All-Optical Formation of an Atomic Bose-Einstein Condensate

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(Received 10 May 2001; published 19 June 2001)

We have created a Bose-Einstein condensate (BEC) of ^{87}Rb atoms directly in an optical trap. We employ a quasielectrostatic dipole force trap formed by two crossed CO_2 laser beams. Loading directly from a sub-Doppler laser-cooled cloud of atoms results in initial phase space densities of $\sim 1/200$. Evaporatively cooling through the BEC transition is achieved by lowering the power in the trapping beams over ~ 2 s. The resulting condensates are $F = 1$ spinors with 3.5×10^4 atoms distributed between the $m_F = (-1, 0, 1)$ states.

DOI: 10.1103/PhysRevLett.87.010404 PACS numbers: 03.75.Fi, 03.67.–a, 32.80.Pj

The first observation of Bose-Einstein condensates (BEC) in dilute atomic vapors in a remarkable series of experiments in 1995 [1–3] has stimulated a tremendous volume of experimental and theoretical work in this field. Condensates are now routinely created in over 30 laboratories around the world, and the pace of theoretical progress is equally impressive [4]. The recipe for forming a BEC is by now well established [5,6]. The atomic vapor is first precooled, typically by laser cooling techniques, to sub-mK temperatures and then transferred to a magnetic trap. Further cooling to BEC is then achieved by evaporatively cooling the atoms in the magnetic trap using energetically selective spin transitions [7].

All-optical methods of reaching the BEC phase transition have been pursued since the early days of laser cooling. Despite many impressive developments beyond the limits set by Doppler cooling, including polarization gradient cooling [8], velocity selective coherent population trapping [9], Raman cooling [10–12], and evaporative cooling in optical dipole force traps [13–15], the best efforts to date produce atomic phase space densities $n\lambda_{dB}^3$ a factor of 10 away from the BEC transition [15]. The principal roadblocks have been attributed to density-dependent heating and losses in laser cooling techniques, residual heating in optical dipole force traps or the unfavorable starting conditions for evaporative cooling. Hence, optical traps have played only an ancillary role in BEC experiments. The MIT group used a magnetic trap with an "optical dimple" to reversibly condense a magnetically confined cloud of atoms evaporatively cooled to just above the phase transition [16]. Additionally, Bose condensates created in magnetic traps have been successfully transferred to shallow optical traps for further study [17–19]. In all these cases, however, magnetic traps provided the principle increase of phase space density (by factors up to $\sim 10^6$) to the BEC transition.

In this Letter, we present an experiment in which we have created a Bose condensate of ^{87}Rb atoms directly in an optical trap formed by tightly focused laser beams. Following initial loading from a laser cooled gas, evaporative cooling through the BEC transition is achieved by simply lowering the depth of the optical trap. Our success is due in part to a high initial phase space density realized in the loading of our optical dipole trap and in part to the tight confinement of the atoms that permits rapid evaporative cooling to the BEC transition in ~ 2 s. This fast evaporation relaxes considerably the requirement for extremely long trap lifetimes typical of magnetic trap BEC experiments. Additionally, in contrast to magnetic traps which confine only one or two magnetic spin projections [20], our technique is spin independent and the condensates that we form are $F = 1$ three-component spinors [18].

We utilize a crossed-beam optical dipole force trap employing tightly focused high-powered (12 W) infrared ($\lambda = 10.6\ \mu$m) laser beams. For trapping fields at this wavelength, the trapping potential for the ground state atoms is very well approximated by $U(\mathbf{r}) = -\frac{1}{2}\alpha_g |E(\mathbf{r})|^2$ where α_g is the ground state dc polarizability of the atom (5.3×10^{-39} m^2 C/V for atomic rubidium) and $E(\mathbf{r})$ is the electric field amplitude. A significant feature of these "quasielectrostatic" traps (QUESTs) [21] is that heating due to spontaneous emission of the atoms is completely negligible. In contrast to previous QUESTs that have employed single focused beams [14,21] or standing wave configurations [22], we employ here a cross-beam geometry [13] to provide a balance of tight confinement in three dimensions (~ 1.5 kHz oscillation frequencies at full power) and a relatively large loading volume.

Our experiments begin with a standard vapor loaded magneto-optical trap (MOT). The trapping beams consist of three orthogonal retroreflected beams in the $\sigma^+ - \sigma^-$ configuration. They are tuned 15 MHz below the $5S_{1/2}$-$5P_{3/2}$ $F = 2 \rightarrow F' = 3$ transition of ^{87}Rb, and each of the three beams has a waist of 0.7 cm and a power of 25 mW. A repump beam tuned to the $F = 1 \rightarrow F' = 2$ transition is overlapped with one of the MOT trapping beams. The MOT is loaded for 5 s directly from the thermal vapor during which we collect 30×10^6 atoms. After loading the MOT, the trap configuration is changed to maximize the transfer of atoms to the optical trap. The repump intensity is first lowered to $\sim 10\ \mu$W/cm^2 for a duration of 20 ms, and then the MOT trap beams are shifted

to the red by 140 MHz for a duration of 40 ms. At this point the MOT beams are extinguished and the current in the MOT coils is turned off. In order to optically pump the atoms into the $F = 1$ hyperfine states, the repump light is shuttered off 1 ms before the trap beams are extinguished; we measure the efficiency of the optical pumping to the $F = 1$ state to be $>95\%$. The CO_2 laser beams are left on at full power (12 W) throughout the MOT loading and dipole trap loading process.

The trapping beams are generated from a commercial CO_2 gas laser ($\lambda = 10.6\ \mu$m). The beams are tightly focused and intersected at right angles; one beam is oriented in the horizontal direction and one beam is inclined at 45° from the vertical direction. Each beam passes through an acousto-optic modulator to provide independent control of the power in the two beams. Additionally, the beams are frequency shifted 80 MHz relative to each other so that any spatial interference patterns between the two beams are time averaged to zero [23]. Each beam has a maximum power of 12 W, and the beams are focused to a minimum waist $\lesssim 50\ \mu$m with $f = 38$ mm focal length ZeZn aspherical lenses inside the chamber.

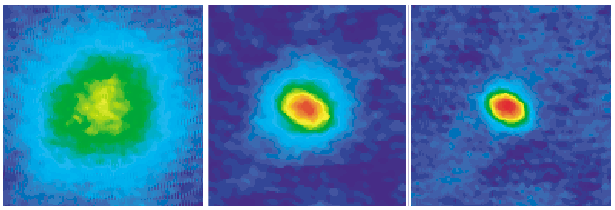
Following standard techniques, the number of trapped atoms and their momentum distribution are observed using absorptive imaging of the released atoms. The trapped atoms are released by suddenly ($<1\ \mu$s) switching off the trapping laser beams. Following a variable ballistic expansion time (typically 2–20 ms), the cloud is illuminated with a 50 μs pulse of $F = 1 \rightarrow F' = 2$ light applied to the atoms concurrent with a vertically oriented circularly polarized probe beam tuned to the $F = 2 \rightarrow F' = 3$ transition. The probe intensity is $\sim 0.3\ \mathrm{mW/cm^2}$, and each atom scatters up to 150 photons from the probe with no observable blurring of the cloud. The shadow of the atom cloud is imaged onto a slow-scan CCD camera. The measured spatial resolution of our imaging system is $\lesssim 10\ \mu$m. From these images, the number of atoms and their temperature are determined. Together with the trap oscillation frequencies (which are measured directly using parametric excitation) the spatial density, elastic collision rate, and phase space density can be derived.

We first discuss the properties of the trap following loading from the MOT without employing forced evaporative cooling. The earliest that we observe the trapped atoms is 100 ms after loading to allow for the untrapped atoms to fall away. At this time, the trap contains 2×10^6 atoms at a temperature of 75 μK. Maintaining full power in the trap beams, we observe a rapid evaporation from the trap in the first 1.5 s, during which two-thirds of the trapped atoms are lost and the temperature falls to 38 μK. The relative phase space density increases by a factor of 3 during this stage. This rapid evaporation gives way to a much slower exponential trap decay with a time constant of 6(1) s. The temperature continues to fall gradually to a final value of 22 μK on a 10 s time scale.

The mean frequency of the trap at these powers is measured to be $1.5(^{+0}_{-5})$ kHz, from which we infer an initial peak density of the trap of $\sim 2 \times 10^{14}\ \mathrm{atoms/cm^3}$. The initial phase space density following the rapid free evaporation stage is calculated to be 1/200 (or 1/600 assuming equal distribution of the atoms in the three trapped internal states). Using the measured value for the three-body loss rate [24] yields an initial three-body loss rate constant of $1.3\ \mathrm{s^{-1}}$. Hence it is possible that three-body inelastic collisions contribute to the rapid initial loss of atoms; however, we note that such collisions do not explain the observed cooling. The estimated elastic collision rate at this point is a remarkable $12 \times 10^3\ \mathrm{s^{-1}}$—higher than the trap oscillation frequency. Although the derived quantities must be taken with some caution, we note that densities of $3 \times 10^{13}\ \mathrm{atoms/cm^3}$ and a phase space density of 1/300 have been reported in a 1D CO_2 lattice trap with ^{85}Rb (albeit with much fewer atoms) [25], and we have measured similar results in our laboratory in 1D CO_2 lattice traps with ^{87}Rb. It is not clear what yields these extremely high initial densities in these traps at these low temperatures. A blue detuned Sisyphus process is suggested in [25] (densities of $\sim 10^{13}\ \mathrm{atoms/cm^3}$ have been observed in a dipole trap with blue detuned Sisyphus cooling [26]), but we suspect that there is an effective dark MOT [27] in the repump beam at the trap center induced by the ac Stark shift due to the dipole trap beams, which reduces density-limiting interactions with the MOT light fields. Using our trap parameters, we estimate that the repump scattering rate is reduced at the trap center by a factor of 40 relative to outside the trap. Our improved performance even relative to the 1D lattice traps may be due to more efficient loading from the "tails" of the crossed trap geometry. In any case, the net result for our trap is a very high initial phase space density combined with a large number of atoms and a fast thermalization time—together these conditions provide a very favorable starting point for evaporative cooling.

Efficient forced evaporation requires selectively ejecting the more energetic atoms from the trap such that the remaining atoms rethermalize at a lower temperature with a higher net phase space density. For optical traps, the simplest way to force evaporation is to lower the trap depth by decreasing the power in the trap beams. This technique was used in one of the first demonstrations of evaporative cooling in alkali atoms [13], where, starting with only 5000 atoms, a phase space density increase of ~ 30 was realized. The drawback to this method is that lowering the trap depth also lowers the trap oscillation frequency and the rethermalization rate. Hence the evaporation rate can slow down prohibitively. In our case, although the rethermalization rate falls by a factor of 50 by the end of the evaporation cycle, it nonetheless remains fast enough to allow us to reach the BEC transition in 2.5 s as described below.

Our procedure for forced evaporation is as follows: immediately after loading the trap, the power in both trap



(a) (b) (c)

FIG. 1 (color). Absorptive images (false color) of atomic cloud after 10 ms free expansion for different final trap laser powers. (a) Thermal cloud above BEC transition ($P = 480$ mW), (b) thermal-condensate mixture ($P = 260$ mW), and (c) pure condensate ($P = 190$ mW). Field of view is 350 μm.

beams is ramped to 1 W in 1 s. The power in both beams is then ramped to a variable final power in 1 s and maintained at this low level for 0.5 s, after which the atoms are released from the trap and imaged as discussed above. Figure 1 shows three such images at different final powers for the trap lasers. The left image shows a cloud well above the BEC transition point, and reveals an isotropic Gaussian momentum distribution expected for a thermal cloud of atoms in equilibrium. As the evaporative cooling proceeds to lower powers, a bimodal momentum distribution appears with a central nonisotropic component characteristic of Bose condensates (Fig. 1, center). As the power is lowered further, the central, nonspherical peak of the distribution becomes more prominent, and the spherical pedestal diminishes. At a trap power of 190 mW (Fig. 1, right), the resulting cloud is almost a pure condensate and contains 3.5×10^4 atoms. For lower powers, the cloud rapidly diminishes as the trap can no longer support gravity. Line profiles of the images in Fig. 1 are shown in Fig. 2 for quantitative comparison. The profiles are taken along the orientation of the minor axis of the condensate. Also shown are Gaussian fits to the data in the wings that clearly show the bimodal nature of the momentum distributions near the BEC phase transition.

The critical condensation temperature T_c is a function of the number of atoms N and the mean trap frequencies $\bar{\omega} = (\omega_1\omega_2\omega_3)^{1/3}$ according to $k_B T_c = \hbar\bar{\omega}(N/1.202)^{1/3}$. Below the critical temperature, the condensate fraction should grow as $N_0/N = 1 - (T/T_c)^3$ [5,6]. We obtain the condensate fraction and the temperature of the normal component from 2D fits to the absorptive images using the methods described in [6]. In Fig. 3, the condensate fraction is plotted versus normalized temperature, $T/T_c(N, \bar{\omega})$ near the critical point, where we assume that $\bar{\omega}^2$ is proportional to the trap power. The agreement with the theoretical curve is reasonable given the scatter in the data. At the trap power of 350 mW, which is near the critical point, the trap contains 180 000 atoms at a temperature of 375 nK. Together with the measured trap frequencies at this power $\omega_1, \omega_2, \omega_3 = 2\pi(72, 175, 350)$ Hz, we infer a phase space density at this point of 1.4 (or 0.45 if the

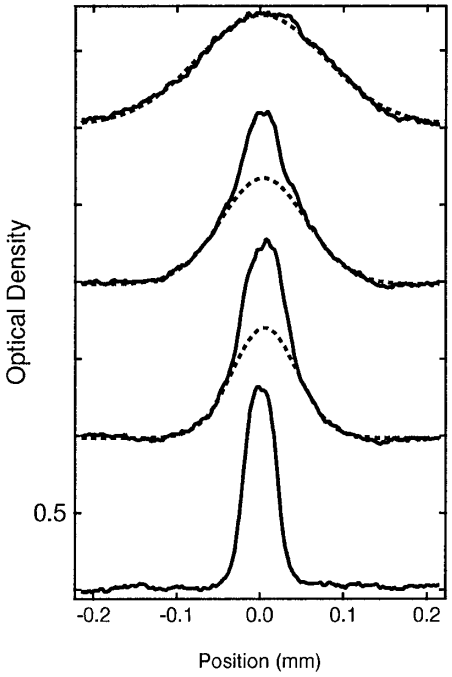


FIG. 2. One-dimensional profiles through the images of Fig. 1 (solid lines) along with Gaussian fits to the wings of the profile (dashed lines). Trap laser powers 480, 310, 260, and 190 mW, top to bottom, respectively.

three internal states are equally populated), a density of 4.8×10^{13} cm^{-3}, and an elastic collision rate of 300 s^{-1}.

We have measured the growth of the freely expanding condensate for expansion times from 5–20 ms. The measured aspect ratio of the cloud is 1.5(0.1) and shows a slight increase for longer expansion times. The measured size of the minor axis of the cloud grows linearly with time (within the limits of our imaging resolution) to a size of 100 μm (full width) at 15 ms. The observed 2D projection of the cloud is oriented at a 30° angle relative to the horizontal trap. Quantitative comparison of the observed condensates with theory requires knowledge of the trap oscillation frequencies as well as orientation of the principal axes of the trap. Although we can measure the frequencies,

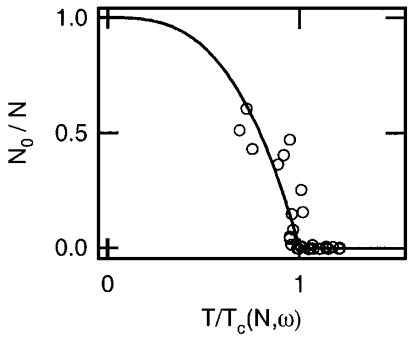


FIG. 3. (circles) Condensate fraction (ratio of condensate atoms to total number of atoms) vs scaled temperature, $T/T_c(N, \bar{\omega})$. Also shown is the theoretical prediction (solid curve).

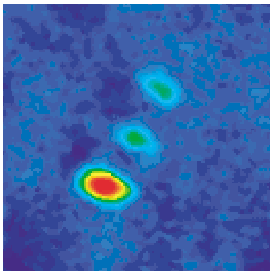


FIG. 4 (color). Absorptive image of atomic cloud after 10 ms free expansion in a Stern-Gerlach magnetic field gradient. Three distinct components are observed corresponding to $F = 1$, $m_F = (-1, 0, 1)$ spin projections from bottom to top, respectively.

the principal axes depend on the beam ellipticity and alignment. In our case, the trap beams are aberrated due to off-center propagation through the focusing lenses (required to overlap the beams), and the fact that the laser output beam is not a pure Gaussian TEM_{00} spatial mode. Nonetheless, using the measured trap frequencies, scaled for power, mean field theory (see, e.g., [4]) predicts aspect ratios of 1.2–1.7 for a 15 ms expansion and cloud sizes of $60-130$ μm, consistent with our observations.

The $1/e$ lifetime of the condensate is measured to be 3.5(1) s, which is somewhat smaller than the 6(1) s lifetime observed in the trap. We observe no residual heating of the condensate for the lifetime of the condensate, although because the trap potential is quite shallow, it is possible that any heating would be offset by subsequent evaporation from the trap.

The trapped atoms are optically pumped during loading into the $F = 1$ ground state; however, no attempt is made to further optically pump the atoms into a single m_F state. Hence we expect the population to be a mixture of the $m_F = -1, 0, 1$ spin projections. To measure the spin content of our condensate, we apply a weak field gradient to the cloud after the cloud is released from the dipole trap [18]. An absorptive image of the cloud is shown in Fig. 4, and reveals that the condensate is composed of a mixture of spin states. Each cloud has a similar nonspherical momentum distribution characteristic of condensates. Determining the relative weights of the spin states is complicated by the differing matrix elements of the probe transitions. Nonetheless, if we assume that the atoms are all optically pumped by the circularly polarized probe and that all atoms scatter the same number of photons, we infer a 3:1:1 weighting of the $m_F = -1, 0, 1$ mixture, respectively, for the image shown in Fig. 4.

In summary, we have realized a Bose condensate of ^{87}Rb atoms directly in an optical trap. This technique seems promising for creating and studying more complex spinor condensates (e.g., ^{85}Rb, $F = 2$ [28]) as well as multiatom mixtures. Additionally, by eliminating the need for a magnetic trap, it may be possible to realize condensates in atoms or molecules lacking a suitable magnetic moment, perhaps by using sympathetic cooling to precool the sample. Finally, our technique offers considerable experimental simplicity and speed, easing the requirement for ultrahigh vacuum environments, and eliminating the need for strong magnetic trapping fields.

We acknowledge the technical assistance of D. Zhu and helpful discussions with T. A. B. Kennedy, C. Raman, S. Yi, and L. You. This work was supported by the National Security Agency (NSA) and Advanced Research and Development Activity (ARDA) under Army Research Office (ARO) Contract No. DAA55-98-1-0370.

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