Production of Two Overlapping Bose-Einstein Condensates by Sympathetic Cooling

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A new apparatus featuring a double magneto-optic trap and an Ioffe-type magnetic trap was used to create condensates of 2×10^6 atoms in either of the $|F = 2,\ m = 2\rangle$ or $|F = 1,\ m = -1\rangle$ spin states of ^{87}Rb. Overlapping condensates of the two states were also created using nearly lossless sympathetic cooling of one state via thermal contact with the other evaporatively cooled state. We observed that (i) the scattering length of the $|1, -1\rangle$ state is positive, (ii) the rate constant for binary inelastic collisions between the two states is $2.2(9) \times 10^{-14}\ \mathrm{cm}^3/\mathrm{s}$, and (iii) there is a repulsive interaction between the two condensates. Similarities and differences between the behaviors of the two spin states are observed. [S0031-9007(96)02208-9]

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One of the more notable recent developments in physics has been the cooling of a trapped dilute atomic gas to below the Bose-Einstein transition temperature [1–3]. This produced a macroscopic quantum state that is both novel and readily observed. Gaseous Bose-Einstein condensation (BEC) was first reported in a cloud of atoms in a single spin state of the ground state of rubidium [1] and later in single spin states of sodium [2] and lithium [3]. To reach the necessary ultralow temperatures, these experiments used laser cooling and trapping followed by magnetic trapping and evaporative cooling. The observation of BEC led to a number of studies of the properties of these two condensates [4]. Here we report the creation of two different condensates in the same trap. The two condensates in this work correspond to two different spin states of rubidium 87, $|F = 1,\ m = -1\rangle$ and $|F = 2,\ m = 2\rangle$. We have created large samples of both condensates separately and compared their properties. We have also created mixtures of the two by using a new cooling technique. The cloud of atoms in the $|1, -1\rangle$ state was cooled by lossy evaporative cooling, as in previous work, but the $|2, 2\rangle$ state cloud was cooled only by thermal contact with $|1, -1\rangle$ atoms. Such "sympathetic" cooling of one species by another has been used at much higher temperatures to cool trapped ions [5] that have strong long-range Coulomb interactions, but this is the first time it has been applied to neutral atoms. This sympathetic evaporative cooling technique may allow the creation of degenerate Fermi gases as well as condensates in rare isotopes. We see differences in the low-temperature behaviors of the atoms in the two spin states in both condensed and uncondensed phases. When the two condensates are overlapped, additional novel features are observed in their interactions. These condensates were created using a new apparatus that incorporates a double magneto-optic trap (MOT) and a magnetic trap. It is based upon the same vapor-cell/diode-laser technology as the original JILA BEC apparatus [1]; however, it produces much larger condensates and is far more tolerant of imperfect experimental conditions [6].

The apparatus is an extension of the double MOT system that has been described previously [7]. The double MOT system has the advantage of allowing a relatively large sample of atoms to be optically trapped in a very low pressure chamber using low power lasers. It is made up of two small differentially pumped vacuum chambers connected by a 40 cm long × 1 cm diam tube that is used to transfer atoms between them. The upper vacuum chamber contains about 2×10^{-9} Torr of rubidium vapor. The transfer tube is lined with strips of permanent magnet that create a hexapole magnetic guiding field. The lower chamber, shown in Fig. 1, is made of glass and is pumped by a 60 L/s ion pump and a small titanium sublimation pump to a pressure of less than 10^{-11} Torr. Three coils outside of this chamber create a "baseball coil" magnetic trap that is similar to that used in our previous work [8] but different from that used in the recent JILA BEC

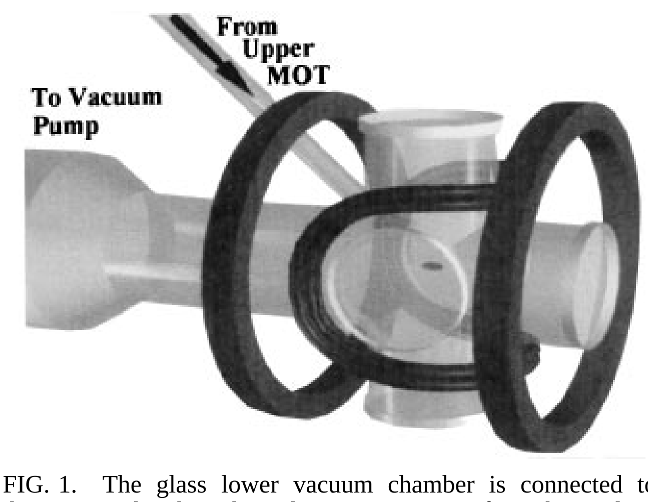

FIG. 1. The glass lower vacuum chamber is connected to the upper chamber through a narrow transfer tube and to sublimation and ion pumps as noted. It is surrounded by the three coils that comprise the magnetic trap. Small additional windows (not shown) allow the cloud to be viewed along some of the diagonals. The trapping laser beams go through the six perpendicular 2.5 cm diam windows, four of which are visible in the figure.

studies [1,4]. The first coil is shaped like the seams on a baseball and provides field curvature in addition to a bias field, while the other two form a Helmholtz pair that can cancel all or part of the bias field. The resulting field configuration is essentially that of an Ioffe-type trap [9]. The three coils are wired in series with a variable shunt resistance across the Helmholtz pair. The trapping potential is axially symmetric with the axis nominally horizontal. There is a small additional coil for producing the adjustable-frequency rf magnetic field used in evaporative cooling. Lenses image the trapped atomic cloud onto both a CCD camera and a calibrated photodiode. The trapping and probing light is provided by low power (50 mW) diode lasers stabilized by grating feedback [10].

Single-species condensates in either the $|2,2\rangle$ or $|1,-1\rangle$ spin states of the $5S$ ground state of rubidium are created and examined using the following procedure. First, atoms are collected in a MOT in the upper chamber for 1.0 s. This load, typically several times 10^7 atoms, is then pushed down the transfer tube using light pressure, and about 80% of them are recaptured in a second MOT in the lower chamber [7]. This procedure is repeated many times to fill the lower MOT with about 10^9 atoms. Next, this cloud of trapped atoms is compressed by increasing the MOT magnetic field gradient as in Ref. [11]. Then the MOT fields (optical and dc magnetic) are turned off and a 1 G bias field turned on. The atoms are then optically pumped into the desired spin state by applying 1 ms pulses of light from two laser beams that excite the $5S_{1/2}, F = 1$ to $5P_{3/2}, F' = 2$ and the $F = 2$ to $F' = 2$ transitions, respectively. By suitable adjustment of the polarization and relative timing of the two beams, we pump the atoms into a single state, either $|1,-1\rangle$ or $|2,2\rangle$, with 90% efficiency. Next, the magnetic trap is turned on around the atoms with full current (200 A) flowing through the baseball coil, but with no current in the Helmholtz pair. The current in the Helmholtz pair is then ramped up in 2 s to reduce the bias field to 1 G. For the $|2,2\rangle$ state this increases the radial frequency from 20 to 400 Hz, while leaving the 10 Hz axial frequency nearly unchanged. (The $|1,-1\rangle$ state has one-half of the $|2,2\rangle$ magnetic moment, and so all of the $|1,-1\rangle$ frequencies are lower by $\sqrt{2}$.) This ramp compresses the cloud and raises its temperature to 250 μK. The cloud is then cooled by rf evaporation, in which the applied rf magnetic field drives the most energetic atoms to untrapped spin states. For this cooling, the frequency of the applied rf is ramped down over a period of 30 s.

The cooled cloud is probed by absorption imaging in a manner similar to that of Ref. [1]. The cloud is released from the magnetic trap, and after it expands ballistically for 20 ms it is illuminated briefly by a near resonant $5S_{1/2}F = 2$ to $5P_{3/2}F' = 3$ probe laser beam, as well as $F = 1$ to $F' = 2$ hyperfine pumping light. The probe laser is normally tuned 1.6 full linewidths off resonance because an expanded condensate cloud is tens of optical depths thick for resonant light. The resulting shadow produced by the cloud in the illuminating beam is imaged onto the CCD camera. This absorption imaging is used to find the temperature of the cloud and the fraction of atoms in the condensate as in Ref. [1]. Also, a measurement of total fluorescence is used to accurately determine the number of atoms in the cloud. The fluorescence is measured by the calibrated photodiode after recapturing the evaporatively cooled atoms in a MOT.

To create mixtures of the two condensates by sympathetic cooling, the procedure is quite similar. If the two clouds are at the same temperature, the $|1,-1\rangle$ cloud is less tightly confined by the magnetic field than the $|2,2\rangle$ cloud because of the difference in magnetic moments and, hence, will extend to a larger magnetic field. This causes the $|1,-1\rangle$ state to be preferentially removed by the rf field. The $|2,2\rangle$ atoms are then cooled by elastic collisions with the evaporatively cooled $|1,-1\rangle$ atoms as long as the two clouds overlap. Because the two states have different magnetic forces but the same gravitational force, the $|2,2\rangle$ cloud is centered slightly above the $|1,-1\rangle$ cloud. However, for the spring constants given above and a horizontal trap axis, one can easily calculate that the relative displacement of the $|1,-1\rangle$ and $|2,2\rangle$ clouds is much less than their widths when they are not condensed. For condensates, the displacement is a significant fraction of the width, but there is still substantial overlap. By starting with the axis of the trap (the direction of the weak spring constant) slightly tilted off perpendicular to the gravitational force, it is possible to form separated condensates, if desired (Fig. 2). One can also separate the two clouds

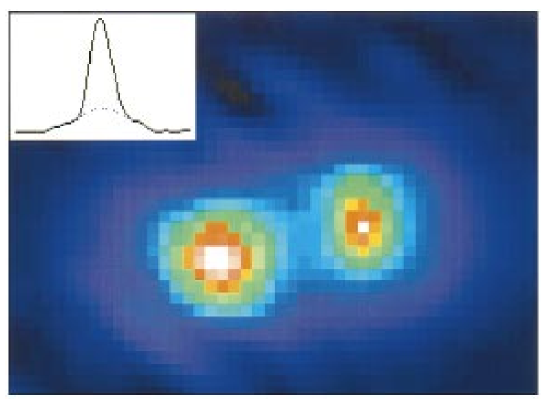

FIG. 2(color). A false-color absorption image (475 μm by 675 μm) showing condensates of both $|2,2\rangle$ (left) and $|1,-1\rangle$ (right) states that were created simultaneously by sympathetic cooling. The condensates are separated because the trap axis was tilted 40 mrad to produce a component of the gravitational force along the weak spring constant direction. The noncondensed parts of the clouds (purple and dark blue) still overlap. The shape of both of the condensates is a function of expansion time, but the difference in their ellipticities reflects the fact that they have different initial confinements and therefore expand at different rates. The inset shows a vertical trace through the cloud on the left. The dotted line is to guide the eye in distinguishing the broad thermal background from the narrow condensate peak.

after cooling by adiabatically lowering the trap spring constants to increase the displacement due to gravity.

For the production of two-species condensates by sympathetic cooling, the MOT portion of a cooling cycle was identical to that given above. However, in the optical pumping the polarization and timing of the two laser beams are set to produce the desired ratio of populations in the $|1,-1\rangle$ and $|2,2\rangle$ states [12]. The evaporative cooling then proceeds exactly as it would for a pure $|1,-1\rangle$ cloud. The probing is modified slightly to obtain state selective absorption images of the mixtures. After the cloud has ballistically expanded we probe it two different ways. First, we use only the near resonant $F = 2$ to $F' = 3$ light to obtain an absorption image of only the $|2,2\rangle$ cloud. We then take a second absorption image with the $F = 1$ to $F' = 2$ light also present [13]. This produces an absorption image of all the atoms independent of their initial state. In Figs. 2 and 3(a) we show pictures of clouds containing two simultaneous condensates.

We have compared the production of condensates for samples of either pure $|2,2\rangle$ or pure $|1,-1\rangle$ atoms, as well as for mixtures. For the pure cases, both the total transfer efficiency from lower MOT to compressed magnetic trap (~50%) and the evaporative cooling results are similar. This is to be expected because the magnitude of the two scattering lengths are similar [14]. For each factor of 5 loss in the number of atoms during evaporation, we decrease the temperature by a factor of 10 and increase the phase space density by 200. This allows us to reach the ~500 nK BEC transition temperature with 6×10^6 atoms. After further cooling down to where we can no longer see any noncondensed atoms, about 2×10^6 atoms remain. The efficiency of the evaporative cooling is relatively insensitive to initial conditions and the details of the rf ramp. This is not surprising since the initial elastic scattering rate in the magnetic trap is about 50 times larger than the ~200 collisions per trap lifetime required for runaway evaporative cooling. For the low densities obtained before evaporative cooling, this lifetime for both states is ~140 s [15]. All of our cooled clouds show the three clear indications of BEC reported in Ref. [1]: a two-component velocity distribution, a nonisotropic velocity distribution, and a sudden large increase in peak density as the temperature is decreased. The first two of these are evident in Figs. 2 and 3. The observed transition temperatures for both states agree with the ideal gas value within our ±20% uncertainty. Also, we find that the previously unknown sign of the scattering length for the $|1,-1\rangle$ state must be positive [16].

We also see differences between the two states. First, when the rf cooling is disabled, we observe a heating rate that is about 10 times larger for the $|2,2\rangle$ state cloud than a comparable cloud in the $|1,-1\rangle$ state. This is true both above and below the BEC transition. Second, we see differences in how the two states are lost from the magnetic trap. At the highest densities, the lifetime of the $|1,-1\rangle$ state remains 140 s but the lifetime for the $|2,2\rangle$ is density dependent and less than 10 s. These differences clearly involve some interesting low-temperature atomic physics that are quite relevant for the creation and study of BEC.

In Fig. 4 we illustrate the nearly lossless sympathetic cooling of the $|2,2\rangle$ atoms in a two species cloud. Nearly one-half of the $|2,2\rangle$ atoms remain after cooling from 250 μK to just above the BEC transition. In contrast, only about $\frac{1}{60}$ of the $|1,-1\rangle$ atoms remain. There is a small loss of $|2,2\rangle$ atoms as the temperature approaches 1 μK (Fig. 4) and a larger loss in going from that point to a pure condensate (not shown). The loss rate depends on the densities of $|1,-1\rangle$ and $|2,2\rangle$ atoms and is consistent with it being due to binary, inelastic collisions (presumably spin exchange) between the species. By measuring the densities and loss rates we find the total rate constant for

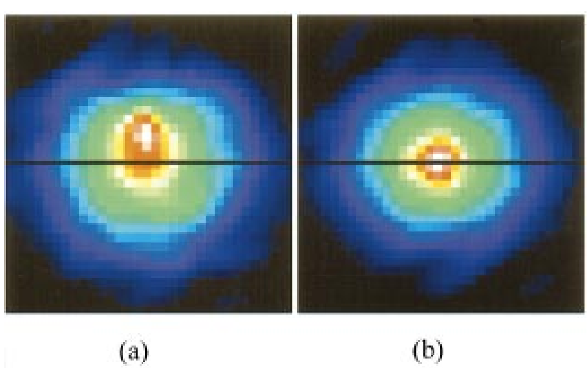

FIG. 3(color). Two 475 μm by 475 μm false-color absorption images of $|2,2\rangle$ atoms. (a) A cloud of two overlapping condensates illuminated so that only the $|2,2\rangle$ state atoms are visible. The condensate (white, red, and yellow) is shifted upwards relative to the center of the thermal uncondensed cloud (green, blue, and purple) due to interactions with the $|1,-1\rangle$ condensate ($|1,-1\rangle$ atoms not visible). (b) A cloud of pure $|2,2\rangle$ atoms cooled to a comparable temperature as in (a). The black line is a guide to the eye going through the center of both thermal clouds.

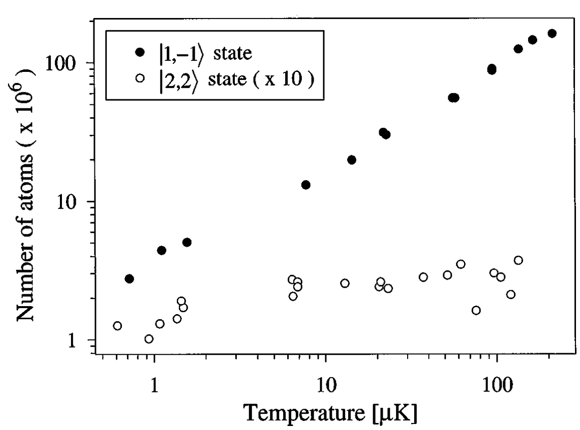

FIG. 4. Number of $|1,-1\rangle$ and $|2,2\rangle$ atoms in a two-species cloud as a function of the temperature during the sympathetic evaporative cooling. The cloud is being cooled from the initial magnetic trap temperature to just above the condensation temperature.

inelastic processes is $2.2(9) \times 10^{-14}$ cm^3/s. When we tilt the trap, as in Fig. 2, we reduce the overlap between the clouds and the observed loss rate. We have measured the temperatures of the $|1, -1\rangle$ and $|2, 2\rangle$ clouds and find that they match closely during the evaporation process. The measured temperature of the $|2, 2\rangle$ state is consistently 5%–10% lower than that of the $|1, -1\rangle$ state; however, this is just at the limit of our resolution and may not indicate a real difference.

Finally, we have briefly examined the degree of interaction of the two overlapping condensates by comparing their ballistic expansion with that observed for single-species condensates. As can be seen in Fig. 3(a), the $|2, 2\rangle$ condensate is pushed upward from its position in a single species cloud by the interaction with the lower lying $|1, -1\rangle$ condensate. This indicates that the interaction is repulsive. We plan to make further studies about the overlap and interactions between the two condensates.

This work has demonstrated an improved apparatus and a new cooling method for producing BEC in rubidium. The large number of atoms and long magnetic trap lifetime in this setup make it relatively easy to obtain BEC [17]. It will be straightforward to use this approach to further explore the detailed interactions between the two overlapping condensates. Also, the method of sympathetic cooling will allow future experiments involving the cooling of rare and/or fermionic isotopes. It would be very difficult to cool fermionic atoms into a highly degenerate regime using normal evaporative cooling because of the requirement of a large number of elastic collisions per trap lifetime, combined with the vanishing elastic collision rate in low-temperature spin-polarized fermionic gases. However, it should be quite feasible to use bosonic atoms as a working fluid to sympathetically cool a fermionic gas into the interesting [18] degenerate regime. This technique will also allow one to cool to BEC the many species for which inelastic processes make it impossible to obtain high enough densities for conventional evaporative cooling.

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Note added.—Recent theoretical studies of binary mixtures of Bose condensates [19] predict a rich variety of interesting behaviors for two component condensates.

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[12] This simple pumping scheme typically results in $\frac{2}{3}$ of the atoms ending up in the other six spin states. However, all of these other states quickly leave the magnetic trap. The only state that is magnetically trapped, other than the $|1, -1\rangle$ and $|2, 2\rangle$ states, is the $|2, 1\rangle$ state. We see this state quickly depleted, presumably by spin-exchange collisions. When there is a large $|2, 2\rangle$ cloud, however, we observe a small residual $|2, 1\rangle$ population that we believe is due to the balance between $|2, 2\rangle + |2, 2\rangle$ dipole collisions populating the $|2, 1\rangle$ state and spin-exchange collisions depleting it.

[13] We take the second image on the subsequent identical cooling cycle.

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[15] This is only achieved after a quite careful shielding against stray laser light.

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