

A Continuous Source of Bose-Einstein Condensed Atoms

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A continuous source of Bose-Einstein condensed sodium atoms was created by periodically replenishing a condensate held in an optical dipole trap with new condensates delivered using optical tweezers. The source contained more than 1×10^6 atoms at all times, raising the possibility of realizing a continuous atom laser.

The gaseous Bose-Einstein condensate (BEC) is a macroscopic quantum system with analogies to superconductors, superfluids, and optical lasers (1, 2). However, unlike these other systems, BECs have so far been only produced in pulsed mode. As with optical lasers, pulsed operation has less stringent technical requirements. In the optical domain, the leap from a pulsed ruby laser (3) to a more complex continuous wave (CW) helium-neon laser (4) took only about 6 months, whereas for atomic condensates, it has taken considerably longer to produce a continuous source of coherent atoms. Such a source is the most crucial prerequisite for realizing continuous atom lasers.

The challenge in realizing a continuous BEC source originates in the extreme parameter space covered during a typical cooling cycle required for BEC production, which consists of laser cooling followed by evaporative cooling. During optical cooling, atoms scatter around 10^7 photons/s, whereas during evaporative cooling any photon scattering would cause heating and trap loss and, therefore, has to be less than 10^{-1} photons/s. During evaporative cooling, atoms are cooled by a factor of a thousand from about $100 \mu\text{K}$ to sub-microkelvin temperatures. This requires a near-perfect isolation of the hot atoms from the cold, because a single laser-cooled atom has enough energy to knock thousands of atoms out of the condensate.

Until now, little progress has been made toward continuous Bose-Einstein condensation. Early theoretical work considered the realization of a continuous-atom laser using optical pumping of incoming atoms into the laser mode (5, 6). More recently, evaporative cooling of a slow atomic beam from the typical phase-space density of laser cooling (10^{-6}) into quantum degeneracy has been suggested (7). Experimental work has so far

only addressed the production and guiding of a beam of laser-cooled atoms (8–10).

Our approach in this work is based on our recent realization of moving optical tweezers for BECs (11, 12). Here, we use the tweezers to transport sodium condensates from where they are produced into a reservoir trap. The freshly produced condensates periodically replenish the condensate in the reservoir trap, thereby continuously maintaining a condensate of more than 10^6 atoms.

Merging of two separate condensates with a random relative phase into one condensate requires dissipation to damp out the excitations caused by the merger. Assuming that the merger creates a solitonlike excitation at the interface of the two condensates, the excitation energy per atom is approximately equal to the chemical potential times the ratio of the healing length to the condensate size. In our experiment, this energy was typically on the order of a nanokelvin and could be dissipated by evaporative cooling with a only a small loss in the number of condensed atoms.

Periodic Replenishment of an Optical Trap

The continuous reservoir was an optical trap located in the “science chamber” of the experimental apparatus that has been described in detail in (11). Condensates were produced in the “production chamber” by a combination of laser cooling and evaporative cooling (1). The magnetically trapped condensate was then adiabatically decompressed and transferred into the focus of the tweezers beam (13). The optical traps for both the tweezers and the continuous reservoir were produced with focused infrared (1064 nm) laser beams with similar trap parameters. The intensities of the beams were controlled independently with two acousto-optic modulators, and the beams were spatially filtered by separate single-mode fibers. The laser beam for the tweezers was expanded and focused by a 500-mm achromatic lens placed on an air-bearing translation stage. Fifty mW of laser power focused to $1/e^2$ beam waist radius of $w_0 = 26 \mu\text{m}$ created a cigar-shaped trap with a radial trapping frequency of 440 Hz

and a depth of about $2.7 \mu\text{K}$. Translation of the 500-mm lens moved condensates in the focus of the tweezers beam by ~ 0.3 m from the production chamber into the science chamber (11). The condensates were transported in 1.25 s and held for 1 s to allow condensate excitations to damp out; only small residual dipole oscillations remained.

The optical axis of the laser beam for the continuous reservoir was parallel to the tweezers beam with a vertical displacement of about $70 \mu\text{m}$, which was sufficient to ensure that the two traps did not affect each other before the merger. The vertical distance between the two traps was controlled by tilting a glass slide in the optical path of the laser beam for the reservoir (Fig. 1A). Condensates held in the tweezers beam were transferred into the reservoir by slowly lowering the reservoir trap to the position of the tweezers focus over 0.5 s (see Fig. 1, B to H). The intensity of the tweezers beam was then linearly ramped to zero in another 0.5 s, and the reservoir was raised back to its original position. Within the next 18 s, a new condensate was produced, transported into the science chamber, and merged with the condensate reservoir. This cycle was repeated many times, and thus, a continuous source of condensed atoms was realized.

The number of atoms in both optical traps was determined from absorption images taken after ballistic expansion (Fig. 1, I and J). Pure condensates with negligible thermal fraction were observed in both traps. Figure 2 demonstrates the continuous presence of more than a million condensate atoms in the reservoir. The optical tweezers delivered a fresh condensate with 2.0×10^6 atoms in each replenishment cycle. Before the merger, the number of condensed atoms in the reservoir had decayed to 1.0×10^6 atoms and grew to 2.3×10^6 atoms after the merger. These numbers were obtained from a simultaneous exponential fit for the three cycles after the first cycle (Fig. 2), with a statistical error of 0.05×10^6 atoms. Therefore, the merged condensate is significantly larger than each of the two condensates before the merger. During the 18 s production and transfer cycle, the condensate in the reservoir decayed with a $1/e$ lifetime of 22 ± 1 s, limited by background pressure.

Overcoming Technical Problems

To maintain a continuous BEC reservoir while making a new condensate, several problems had to be addressed: stray resonant light during laser cooling, stray magnetic fields during laser and evaporative cooling, fast production of condensates in the production chamber, and merging of two condensates without excessive heating and atom loss.

Stray resonant light scattered by the atoms trapped in the magneto-optical trap

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(MOT) was detrimental to the condensed atoms stored in the reservoir. This light had a direct line-of-sight to the reservoir through the 1-cm aperture separating the production and science chambers. At a distance of about 0.3 m from the MOT, an estimated 1 mW of isotropically scattered resonant light leads to photon scattering rates of several Hz, and indeed, we observed an immediate loss of the condensate in the reservoir when this light was not blocked by a mechanical shutter. The shutter consisted of a simple aluminum plate that covered the aperture between the two chambers during the 2 s that the MOT was on. It was operated with a pneumatic linear actuator using ultrahigh vacuum bellows. Unfortunately, during the motion of the shutter, some residual gases were released, which increased the background pressure, limiting the lifetime of the atoms in the science chamber to 22 s.

Due to this relatively short lifetime, the production cycle for condensates had to be short-

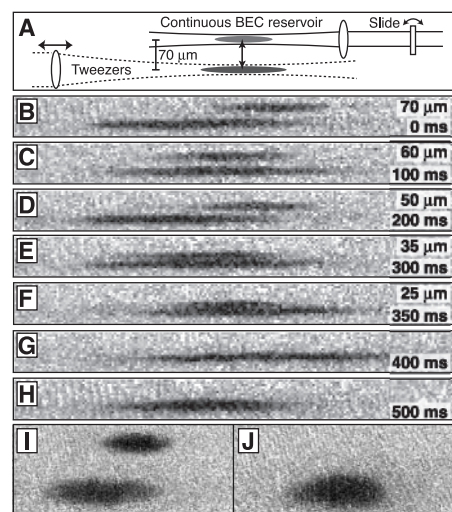


Fig. 1. Merging of two condensates. (A) Arrangement of the two optical traps. Both optical traps were horizontal. The focus of the tweezers beam was translated about 0.3 m from the production chamber to the science chamber. The tweezers beam placed a new condensate $70\ \mu\text{m}$ below the condensate held in the reservoir. The merging of the two condensates was accomplished by tilting a glass slide, which translated the reservoir laser beam vertically. The schematic is not drawn to scale. The absorption images (B to H), taken after 2 ms of ballistic expansion, show the approach and merging of the two condensates. The distance between the two traps and the elapsed time are given. In (G) and (H), the traps overlapped. (I) is an absorption image before the merger with 12 ms of ballistic expansion for the condensate trapped by the tweezers and 9 ms for the condensate in the continuous reservoir. (J) is an absorption image after complete merger, with 12 ms of ballistic expansion. The field of view is $0.2 \times 4.2\ \text{mm}$ (B) to (H) and $0.7 \times 1.7\ \text{mm}$ (I) and (J).

ened from the usual 35 to 12 s. This was achieved primarily by shortening the evaporation cycle from 30 to 9 s. The shortened cycle reduced the typical condensate number before the transfer into the tweezers beam to 6×10^6 atoms, which is a factor of three lower than our usual operating conditions. Nonetheless, the number of condensed atoms transported to the science chamber did not change noticeably. The smaller condensates suffered from less three-body loss during the transfer from the magnetic to the tweezers trap.

It was essential to use an optical-dipole trap for the continuous condensate source, because atoms in optical traps are insensitive to stray magnetic bias fields produced during the condensate production cycle. We initially tried to hold atoms in the science chamber in a magnetic trap (12), but the atoms were lost when the magnetic fields for the “Zeeman slower” and the MOT were switched on and displaced the center of the magnetic trap. Another problem with a magnetic trap is its long range. Magnetic forces would accelerate the condensate in the tweezers as it approached the magnetic trap, and the new condensate would collide violently with the condensate in the reservoir. Optical traps, on the other hand, have a more limited trap volume and depth. Hence, we could bring the condensates as close as the traps’ beam waist before they were affected by each other’s presence.

Condensate atoms in the reservoir were immune to magnetic bias fields, but not to stray field gradients, because the atoms were in the magnetically sensitive $|F = 1, m_F = -1\rangle$ hyperfine state. However, no detrimental effects were observed during BEC production, consistent with gradient fields measured to be below 100 mG/cm. We also produced a continuous BEC source containing atoms in the magnetically insensitive $|F = 1, m_F = 0\rangle$ hyperfine state. For that, a Landau-Zener sweep (1) transferred condensate atoms from the $m_F = -1$ to the $m_F = 0$ state after the condensate was loaded into the tweezers beam in the production chamber. The number of condensed atoms in

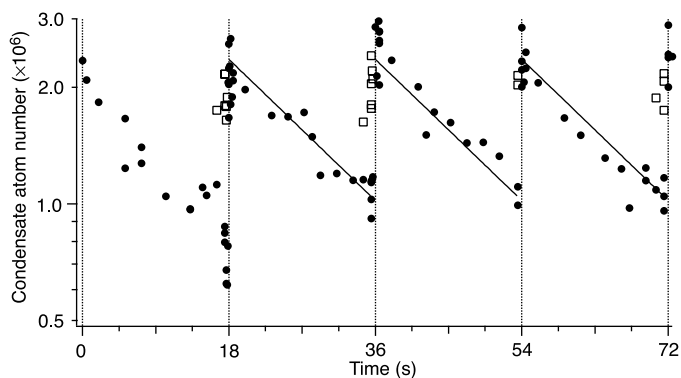
the reservoir trap was similar to the number measured for $m_F = -1$ atoms.

Finally, the key step in realizing a continuous condensate source was adding the freshly prepared condensates to the reservoir trap with minimal excitations of the condensate. It was critical to merge the condensates along the tightly confining radial direction. The large radial trap frequencies ($>400\ \text{Hz}$) ensured that the merger could be done quickly and yet be almost adiabatic and that the radial excitations during the merger could be damped out quickly. The collinear arrangement and the similar trapping frequencies ensured good overlap and “mode matching” during the merger of the two traps. After careful optimization of all parameters, condensates could be merged with a 25% loss in the total atom number (Fig. 2). These losses are due partially to three-body recombination in the combined trap and partially to the dissipation of excitations caused during the merger. The finite trap depth of the optical trap ensured dissipation by evaporative cooling.

In a preliminary experiment, we showed that it was also possible to merge two condensates in a crossed dipole configuration, where the axis of the tweezers beam was perpendicular to the reservoir trap. We produced a continuous BEC source in this configuration as well, albeit with atom numbers lower by an order of magnitude. We observed rapid loss of atoms when the two traps overlapped, possibly due to three-body recombination resulting from increased density.

In principle, multiple replenishments of a condensate could lead to a vast improvement in the size of the condensates. With an improved lifetime in the science chamber, the condensate number would increase after each merge, whereas we reached equilibrium after just two fillings due to the limited lifetime of 22 s. However, the accumulation of more atoms in an optical trap will increase the density, and therefore, the loss of atoms by inelastic processes. This loss could be mitigated by an increase in trap volume, as was realized using cylindrical optics (14, 15). With such improvements, it

Fig. 2. A continuous source of Bose-Einstein condensed atoms. The solid circles in the semi-log plot represent the atom number in the continuous reservoir, and the open squares show the number of condensate atoms transferred from the production chamber. The dashed lines indicate the beginning of a new cycle, and the solid lines are exponentially decaying curves determined by a simultaneous fit to the three cycles after the first cycle. The number of atoms for each data point was obtained from a separate absorption image, similar to the ones in Fig. 1, I and J.



should be possible to transfer condensates containing more than 10^7 atoms and accumulate more than 10^8 atoms in the continuous source. This would be larger than any condensate produced thus far using the standard combination of laser cooling and evaporative cooling.

Outlook: Condensate Phase and CW Atom Lasers

An interesting aspect of the continuous BEC is its phase. So far, the phase evolution of condensates have been traced only over sub-second time intervals (16, 17). A measurement of the phase of the continuous BEC source would require separating a small part of the source as a local oscillator and maintaining its phase over the duration of the entire experiment. Although this seems to be out of the reach of current experiments, one may speculate on how the phase would evolve during replenishment of a condensate. The freshly prepared condensates have a random phase relative to the condensate in the reservoir trap, and therefore, in the current experiment, the phase of the source after replenishment will be random relative to the phase before the merger. However, in the limit of a large continuously held condensate merging with a smaller condensate, one would expect the phase of the large condensate to dominate. Each replenishment would create some excitation, and relaxation would result in a condensate with a slightly modified phase, a process reminiscent of phase diffusion in an optical laser. This and other aspects of the merger warrant future theoretical studies, such as of phase coherence, dissipation, and the role of quantum tunnelling during the merger.

In principle, it would be possible to re-

plenish a stationary continuous BEC source with an incoming moving condensate using phase coherent amplification (18, 19). While a stationary source overlaps with a moving condensate dressed by a laser beam, light scattering could phase-coherently amplify the condensate in the reservoir using atoms from the moving condensate. In this scheme, the necessary dissipation is provided by the optical pumping process.

All atom lasers to date (16, 20–22) have operated in a pulsed mode. Coherent streams of atoms were generated until a single condensate was completely depleted. Using our continuous BEC source, one could implement CW-outcoupling and create a truly continuous atom laser. By varying the intensity of the outcoupling field with some feedback, one could compensate for the cyclic variation in the density of the continuous BEC source, thereby outcoupling a continuous atomic-matter wave with constant amplitude. The optical analog of this configuration would be a pulsed laser that delivers photons to an external storage cavity from which a CW laser beam is then extracted. Although a long storage time for photons is not feasible, it is straightforward for atoms. Furthermore, the merger of several pulses requires dissipation and cooling, and therefore interactions, which are present between atoms, but not between photons.

Conclusion

In this work, techniques were developed to produce a new condensate in proximity to another condensate and to merge condensates. We have used these techniques to create a continuous source of Bose-Einstein condensed atoms.

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23. Funded by the Office of Naval Research, NSF, Army Research Office, NASA, and the David and Lucile Packard Foundation. A.E.L. acknowledges additional support from NSF. We thank Z. Hadzibabic for a critical reading of the manuscript.

12 April 2002; accepted 8 May 2002

REPORTS

Coherent Spin Oscillations in a Disordered Magnet

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Most materials freeze when cooled to sufficiently low temperature. We find that magnetic dipoles randomly distributed in a solid matrix condense into a spin liquid with spectral properties on cooling that are the diametric opposite of those for conventional glasses. Measurements of the nonlinear magnetic dynamics in the low-temperature liquid reveal the presence of coherent spin oscillations composed of hundreds of spins with lifetimes of up to 10 seconds. These excitations can be labeled by frequency and manipulated by the magnetic fields from a loop of wire and can permit the encoding of information at multiple frequencies simultaneously.

Magnetic solids offer arrays of quantum degrees of freedom, or spins, that interact with each other in a manner and strength ranging from the long-range ferromagnetism of iron and nickel to the nano-antiferromagnetism of vortices in high-temperature superconduc-

tors. Unfortunately, there is a large barrier to exploiting quantum effects in magnetic solids; namely, the rarity of coherence effects that can be simply manipulated and observed (1). In particular, it is difficult to create the magnetization oscillations corresponding to

prepared superpositions of states, which are so straightforwardly created in liquid-phase nuclear magnetic resonance experiments. The “decoherence” for the solid magnets is generally attributed to disorder and to the coupling of the electronic spins to other degrees of freedom, such as nuclear spins, atomic motion, and conduction electrons. Here we describe coherence effects in a magnet, $\text{LiHo}_{0.045}\text{Y}_{0.955}\text{F}_4$, which is highly disordered but does not suffer from coupling to either conduction electrons or to atomic motions, because it is a strongly ionic insulator with the spins derived from small, nonoverlapping electronic orbitals.

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