PHYSICAL REVIEW A **71**, 011602(R) (2005)

# All-optical Bose-Einstein condensation using a compressible crossed dipole trap

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(Received 15 April 2004; revised manuscript received 22 June 2004; published 10 January 2005)

We describe an all-optical method of making a $^{87}$Rb Bose-Einstein condensate (BEC). Atoms are first cooled in an optical lattice and loaded into a crossed dipole trap with 1.06 $\mu$m light. Then the density is increased by dynamically reducing the trap size, while the atoms are evaporatively cooled by reducing the light intensity. Every 3.3 s, we obtain a nearly pure BEC with $3.5\times10^5$ atoms in their lowest internal energy state.

DOI: 10.1103/PhysRevA.71.011602 PACS number(s): 03.75.Hh, 32.80.Pj, 87.80.Cc

A Bose-Einstein condensate (BEC) of an atomic gas was first produced by evaporative cooling [1] in a magnetic trap [2], and most BECs since have been made in one of several magnetic trap variants [3]. More recently, BECs have been made in optical traps of various types. These include an $^{87}$Rb BEC using crossed $CO_2$ laser beams (10.6-$\mu$m wavelength) [4], a Cs BEC in a crossed $CO_2$ laser beams plus an additional focused yttrium aluminum garnet (YAG) laser beam (1.064-$\mu$m wavelength) [5], an Yb BEC in a doubled YAG laser (532 nm) crossed dipole trap [6], an $^{87}$Rb BEC in a single focused $CO_2$ beam [7], and a Cs BEC in a two-dimensional (2D), YAG laser-based optical surface trap [8]. There are several reasons to create a BEC in an optical trap. BEC can be achieved quickly, making condensed atoms more attractive for precision measurements, where counting statistics are an issue. High current or permanent magnets are not required, which can be desirable if precision measurements will be done in the vicinity, and which allows for better optical access in the region where the atoms are condensed. Atoms in optical traps can be trapped in their lowest internal energy state, so that two-body losses can be avoided. Magnetic bias fields can be tuned without affecting the trapping, making it easier to use Feshbach resonances to tailor the evaporation path [5,9]. Finally, it is the only clear option for atoms without ground-state magnetic moments [6]. In this paper, we report the creation of a BEC of $^{87}$Rb atoms in a compressible, crossed dipole YAG laser trap. The compressibility of our trap makes loading and evaporation proceed differently from previous optical approaches to BEC, yielding larger BECs more quickly. Compared to $CO_2$ traps, the YAG trap has the practical advantage that it does not require special windows, and so is readily compatible with standard vacuum chambers, including glass or fused silica cells.

An all-optical BEC experiment needs to obtain a high enough atomic density that evaporative cooling, which is typically density limited, increases the phase-space density faster than heating and losses decrease it. Such densities have been achieved with light traps in essentially two distinct ways. In Refs. [4,6], the numerical aperture of the focused crossed dipole beams is large, so the beams diverge sharply near the waists. The result is that many more atoms are loaded into the trap's arms than into the crossing region. Atoms in the arms experience a large restoring force into the crossing region, and when they arrive, unforced evaporative cooling proceeds quickly and leaves a high-density remnant [10]. In Ref. [5] and in this work, the atoms are directly loaded into a large volume trap, and then the trap shape is dynamically changed, by an additional "dimple" laser beam [5] or a zoom lens (this work), to increase the collision rate. Because large volume traps are shallow, due to laser power limitations, this approach requires superlative high-density laser cooling. Its advantage is that more atoms can be loaded into the light trap, and those that are loaded have a higher phase-space density.

Using compression, either as implemented here, with the "dimple" trap method [5], or in the optical surface trap [8], the speed of evaporation is comparable to other optical approaches and to magnetic microtraps [11], but with at least an order of magnitude more BEC atoms. In the results presented here, a new condensate with $3.5\times10^5$ atoms is created every 3.3 s, although the lifetime of the trap is limited by the vacuum to 3 s. The path to BEC presented below is not unique to $^{87}$Rb, and should be applicable to the other species that have been optically condensed, and no doubt others as well.

The experiment proceeds as follows. We first load the atoms from an atomic beam into a magneto-optic trap (MOT). After 0.5 s, we change the MOT parameters in order to dynamically compress the trap [12]. When we reach the peak density, $1.5\times10^{12}$ atoms cm$^{-3}$, we turn off the magnetic field and turn on a three-dimensional (3D) far-off-resonant optical lattice. The lattice is blue detuned by 160 GHz and is 300-$\mu$K deep. It consists of three orthogonal linearly polarized standing waves with frequencies that differ by 100 MHz so that it is effectively linearly polarized everywhere [13]. To bind most of the atoms at sites, the lattice is first turned on suddenly to 60% of its maximum depth, which is about twice the atoms' thermal kinetic energy. Then it is turned on to its full depth in 135 $\mu$s, which is adiabatic with respect to the lattice oscillations. With the atoms now mostly bound to sites in the lattice, the MOT cooling light is turned back on, with lower power, larger detuning, and less repumping. Polarization gradient cooling in the lattice cools them to the lowest few vibrational levels [13]. After cooling, 95% of the atoms are optically pumped to the $F=1$ $m_F=1$ hyperfine sublevel. Then the lattice is adiabatically shut off, leaving them at 1.5 $\mu$K with a density of $5\times10^{11}$ atoms cm$^{-3}$, a phase-space density of $1/550$.

The atoms are released from the lattice into a superimposed crossed dipole trap, which has been previously de-

 

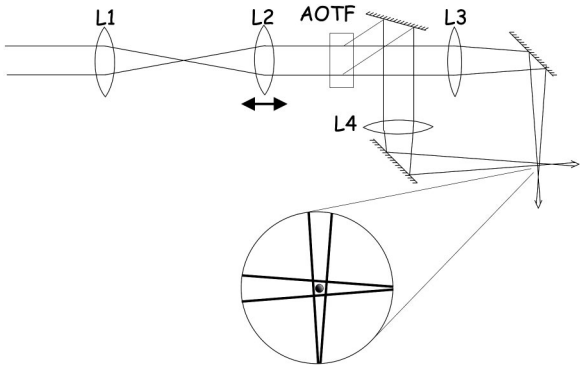


FIG. 1. Diagram of the optical system for the compressible crossed dipole trap. Computer-controlled translation of lens L2 changes the waist of the beams at their crossing point. The beams are divided and frequency shifted with an acousto-optic tunable filter (AOTF).

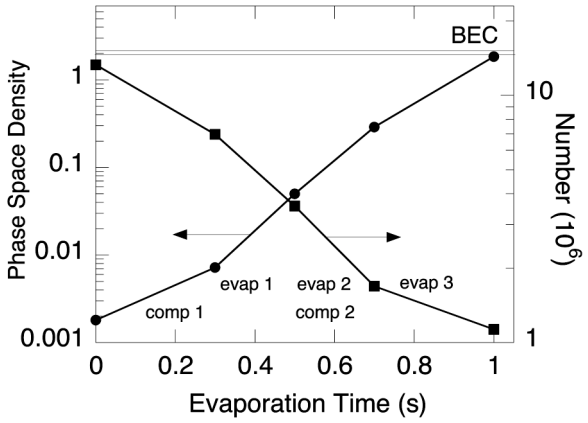


FIG. 2. Phase-space density during compression and evaporation. There are two compressions, first to 120-$\mu$m waist, then to 50 $\mu$m. Evaporation takes place in five stages, and BEC is reached immediately after the third stage.

scribed in the context of a Cs experiment [14]. Two focused YAG laser beams traveling in a horizontal plane are crossed at 90° and overlapped, as shown in Fig. 1. They are shifted by 100 MHz with respect to each other to avoid standing waves. The YAG beams, each with $P_0=3.1$ W are initially overlapped at the point where their beam waists ($e^{-2}$ radii) are 300 $\mu$m. In this 3-$\mu$K-deep trap, only the hottest atoms are not trapped by the YAG light. Because the gravitational potential-energy change across the beam waist is 31 $\mu$K $\times k_B$, it is necessary to use a vertical gradient magnetic field to cancel out gravity for the $F=1$, $m_F=1$ atoms. The required field gradient, plus a 23-G bias field for optical pumping, is made using unbalanced currents in the MOT's anti-Helmholtz coils.

The YAG beams are in a lens configuration as shown in Fig. 1, so we can dynamically change the size of the trap [14]. After loading, one lens is moved by 5.4 mm in 0.6 s, in two stages. The result is that the beam waist, $w$, is reduced in the overlap region to 50 $\mu$m, so that the trap volume $V$ is decreased by a factor of 200. As a result, the thermalization time decreases, and therefore the rate of evaporative cooling dramatically increases.

We can derive the decrease in thermalization time by simple scaling laws. Without evaporation, when trap compression is accomplished by adiabatically changing the beam waists, the ratio of the temperature of the atoms to the depth of the trap does not change [14]. This is straightforward to prove. With fixed laser power, the depth of the trap, $U \propto w^{-2}$. To the extent that the potential is harmonic, the trap oscillation frequency, $\omega \propto \sqrt{U} w^{-1}$. Adiabatic changes mean that atoms stay on average in the same vibrational states, so the temperature, $T \propto \omega \propto \sqrt{U} w^{-1} \propto w^{-2}$, the same dependence as $U$. Thus $T/U$ remains constant. The phase-space density, $\rho \propto nT^{-3/2}$, where $n$ is the spatial density, also stays fixed during adiabatic changes in the same shape trap. Therefore $n$ increases when $w$ is decreased, $n \propto T^{3/2} \propto w^{-3} \propto V^{-1}$. In our case, $n$ increases by 200. The collision rate $\Gamma \propto nT^{1/2} \propto V^{-4/3}$. Without evaporation, our compression would increase $\Gamma$ by over a factor of 1000. The thermalization time is inversely proportional to $\Gamma$, unless the system enters the hydrodynamic limit, where thermalization is limited by the trap period, $1/\omega$. Note that when atoms are compressed in a light trap by increasing laser power instead of decreasing beam waists, the above scaling laws are different and it is harder to get as dramatic a reduction in the thermalization times.

In fact, evaporation starts to some degree as soon as the atoms are loaded into the trap. Even as we compress the trap, we force a steady evaporation by decreasing the intensity of the trapping light. For much of the evaporative cooling process, the system is not far from the border of the hydrodynamic limit. In total, we reduce the trap depth by a factor of 240 in five independently optimized steps. The initial horizontal trap frequency is 17 Hz. During compression and evaporation, the calculated spontaneous emission rate reaches a maximum of 0.4 Hz. The final trap frequency is 40 Hz, with a negligible spontaneous emission rate of 0.0065 Hz.

Even though the dipole potential itself falls off gradually as the atoms move away from the trap center, the sum of all trapping fields presents a well-defined lip all around the center for the atoms to escape over. This is because the second derivative of the bias field is antitrapping and has a much longer range than the dipole trap. When atoms reach the edge of the trap (the point in the combined optical, magnetic, and gravitational potential where the potential-energy slope is away from the trap center), they do not return.

In order to test for heating during compression due to the translating lens motion, we first turn off evaporation by adiabatically increasing the power at a late stage in evaporation. We then compress the cloud and then decompress it back. The temperature of the atoms is not measurably increased by this process.

The YAG trap has twice the depth in the vertical than the horizontal direction. We have performed Monte Carlo simulations that show that the effective dimension of evaporation in this trap is about halfway between two (atoms escape from points on ring) and three (atoms escape from points on a closed surface). For efficient evaporation to be realized, it is important to be at the center of symmetry of the levitating field to prevent atoms from exiting predominantly from one side of the trap. We ensure this by adjusting transverse bias

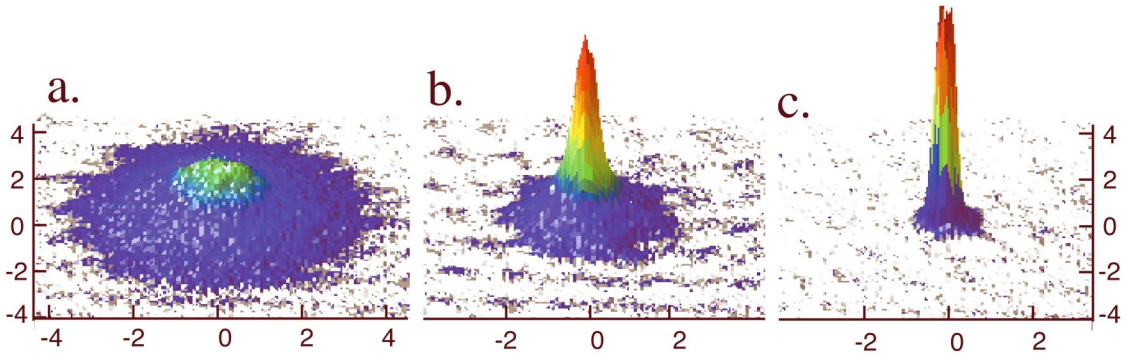


FIG. 3. Absorption images of the atom distribution at various evaporation stages. (a) After 1 s, just before the BEC transition. (b) After 1.6 s, with half the atoms in the BEC. (c) After 2.6 s, a nearly pure BEC. The atom number is color coded and shown on the vertical axis. The horizontal units are Rb photon recoil momentum (the size of the cloud before expansion is much smaller than after expansion.) We can routinely create nearly pure BECs with $3.5\times10^5$ atoms.

fields until the atoms do not drift in any direction in the magnetic field after the YAG trap is shut off.

As evaporation progresses, the phase-space density increases nearly exponentially, as shown in Fig. 2. BEC is reached when $P=P_0/30$. For several points during the evaporation, Fig. 3 shows standard absorption images of atoms suddenly released from the YAG trap and allowed to freely expand for 20 ms. After 2 s of evaporation, Fig. 3(c) shows a $>90\%$ pure BEC with $2.5\times10^5$ atoms. When the atoms are released from the trap, the mean-field-dominated expansion has a release energy of $k_B$ times 7.5 nK (which looks like a thermal expansion with $T=15$ nK). Further optimization has yielded, in the same evaporation time, $>98\%$ pure BECs with $3.5\times10^5$ atoms.

The experiment described here could be optimized in straightforward ways to increase the number of condensed atoms by nearly two orders of magnitude. Obviously the vacuum could be improved, which would give a threefold improvement just due to decreased losses. We currently use a 10-W YAG laser, but lasers and amplifiers with at least four times more power in their $TEM_{00}$ modes are now commercially available. This would allow the YAG beams to be twice as large while maintaining the same depth, thus increasing the initial trap volume by a factor of 8. Since this is still smaller than the compressed MOT and lattice volumes, it would lead to nearly a factor of 8 more initially trapped atoms. Alternately, or additionally, 3D Raman sideband cooling in the optical lattice could be implemented to decrease the initial temperature of atoms to be loaded into the dipole trap to 300 nK [5,15], thus making it possible to capture all the compressed MOT atoms in the dipole trap. Since the evaporation rate in the early stages are limited by the elastic collision rate, with less loss to vacuum collisions and more initial atoms, evaporation to a $10^7$ atom BEC would still take only a couple of seconds. With these improvements, this optical approach would yield a result on par with the largest alkali BEC, obtained with Na [16], producing 1/5 the number of condensed atoms, but in 1/10 the time.

In conclusion, we have described an all-optical approach to BEC. By first laser cooling in a far-off-resonant optical lattice, atoms are loaded into a large, shallow crossed dipole trap. Then the volume of the trap is reduced by a factor of 200, thus allowing for much higher atom densities and faster evaporation. We obtain a nearly pure BEC of $3.5\times10^5$ $^{87}$Rb atoms every 3.3 s.

The authors thank K.E. Gibble for useful discussions, and S. Wolf and D.J. Han for experimental and theoretical contributions. We acknowledge support from the National Science Foundation.

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