

Magnetic Forces Need Not Apply: Bose-Einstein Condensates Can Be Made in an Optical Trap

It's not a simple matter to cool a gas of atoms and confine it tightly enough that all the atoms enter a single quantum state, known as a Bose-Einstein condensate (BEC). It took years of effort before the feat was finally accomplished in 1995, using an approach that requires both magnetic fields and laser beams to slow and trap the atoms. (See *PHYSICS TODAY*, August 1995, page 17, and March 1996, page 18.) Laboratories around the world now routinely probe the fascinating behavior of BECs using the same basic approach, which relies on the interaction between a magnetic field and the ground state magnetic dipole moment of the atoms to trap atoms during the final cooling step.

But not all atoms are amenable to being held in a magnetic trap: Atoms that lack an unpaired outer electron, for example, are impervious to magnetic fields. So the search for a more versatile way to form a BEC has continued. Success was reported by Murray Barrett, Jacob Sauer, and Michael Chapman of Georgia Tech at the annual meeting of the American Physical Society's division of atomic, molecular, and optical physics, held in May in London, Ontario.¹

The technique, in which the final cooling is done in an optical trap, has generated considerable excitement. "It's very fast, it avoids a number of loss processes inherent in magnetic traps, and—best of all—it looks downright easy," remarked Carl Wieman of JILA and the University of Colorado, Boulder. Wolfgang Ketterle of MIT added that an optical trap has a very simple geometry. To gain the advantages of doing experiments in an optical trap, Ketterle's group routinely transfers a BEC from a magnetic trap, where it's formed, into an optical trap. An optical trap also opens the possibility of forming condensates of non-magnetic atoms, of molecules, and of several spin states of the same atom.

Evaporative cooling

In magnetic traps, atoms in a particular spin state are brought to BEC temperatures by evaporative cooling, a technique that selectively ejects the hottest atoms from the trap, leaving the cooler ones behind. The atoms are confined in an effective potential well created

Researchers have found a way to make a BEC that is quicker, possibly simpler—and applicable to a wider variety of atoms.

by the magnetic fields. Lowering the walls of the potential well can cause the more energetic atoms to spill over the sides. Alternatively, applying a radio-frequency field can selectively address only those atoms at the edge of the trap—the most energetic atoms—flipping their spins and ejecting them from the trap.

Evaporative cooling works in a similar manner for an optical trap, which is simply a tightly focused laser beam. Evaporation in an optical trap occurs as the laser power is reduced. Atoms (regardless of spin state) are attracted to the regions of highest intensity in such a beam because of electric dipole forces. These beams are far from any atomic resonance. In fact, the frequency of the carbon dioxide laser used by the Georgia Tech group is so low compared to the resonant frequency that the atoms essentially see a DC field. One advantage of light tuned far from resonance is that it does not scatter off the atoms and hence does not heat them.

In 1995, Steven Chu and his coworkers at Stanford University demonstrated evaporative cooling in an optical trap using an ytterbium aluminum garnet (YAG) laser; Chu's group reduced the temperature of sodium atoms to about 4 μ K, although the experiment fell short of achieving the phase-space density needed for condensation.² (Phase space density—spatial density multiplied by the cube

of the de Broglie wavelength—is basically a measure of how nearly the atoms overlap; it must equal 2.6 to form a BEC.) Chu's group used not one but two crossed beams, at right angles to one another. His group has continued to pursue the optical route to BEC, as have a number of other groups. David Weiss (who moves soon from Berkeley to Penn State) has come close to the phase-space density required for a BEC by using cesium atoms, a pair of crossed beams and evaporative cooling.³ (Another group has gotten high densities by Doppler cooling strontium atoms.⁵)

The Georgia Tech team used a crossed-beam arrangement (see figure 1) to evaporatively cool a different atom—rubidium-87—with a lower frequency CO₂ laser. The first step in the Georgia Tech approach, and in most methods of generating a BEC, is to reduce the temperature of the gas enough and get its density high enough that it can be loaded into the optical trap. This initial cooling is done in a magneto-optic trap (MOT), which features a weak magnetic field and three orthogonal pairs of laser beams, with members of each pair pointed toward one another. With this arrangement, an atom moving in any direction whatsoever will always have a velocity component toward at least one of the six lasers. These cooling lasers are tuned slightly below the atomic resonance, so that atoms moving toward them see the light as Doppler-shifted into resonance. Atoms absorb these oppositely directed photons and get a momentum kick that slows their movement.

The second stage is evaporative cooling, which occurs in the optical dipole trap. The first-stage MOT and second-stage optical trap do not occupy physically separate spaces. The extreme detuning of the CO₂ lasers permits the optical trap to be present even during the Doppler cooling stage of the MOT. To "transfer" atoms into the optical trap, the experimenters can simply turn off the magnetic field and the near-resonance lasers, leaving atoms in the grip of the far-off-resonance crossed beams.

Georgia Tech's optical trap produced a condensate of ⁸⁷Rb atoms in about two seconds, ten times faster than typical

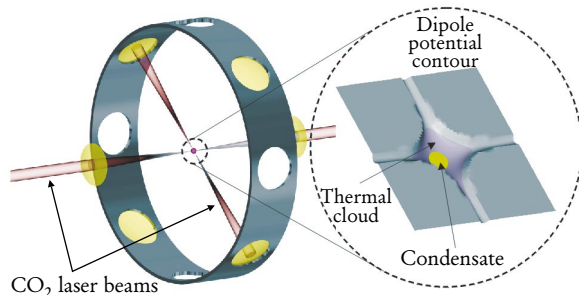


FIGURE 1. OPTICAL TRAP consists of two CO₂ laser beams focused by lenses (yellow) to a small spot in the trap center. The atoms are trapped by the lasers' dipole potential (see enlargement) and are cooled by evaporation as the laser power is lowered. The condensate appears in the center of the thermal cloud. (Courtesy of Jacob Sauer.)

evaporation cycles in magnetic traps. The shorter evaporation time means that the trap does not need to hold the atoms in the trap nearly as long. The condensate itself has a 3-s lifetime, which is long enough to accomplish most BEC experiments.

As illustrated in figure 2, the BEC produced was measured by the absorption of light shone through the freely expanding condensate; the regions of greater absorption, signaling a higher density of atoms, are shown in red. The plot shows the spatial distribution, but the distance traveled by an atom in the condensate was directly proportional to the momentum it had when released from the trap. The signature of a BEC is the sharply peaked momentum distribution seen in the third panel.

John Thomas of Duke University told us that some researchers had doubted whether optical cooling would work because they thought the evaporative cooling might shut down when the trap power got too low. But, he notes, the phase space density in the Georgia Tech experiment appears to increase with decreasing trap depth according to a scaling law developed by his group. (Thomas and his colleagues have been working on a CO₂ laser trap for a number of years.)

What's the secret?

In their paper, Chapman and company attribute their success in part to the high densities they achieve as they load the gas from the MOT into the optical dipole trap, before the final, evaporative cooling. Most observers have in fact been surprised at the high density that was reported: 2×10^{14} atoms/cm³, or almost an order of magnitude higher than others had gotten in loading from a MOT.⁴ The high density is a puzzle that remains to be explained.

Thomas and his coworkers speculate that the high density arises in part from a high ratio of trap depth to loading temperature and from the formation of a dark trap, which inhibits the scattering from the cooling beams

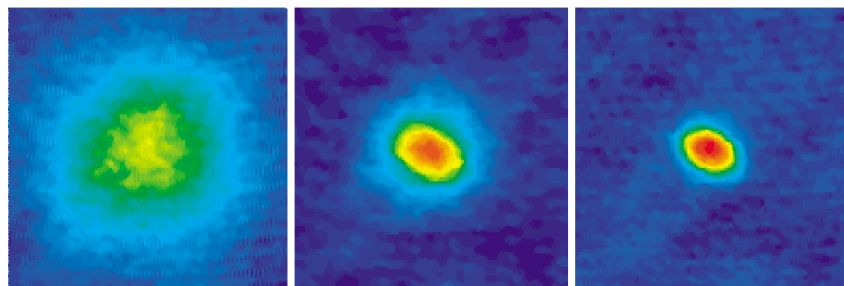


FIGURE 2. THE ATOMIC CLOUD seen by absorptive imaging 10 ms after being released from an optical dipole trap. The cloud had a thermal distribution when the laser power during evaporative cooling was reduced to 480 mW (left); included a group of atoms with the same momenta (middle) when the laser power was taken down to 260 mW, signaling that some of the atoms have entered a condensate; and looked like a pure condensate (right) for a final power of 190 mW. Each panel measures 350 μm on a side. (Adapted from ref. 1.)

that normally limits the maximum density. Rainer Scheunemann of the Max Planck Institute for Quantum Optics in Garching, Germany, adds that "perhaps the crossed dipoles constitute an ideal experimental realization of a trap, because the place where the atoms accumulate is also the place where they scatter the fewest photons. This agrees well with our findings⁴ of high densities (in the range of 10^{13} atoms/cm³) in an optical lattice formed by CO₂ lasers."

Weiss wonders whether the real key to success isn't the rubidium atoms themselves. ⁸⁷Rb can be cooled evaporatively more readily than other atoms and it has proved itself in many BEC experiments; its large elastic scattering rate is essential to evaporative cooling, and its low inelastic scattering rate helps minimize losses.

Could the use of CO₂ lasers account for the success of the Georgia Tech team? CO₂ lasers are farther from resonance than YAG lasers and they are known to be exceptionally stable; both factors can minimize heating of the trapped atoms. This question is still open.

Applications

Chapman thinks the optical trap offers lots of experimental opportunities. One is the chance to study a BEC

that consists of multiple spin states; the ⁸⁷Rb condensate they formed, for example, consisted of the three spin projections $m_F = -1, 0, 1$ of the $F = 1$ hyperfine ground state. A short-term goal of Chapman and his colleagues is to understand the observed population of the three spin states in their experiment. Longer term, Chapman and his colleagues hope to use optical traps to explore quantum entanglement in the BEC systems, perhaps by exploring the interaction between such condensates and single photons in cavity quantum electrodynamics.

Another possible application of the optical trap is to form a molecular BEC, because the CO₂ lasers trap molecules just as well as they trap atoms. Thomas is hoping that the recent success with ⁸⁷Rb atoms bodes well for his group's attempt at an optical route to a degenerate Fermi gas.

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Solid Acids Show Potential for Fuel Cell Electrolytes

In the quest for alternative sources of energy, one active area of exploration is fuel cells. These devices use the same net oxidation reaction as burning, but by spatially separating the reactants, fuel cells convert chemical energy directly into electrical energy instead of generating heat as an intermediary (see the review by

Solid acids can have high proton conductivities. Recent experiments demonstrate that they may be sufficiently stable to form the core of new, higher efficiency fuel cells.

Sivan Kartha and Patrick Grimes in *PHYSICS TODAY*, November 1994, page 54). So fuel cells have the potential to

be a clean and efficient means of electrical energy production.

A critical part of a fuel cell is the electrolyte, which conducts ions between the cell's electrodes but is impervious to electrons. Electrons must instead flow around the electrolyte and can power external loads. There are many different approaches