Optical Confinement of a Bose-Einstein Condensate

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Bose-Einstein condensates of sodium atoms have been confined in an optical dipole trap using a single focused infrared laser beam. This eliminates the restrictions of magnetic traps for further studies of atom lasers and Bose-Einstein condensates. More than 5×10^6 condensed atoms were transferred into the optical trap. Densities of up to 3×10^{15} cm^{-3} of Bose condensed atoms were obtained, allowing for a measurement of the three-body loss rate constant for sodium condensates as $K_3 = 1.1(3) \times 10^{-30}$ cm^6 s^{-1}. At lower densities, the observed $1/e$ lifetime was longer than 10 s. Simultaneous confinement of Bose-Einstein condensates in several hyperfine states was demonstrated.
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The recent realization of Bose-Einstein condensation [1–3] and of an atom laser [4,5] have sparked many theoretical and experimental studies of coherent atomic matter [6]. Yet, these studies are limited by the magnetic traps used by all experiments so far. For example, in the first demonstration of an atom laser, coherent atomic pulses were coupled out into an inhomogeneous magnetic field, which served to confine the remaining condensate. Thus, during propagation, the pulses were exposed to Zeeman shifts. While these shifts were mitigated by producing $m_F = 0$ atoms, quadratic Zeeman shifts may preclude precision experiments on such pulses. Magnetic trapping also imposes limitations on the study of Bose-Einstein condensates, because only the weak-field seeking atomic states are confined. Since the atomic ground state is always strong-field seeking, weak-field seeking states can inelastically scatter into the ground state (dipolar relaxation), resulting in heating and trap loss. Furthermore, trap loss may dramatically increase through spin relaxation collisions when different hyperfine states are simultaneously trapped, restricting the study of multicomponent condensates. Although in ^{87}Rb this increase is less dramatic due to a fortuitous cancellation of transition amplitudes [7], spin relaxation is still the dominant decay mechanism for double condensates in this system.

All these problems are avoided if Bose-Einstein condensation is achieved in an optical trap based on the optical dipole force which confines atoms in all hyperfine states. This has been one motivation for the development of subrecoil cooling techniques [8,9], the development of various optical dipole traps [10–14], and for pursuing Raman cooling [15,16] and evaporative cooling [17] in such traps. The highest phase space density achieved by purely optical means was a factor of 400 below that required for Bose-Einstein condensation [15].

In this paper, we report the successful optical trapping of a Bose-Einstein condensate using a different approach: first evaporatively cooling the atoms in a magnetic trap, and then transferring them into an optical trap. This approach circumvents many difficulties usually encountered with optical dipole traps. Since the temperature of atoms is reduced through rf evaporation by a factor of 100, only milliwatts of laser power are needed as compared with several watts used to directly trap laser-cooled atoms. This ameliorates trap loss from heating processes in an optical dipole trap which are proportional to laser power, such as off-resonant Rayleigh scattering, and heating due to fluctuations in the intensity and position of the laser beam [18]. Furthermore, since the cloud shrinks while being cooled in the magnetic trap, the transfer efficiency into the small trapping volume of an optical dipole trap is increased.

The experimental setup for creating Bose-Einstein condensates was similar to our previous work [19]. Sodium atoms were optically cooled and trapped, and transferred into a magnetic trap where they were further cooled by rf-induced evaporation. The transition point was reached at densities of $\sim 1 \times 10^{14}$ cm^{-3} and temperatures of 1–$2\ \mu$K. Further evaporation produced condensates containing $5 - 10 \times 10^6$ atoms in the $F = 1, m_F = -1$ electronic ground state. The atom clouds were cigar-shaped with the long axis horizontal, and had a typical aspect ratio of 15 due to the anisotropic trapping potential of the cloverleaf magnetic trap.

The optical trap was formed by focusing a near-infrared laser beam into the center of the magnetic trap along the axial direction. For this, the output of a diode laser operating at 985 nm was sent through a single-mode optical fiber and focused to a spot with a beam-waist parameter w_0 ($1/e^2$ radius for the intensity) of about $6\ \mu$m. This realized the simple single-beam arrangement for an optical dipole trap [10–13]. The infrared laser focus and the atom cloud were overlapped in three dimensions by imaging both with a CCD camera. It was necessary to compensate for focal and lateral chromatic shifts of the imaging system which were measured using an optical test pattern illuminated either at 589 or 985 nm.

The parameters of the optical trapping potential are characterized by the total laser power P and the beam-waist parameter w_0. The trap depth is proportional to P/w_0^2. For a circular Gaussian beam with $w_0 = 6$ μm, the trap depth is 1 μK/mW [20], and the aspect ratio of the atom cloud is 27. At $P = 4$ mW, the geometric mean trapping frequency $\bar{\nu}$ is 670 Hz. The measured frequencies [see Eq. (1)] were about half the expected values, presumably due to imperfect beam quality and the coarse measurements of P and w_0 (an underestimation of w_0 by 40% would account for this discrepancy). Finally, due to the large detuning, the spontaneous scattering rate is small (5×10^{-3} s^{-1} per μK trap depth), leading to an estimated trapping time of 400 s.

Condensates were transferred into the optical trap by holding them in a steady magnetic trap while ramping up the infrared laser power, and then suddenly switching off the magnetic trap. A ramp-up time of 125 ms was chosen as slow enough to allow for adiabatic transfer, yet fast enough to minimize trap loss during the ramp-up due to high densities in the combined optical and magnetic traps. The highest transfer efficiency (85%) was observed for a laser power of about 4 mW, with a measured mean trapping frequency $\bar{\nu} = 370$ Hz [see Eq. (1)]. The transfer efficiency dropped for higher laser power due to trap loss during the ramp-up, and decreased rapidly for smaller laser power due to the smaller trap depth. The sudden switch-off of the magnetic fields was necessitated by imperfections in the trapping coils which displaced the center of the magnetic trap during a slow switch-off. This caused transient oscillations of the atom cloud and can be overcome in the future with auxiliary steering coils.

After 500 ms of purely optical trapping, the transferred atoms were probed by suddenly switching off the optical trap, and observing the freely expanding cloud using absorption imaging (Fig. 1). The strong anisotropic expansion after 40 ms time of flight is characteristic of Bose-Einstein condensates in strongly anisotropic trapping potentials.

We also loaded the optical trap with magnetically trapped atoms at higher temperatures and lower densities than those used in Fig. 1. In this case, depending on the temperature of the atoms loaded into the optical trap, we observed the sudden onset of a dense, low energy core of atoms amidst a broad background of noncondensed atoms (Fig. 2). Two aspects are worth noting. First, the number of thermal atoms ($\sim 10^4$) is small compared both to the number of atoms before transfer ($\sim 10^8$) and to the number of condensed atoms transferred under the optimum conditions described above ($\sim 10^6$). This is due to the small trapping volume and shallow trap depth of the optical trap which leads to a very small transfer efficiency for thermal atoms. In comparison, in magnetic traps, the number of noncondensed atoms at the transition temperature is much larger than the largest number of condensate atoms eventually produced [19,21]. The maxi-
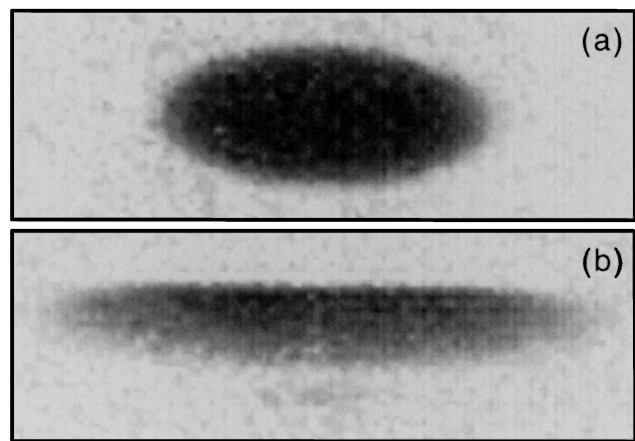

FIG. 1. Absorption images of expanding Bose-Einstein condensates, released (a) from the magnetic trap, and (b) from the optical trap ($\bar{\nu} = 370$ Hz, $P \sim 4$ mW). The faster expansion in (b) is indicative of the higher densities of the optical trap. The time of flight was 40 ms. The field of view for each image is 2.2 by 0.8 mm.

mum number of thermal atoms in Fig. 2 was measured to be 24 000, in agreement with a prediction based on the observed trap depth and trapping frequencies, and the assumption that the thermal atoms arrive at a temperature $1/10$ of the trap depth by evaporation. Second, condensates were observed in the optical trap even when there was no condensate in the magnetic trap from which it was loaded. This was due to the partial condensation of the gas during the adiabatic deformation of the trapping potential when the infrared light was ramped up. During this deformation, the entropy remained constant through collisional equilibration while the phase space density increased [22]. A detailed study of this effect will be reported elsewhere.
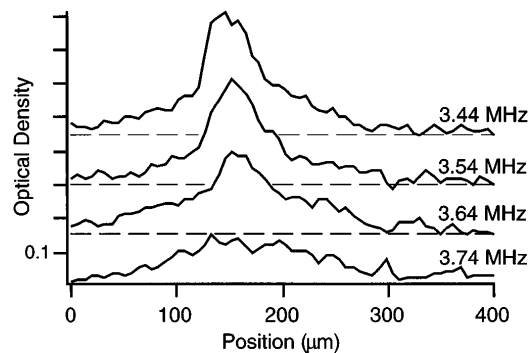

FIG. 2. Optical density profiles of optically trapped atoms at the onset of Bose-Einstein condensation. Because of the short time of flight (1 ms), the profiles show the spatial distribution along the long axis of the optical trap. Data were obtained after 125 ms of purely optical trapping. Labels give the final rf frequency used in the evaporative cooling cycle. The bimodality observed below 3.74 MHz indicates the presence of a small ($\sim 10^4$ atoms) Bose-Einstein condensate.

After the trap is switched off, the internal repulsive (mean-field) energy of the condensate is transformed into kinetic energy of the expanding cloud. This allows for the determination of peak densities n_0 and mean trapping frequencies $\bar{\nu}$ from time-of-flight data [19]. For a harmonic trapping potential in the Thomas-Fermi approximation, the average mean-field energy per atom is $2/7\, n_0\tilde{U}$, where $\tilde{U} = 4\pi\hbar^2 a/m$ is proportional to the scattering length $a = 2.75$ nm [23]. Assuming a predominantly radial expansion, the peak density was determined from the maximum velocity observed in time-of-flight images $v_{\max}$ by $n_0\tilde{U} = mv_{\max}^2/2$. The number of condensed atoms N was measured by integrating the optical density in time-of-flight images. The mean trapping frequencies $\bar{\nu}$ are related to N and n_0 by [19]

$$\bar{\nu} = 0.945\, \frac{\hbar\sqrt{a}}{m}\, n_0^{5/6} N^{-1/3}. \qquad (1)$$

The density of condensates in the optical trap was varied by either doubling or halving the infrared power in the all-optical trap, after having transferred the atoms at settings which maximized the initial transfer efficiency (see above). Thereafter, the infrared power was kept constant for lifetime studies. The peak densities achieved in this manner ranged from 3×10^{14} cm^{-3} in the weakest optical trap to 3×10^{15} cm^{-3} in the tightest. For the lowest infrared power used ($P \sim 2$ mW), atoms were observed spilling out of the optical trap, indicating that the depth of the trap was comparable to the 200 nK mean-field energy of the condensate which remained.

The lifetime of condensates was studied by measuring the number of condensed atoms in time-of-flight images after a variable storage time in the optical trap. Results are shown in Fig. 3 and compared to those for the magnetic trap. The lifetime in the magnetic trap was
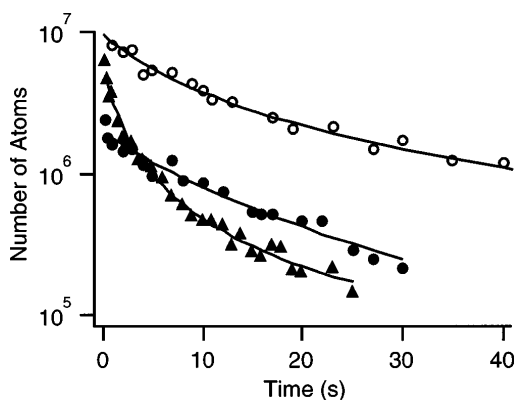

FIG. 3. Lifetime of Bose-Einstein condensates in the optical and magnetic traps. Shown is the number of condensed atoms vs trapping time. Closed triangles and circles represent data for the optical traps with the best transfer efficiency ($\bar{\nu} = 370$ Hz, $P \sim 4$ mW) and the slowest decay (weakest trap, $P \sim 2$ mW), respectively. Open circles represent data for the rf-shielded magnetic trap. Error in the number measurements is estimated as 10%. Lines are fits based on Eq. (2).

very short unless the trap depth was lowered by "rf shielding" [19,24], allowing collisionally heated atoms to escape. Similarly, the long lifetimes observed in the optical trap were made possible by its limited trap depth. The observed loss rates per atom in the optical trap ranged from 4 s^{-1} at a peak density $n_0 = 3 \times 10^{15}$ cm^{-3} to less than $1/10$ s^{-1} at $n_0 = 3 \times 10^{14}$ cm^{-3}.

The decay curves in Fig. 3 are described by

$$\frac{dN}{dt} = -K_1 N - K_3 N \langle n^2 \rangle, \qquad (2)$$

where K_1 accounts for density independent loss processes such as residual gas scattering, Rayleigh scattering, and other external heating processes, and K_3 is the loss rate constant for three-body decay. For a harmonic trap, the mean squared density $\langle n^2 \rangle$ is related to the measured peak density by $\langle n^2 \rangle = 8/21\, n_0^2$ [25].

Three-body decay was found to be the dominant loss mechanism in both the optical and the magnetic trap. By fitting the solution of Eq. (2) to the decay curves for the various optical traps we obtained $K_1 = 0.03(2)$ s^{-1} and $K_3 = 1.1(3) \times 10^{-30}$ cm^6 s^{-1}. This three-body loss rate constant for ^{23}Na is a factor of 5 smaller than for ^{87}Rb [24], and can be ascribed completely to collisions among condensed atoms due to the small number of noncondensed atoms in the optical trap. Our result lies between two theoretical predictions for the loss rate constant of $K_3 = 3 \times 10^{-29}$ cm^6 s^{-1} [26] and $K_3 = 3.9\hbar a^4/2m = 3 \times 10^{-31}$ cm^6 s^{-1} [27,28]. The loss rate due to dipolar relaxation (two-body decay) was predicted to be negligible at the densities considered [29]. While the decay curves show three-body decay to be the dominant loss mechanism, they do not exclude two-body decay rates comparable to K_1.

One major advantage of the optical trap over magnetic traps is its ability to confine atoms in arbitrary hyperfine states. To demonstrate this, the atoms were put into a superposition of $F = 1$ hyperfine states by applying an rf field which was swept from 0 to 2 MHz in 2 ms. Parameters were chosen in such a way that the sweep was neither adiabatic nor diabatic, similar to our work on the rf output coupler [5]. The distribution over hyperfine states was analyzed through Stern-Gerlach separation by pulsing on a magnetic field gradient of a few G/cm during the 40 ms time of flight. Figure 4 demonstrates that all three states were optically trapped. By extending the time between the rf sweep and the probing, we confirmed that all $F = 1$ hyperfine states were stored stably for several seconds. The optical potential for the three sublevels is nearly identical, the relative difference being less than the ratio of the fine structure splitting to the large detuning (2.5×10^{-3}).

In conclusion, we have realized an optical trap for Bose-Einstein condensates. Because of the low energy of the condensates, just milliwatts of far-detuned laser radiation were sufficient to provide tight confinement.
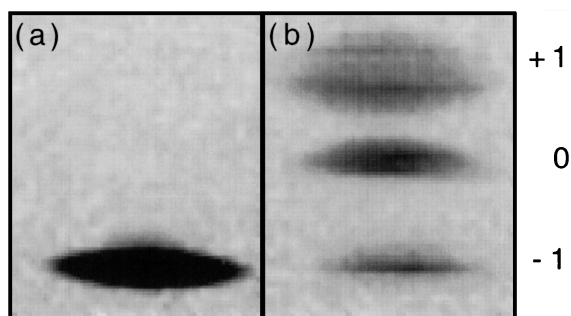
FIG. 4. Optical trapping of condensates in all $F = 1$ hyperfine states. Shown are absorbtion images after (a) 250 ms, and (b) 340 ms of optical confinement. Hyperfine states were separated by a magnetic field gradient pulse during the 40 ms time of flight. Atoms remain spin polarized in the optical trap (a). In (b) the atoms were exposed to an rf sweep which populated all hyperfine states, 90 ms before release from the trap. The absorption of the σ^- probe light is weaker for the $m_F = 0, +1$ states than for the $m_F = -1$ state. The field of view for each image is 1.6 by 1.8 mm.

More than five million condensed atoms were trapped, and lifetimes comparable to those in our dc magnetic trap were observed. Densities of 3×10^{15} cm^{-3} were achieved, unprecedented for both Bose condensates and for optically trapped atomic clouds. High densities and high condensate fractions allowed for a determination of the three-body loss rate constant in sodium as $K_3 = 1.1(3) \times 10^{-30}$ cm^6 s^{-1}. This trap offers many new opportunities to study Bose-Einstein condensates and atom lasers. Since the optical trap works at arbitrary external magnetic fields, Feshbach resonances in the scattering length [30] might now be observed for strong-field seeking states. One can study condensates in superpositions of degenerate hyperfine sublevels, and, since the spin degree of freedom is no longer constrained by magnetic trapping, it may be possible to study spin waves [31] in a Bose-condensed gas. The shallow and well controlled trap depth allows for new output-coupling schemes [32]. Finally, the optical trap may also serve as an "optical tweezers" to move condensates, and, for example, place them in optical and microwave cavities and close to surfaces.

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