New Atom Lasers Eject Atoms or Run CW

> Recently, a Munich atom laser ran continuously for 100 ms until it ran out of condensate. And a NIST atom laser shot out atoms with a chosen velocity.

The experimental observation of Bose–Einstein condensation (BEC) in rubidium in 1995 demonstrated that a macroscopic number of bosons could be produced in a single quantum state of trapped atoms. The occupation of a single quantum state by a large number of identical bosons is the matter-wave analog of the storage of photons in a single mode of a laser cavity. In a conventional laser, one extracts a coherent beam of photons from a cavity by using a partially transmitting mirror as an output coupler. In 1997, Wolfgang Ketterle and his collaborators at MIT built a pulsed output coupler that extracted matter waves from a condensate, and they observed interference between atoms from two separate condensates, thereby demonstrating an atom laser for the first time (see PHYSICS TODAY, March 1997, page 17).

Recently, Theodor W. Hänsch and his collaborators at the University of Munich and the Max Planck Institute for Quantum Optics in Garching reported the first atom laser that operates continuously—until it runs out of condensate 100 ms later. Meanwhile, William D. Phillips and his collaborators at the National Institute of Standards and Technology (NIST) have made a quasi-continuous atom laser that doesn't rely on gravity but instead ejects atoms from the condensate with a chosen velocity. Both atom lasers have promising applications in atom optics. A third, related experiment, by Mark Kasevich and Brian Anderson at Yale University, combines laser fields and condensates to produce a string of atom pulses that behaves somewhat like a mode-locked laser.

"A true CW [continuous wave] atom laser requires refilling atoms into the trap; that remains a major challenge," says Ketterle. "But at least we now have continuous or quasi-continuous output couplers, which will be a crucial element for a future continuous atom laser."

Munich CW output coupler

Hänsch, Immanuel Bloch and Tilman Esslinger produce a Bose–Einstein condensate in a novel magnetic trap that provides an extremely stable trapping potential, which fluctuates only at the submilligauss level.[1]

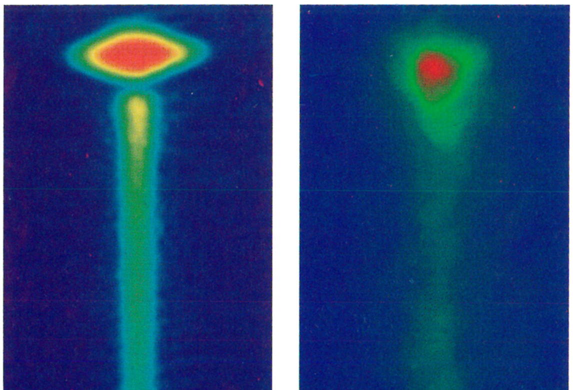
The simple, low-power magnetic trap, called a "quadrupole-Ioffe-configuration" (QUIC) trap, uses only three coils. The Munich team takes magneto-optically trapped ^{87}Rb atoms, loads them into a magnetic quadrupole and then smoothly converts the field into the parabolic geometry of a Ioffe trap. During the process, the trapped atomic cloud moves close to one of the magnet coils, yielding tight confinement. The trap is placed inside a box that reduces the magnetic field of the environment and its fluctuations by a factor of about 100, below 0.1 mG. CW output coupling, as done in the Munich experiment, can only be achieved if the field fluctuations are minimized, and, in particular, they need to be much less than the change of the magnetic trapping field over the spatial size of the condensate.

To produce BEC, the group traps 10^9 atoms in a magneto-optical trap, then transfers the cold atoms into the magnetic QUIC trap and further cools them by RF-induced evaporation. To extract the atoms from the condensate, the group switches on for 15 ms a weak RF field accurate to a few kilohertz. The resonance at which the atoms can be coupled out is only a few kHz wide. For continuous output coupling, the trapping field must be sufficiently stable that the resonance doesn't drift from the applied RF.

The figure at left shows the collimated atomic beam derived from the BEC over a 15-ms period of continuous output coupling. To obtain an output beam over a longer period, the team reduces the magnetic field amplitude of the RF field.

The brightness of the atom laser beam is defined as the integrated flux of atoms per source size divided by the velocity spreads in each dimension. Just as a laser is enormously brighter than a thermal or other incoherent light source, an atom laser is enormously brighter than a thermal or incoherent atom source. The Munich group estimates its laser's brightness to be at least 2×10^{24} atoms s^2 m^{-5}. For comparison, says Hänsch, the brightness of the atom sources used to feed the atom laser is six to eight orders of magnitude lower than the atom laser's brightness.

"The de Broglie wavelength of our single-frequency atom laser beam changes with height as the atoms are accelerated by gravity," says Hänsch. "After the atoms have dropped the first millimeter, the wavelength has shrunk to about 30 nm. This small and changing wavelength makes it nontrivial to measure the longitudinal coherence of the atom laser beam by



ATOM LASER OUTPUTS. Height shown corresponds to 2.5 mm (Munich) and 1.4 mm (NIST). Munich beam (left) is derived from condensate (red and yellow ellipse at top) over 15-ms period when CW output coupler lets atoms escape coherently from magnetic trap. (Courtesy T. Esslinger, Munich.) NIST beam (right) is produced by firing 140 Raman pulses in synchrony with the 20 kHz frequency of the rotating bias field. Individual pulses are highly overlapped. (Courtesy S. Rolston, NIST.)

optical means." He speculates that one could reflect the atom beam back on itself with an atom mirror and observe the resulting standing wave pattern. Or, one could build a suitable Fabry–Pérot or Michelson interferometer for matter waves. "Although we don't have experimental proof, we expect the wavefunction of each atom to be spread out over the entire length of the atom laser beam, making it a quantum object of truly macroscopic dimensions as long as we don't measure the atom position. The coherence time of our present atom laser is likely limited by mechanical noise and residual magnetic field fluctuations to something like 1 millisecond."

Since their paper was sent to *Physical Review Letters,* the Munich group has experimented with turning on the output coupler before BEC occurs. "With continued evaporative cooling of the laser medium of uncondensed atoms, the atom laser reaches threshold, proving that there is gain at least equal to the roundtrip losses of the magnetic atom cavity. Unlike a Bose–Einstein condensate in thermal equilibrium, our atom laser is now operating with matter-wave amplification by stimulated emission of radiation, says Hänsch. "I feel certain that some clever tricks can be found to continuously replenish the reservoir of cold atoms so that we can realize a true CW atom laser."

NIST highly collimated atom laser

At NIST, Edward Hagler, Lu Deng, Mikio Kozuma, Jesse Wen, Kristian Helmerson, Steven Rolston and Phillips have reported a well-collimated quasi-continuous atom laser.[2] Unlike the MIT and Munich atom lasers, says Phillips, the NIST output coupler "pushes the atom out of the condensate in a chosen direction. So we avoid the spreading."

The NIST experimenters extract sodium atoms from a trapped Bose–Einstein condensate using stimulated Raman transitions between magnetic sublevels. In contrast to the MIT and Munich experiments, in the NIST work, says Rolston, when the atoms are transferred to a magnetic sublevel unaffected by the trapping potential, they're also given a momentum kick from the photon recoil. So, says Ralston, "atoms acquire a well-defined momentum much larger than their initial momentum spread, and they exit the trap in a well-defined beam whose direction and velocity are governed by the details of the Raman laser." That means it's possible to choose the energy of the extracted de Broglie wave.

The team employs a hybrid evaporation technique involving a time orbiting potential (TOP) trap to form the condensate. About 10^6 atoms are produced in a single state, the $3S_{1/2}$, F=1, m = −1 state. After they form the condensate, the experimenters adiabatically expand the trapping potential in 0.5 s by simultaneously changing the magnetic field gradient and the rotating bias field, resulting in an RMS momentum width of the released condensate of 0.09 $\hbar k$.

Compared to methods such as RF output coupling, the Raman output coupling scheme reduces the transverse momentum width of the extracted atoms by a factor of more than 20, says Rolston. For atoms coupled out of a spherically symmetric trap without an initial momentum kick, the repulsion due to atom–atom interactions causes an isotropic momentum spread. But in the NIST experiment, this release energy gets channeled primarily in the forward direction, producing a highly collimated output beam.

To produce quasicontinuous output coupling, the group used multiple Raman pulses. In the results shown in the figure on page 17, since the frequency is an integral multiple of the 20 kHz output coupling repetition rate, the interference of successive pulses was almost completely constructive. In the time between two Raman pulses, each output-coupled wave packet moved only 2.9 μm, much less than the 50 μm size of the condensate. So, says Rolston, "the individual pulses were highly overlapped, forming an essentially continuous coherent matter wave." The NIST group needed to use pulses because the TOP trap had a time-varying magnetic field. Says Phillips, "In a static trap, the outcoupling could be done continuously." He adds that extracting atoms with momentum can substantially increase the laser's brightness because it reduces the velocity spreads.

Yale's AC Josephson effect analog

In the experiment[3] done by Anderson and Kasevich at Yale, they created a BEC and produced coherent pulses. To do so, they laser-cooled and trapped atoms into a magnetic TOP trap, and evaporatively cooled them until they Bose-condensed about 3×10^4 atoms. Then the experimenters transferred the condensate into the standing wave of a laser field, a so-called optical lattice, and they turned off the magnetic trap. The condensate atoms, along with their macroscopic wavefunction, were held in the laser field, spread across many potential wells. Due to gravity, atoms tunneled out of the wells and "fell down." Because of the coherence of the condensate atoms, the atoms leaking out from different wells interfered, resulting in periodic pulses of coherent matter waves. By adjusting the depth of the optical wells, the experimenters could control the tunneling rate from the wells so that it was fast enough to observe the atoms leaving the traps, but slow enough to directly observe many periods of the temporally modulated signal. The pulse frequency is determined by the gravitational potential energy difference between adjacent potential wells. This macroscopic quantum interference from atomic tunnel arrays, the Yale team says, is closely related to the AC Josephson effect observed in superconducting electronics. Anderson and Kasevich regard their experiment as an atom laser whose coherence length (greater than 500 μm) greatly exceeds the dimensions of the resonator.

The difference between the Yale experiment and those at MIT and at NIST, says Ketterle, is that at Yale, "the pulsing happened by itself—self oscillations of the condensate," yielding a string of atom pulses, analogous to a mode-locked laser, in which the laser produces a train of pulses.

Applications

What next for atom lasers? It's conceivable that one could produce diffraction-limited atomic beams that could be focused down to a spot size much less than 1 nm, according to the Munich experimenters. And, they suggest, one could create atom interferometers with large enclosed areas and excellent signal-to-noise ratios, making them eminently suitable for precision measurements. In all such applications, however, the atom interactions would play a limiting role in the usable atom flux.

The NIST experimenters believe that their approach, too, may be useful in observing matter-wave interference, which would be valuable for studying spatial phase variations. Furthermore, they suggest it could be used in quantum chemistry to study collisions between atoms in well-defined internal states with a well-defined relative momentum.

Kasevich and Anderson have already used their technique to measure the acceleration due to gravity, and, says Kasevich, "We have the potential to do very much better."

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References

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