Working with the coupling and probe laser beams in an orthogonal geometry allows us to impart a significant two-photon recoil to the atoms during the imprinting process. In fact, we have used this set-up to produce a pulsed atom-laser by coherently transferring Bose-condensed atoms from one internal quantum mechanical state ($|1\rangle$) to another ($|2\rangle$), which is repelled from the electromagnet.[4]

Figure 2(b) shows a light-stopping experiment performed in a Bose-Einstein condensate, with two probe pulses incident on the condensate from opposite directions. The light pulses are stopped in the atom cloud just before they collide, resulting in an imprint with a double boomerang shape (0 ms). The photon

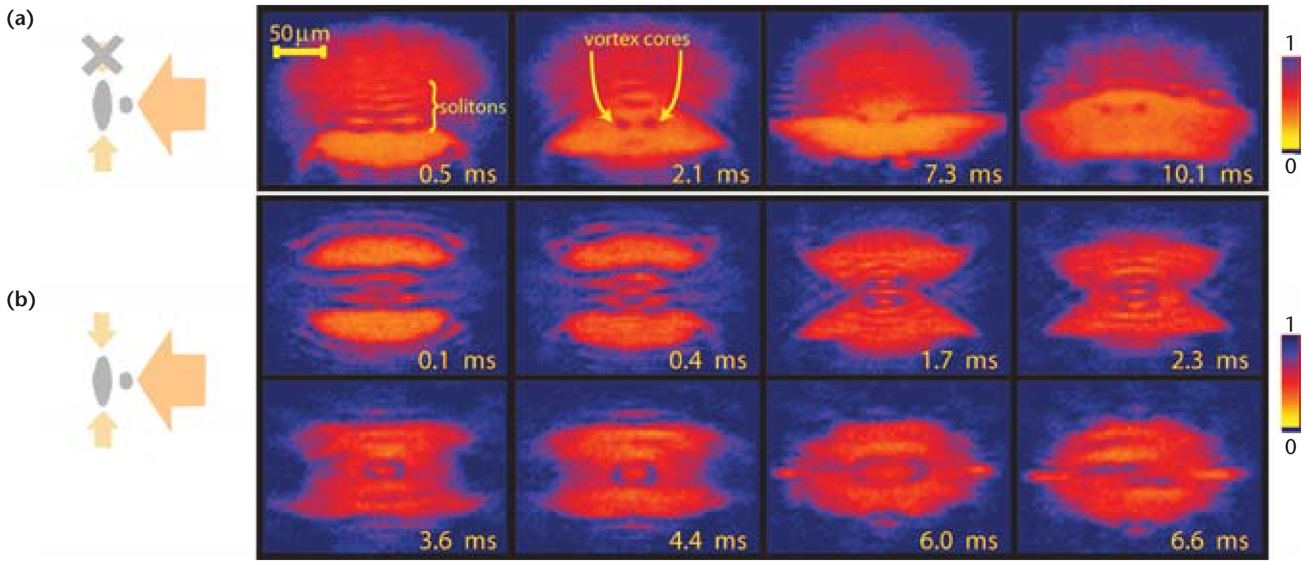

Figure 3. Non-linear excitations in a superfluid BEC. Each image represents the optical transmission of a resonant imaging beam through the central cross-section of a BEC that has been injected with slow-light pulses, allowed to evolve in the magnetic trap for the time indicated, and then released from the trap to expand for 19.9 ms: (a) nonlinear excitations in BECs generated using a single light roadblock, and (b) generation and evolution of hybrid soliton vortex-ring structures in BECs, seeded from sub-optical-resolution density defects created in the atom cloud at a double light roadblock. [Ref. 7.]

recoil received by the transferred atoms determines the directions in which the atom imprints are outcoupled from their original cloud. As a result, the two boomerangs shoot out at +45° and -45°, each with a velocity of 4.2 cm/s. This shows very directly that the process is fully coherent: to have reached $|2\rangle$, the atoms absorbed a probe photon and emitted a coupling photon through stimulated emission.

Nonlinear waves in BECs

We can also create sub-optical-resolution holes in the middle of 100-µm-long BECs by spatially engineering the coupling laser beam—a technique we call the light roadblock.[5] This strategy significantly enhances the spatial compression of slowed light pulses. By rapidly ramping down the coupling field in space, the group velocity of a light pulse hitting the roadblock further decreases and the pulse compression increases proportionally.

Thus, the probe width will decrease to only a few micrometers. Again, as a consequence of the dark state, a large fraction of atoms originally prepared in $|1\rangle$ are driven into the untrapped state, $|2\rangle$, at the light roadblock, and are subsequently shot out of the condensate. This causes a deep depletion of $|1\rangle$ atoms in a very confined region of the BEC.

After the condensate receives this puncture, the atom–atom interaction potential in the cloud causes it to behave like a quantum fluid, flowing this way and that, as it has been perturbed far from its equilibrium state. The quantum nature of the BEC fluid is manifested in part by its ability to flow without any viscosity; it is, therefore, called a superfluid. Many nonlinear excitations can evolve from the initial defect as a result of the interatomic density-dependent potential.

For example, solitons can develop and propagate in the medium, much like optical solitons in fibers. Unlike the solitons traditionally created in one-dimensional systems, the multidimensional solitary waves that we create appear as density depressions rather than enhancements, and they are unstable against the transverse density variations in the BEC[6] [Fig. 3(a)]. Therefore, we can induce the decay of solitons into either pairs of oppositely circulating vortex filaments, like tiny tornadoes, or vortex rings that resemble smoke rings or tornadoes wrapped up on themselves.

Adjusting the density of the fluid also adjusts its degree of nonlinearity and makes it possible to force the solitons to interact with vortex rings and form recently discovered intricate hybrid structures[7] [Fig. 3(b)]. These structures are dynamic excitations: they are soliton-like shells of low density with embedded vortex rings. Because the vortex rings are found inside the shells, it is difficult to pick them out visually. However, the flow fields created by the vortex rings make them identifiable as they contribute to the flexing and overall movement of the structures. The ability to create, observe and describe these micrometer-sized structures inside a BEC demonstrates the current degree of control that may be achieved in quantum fluid dynamics.

Single-atom detector: a “PMT” for atoms

Recently, significant effort in cold-atom physics has been focused on the development of atom-optics: the creation of atom beams that behave in ways analogous to optical beams—such as the

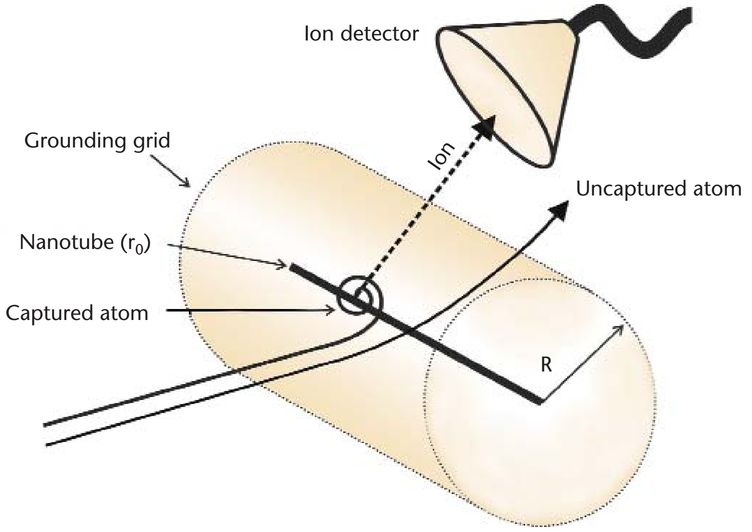

Figure 4. Schematic of the single-atom detector. A large, highly localized electric field surrounds the positively biased carbon nanotube. A neutral atom, with angular momentum below a critical value proportional to the voltage on the wire, will spiral in toward the nanotube and subsequently field ionize. The ejected ion is readily detected and counted.

pulsed-atom laser. As another example, atom interferometers form the basis for state-of-the-art gyroscopes and gravitometers. Therefore, it is necessary to develop tools for making the same kinds of measurements in quantum atom-optics experiments as those now common in quantum-optics research.

We have developed the design for a single-atom detector,[8] the atom equivalent of a photomultiplier tube (PMT) or avalanche photodiode; like these devices, our detector counts particles with single-atom resolution. Although the PMT has served as a mainstay of optics for decades, the atom-optics toolbox has lacked a compact, high quantum-efficiency, low-power single-atom detector. Just as the biased, optically active, low-work-function surface of a PMT converts photons to electrons that are then avalanche multiplied, a biased single-wall nanotube can be used to convert a neutral atom to an ion via field ionization with nearly 100 percent efficiency, and a channelton electron-multiplier can subsequently detect the ion.

Figure 4 illustrates the geometry of this type of detector. The nanotube's small size and robustness allow low voltages to be applied to the tube and create electric fields large enough to field-ionize an incident atom just before it hits the nanotube surface. The atom detector has a species-dependent voltage threshold at which the electric field becomes sufficient to strip an electron from the atom and yield an ion. This is similar to the energy or frequency threshold set by the work function in a PMT, based on the principles of the photoelectric effect.

The nanotube detector has the added advantage of high spatial and temporal resolution, as the field ionization occurs within a nanometer of the nanotube surface and the system has very low capacitance.

Further, because the static electric field of the nanotube creates a $1/r^2$ attractive potential for a polarizable neutral atom, the cross-section for ionization—and thus, the total ionization rate—depends on the angular momentum for atomic motion around the nanotube. Quantum mechanics restrict angular momentum to integer multiples of Planck's constant, and the ion counting rate as a function of bias voltage is, therefore, expected to increase in discrete jumps. Laser-cooled atoms are required for achieving sufficiently high resolution to distinguish individual steps of this "quantum ladder." Studies of the quantum ladder are interesting in their own right because they reveal at a macroscopic level the atomic DeBroglie matter waves associated with atoms spiraling around the nanotube.

The behavior of atoms exposed to a combination of laser beams and static-electric fields from the voltage-biased nanotube is highly sensitive to voltage, laser frequency and internal state of the atoms. The use of optical pumping of atoms in dc field gradients around nanostructures could prove extremely important for optically controlled read/write operations in a quantum information processor based on trapped atoms around nanotubes.

Outlook

The coupling of coherent electromagnetic and atomic-matter fields allows for the ultimate control of light with matter and vice versa. The marriage of Bose-Einstein condensation and ultraslow light has led to far-reaching physics, such as pulsed-atom lasers with spatially controlled output modes, and the discovery of intricate nonlinear excitations in superfluids.

The next generation of optical communication may exploit some of the unprecedented optical control and processing capabilities provided by this system. The steep refractive index profiles associated with slow light give rise to nonlinear refractive index effects some 12 orders of magnitude larger than those found, for example, in optical fibers.

Christopher Slowe (slowe@physics.harvard.edu), Naomi S. Ginsberg, Trygve Ristroph, Anne Goodsell and Lene Vestergaard Hau are with the physics department and the Division of Engineering and Applied Sciences at Harvard University. The work was supported by AFOSR, NASA, NSF and ARO (MURI program).

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