

# Stable $^{85}\text{Rb}$ Bose-Einstein Condensates with Widely Tunable Interactions

S. L. Cornish, N. R. Claussen, J. L. Roberts, E. A. Cornell\* and C. E. Wieman

*JILA, National Institute of Standards and Technology and the University of Colorado, and the  
Department of Physics, University of Colorado, Boulder, Colorado 80309-0440*

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## Abstract

Bose-Einstein condensation has been achieved in a magnetically trapped sample of  $^{85}\text{Rb}$  atoms. Long-lived condensates of up to  $10^4$  atoms have been produced by using a magnetic-field-induced Feshbach resonance to reverse the sign of the scattering length. This system provides many unique opportunities for the study of condensate physics. The variation of the scattering length near the resonance has been used to magnetically tune the condensate self-interaction energy over a very wide range. This range extended from very strong repulsive to large attractive self-interactions. When the interactions were switched from repulsive to attractive, the condensate shrank to below our resolution limit, and after  $\sim 5$  ms emitted a burst of high-energy atoms.

Atom-atom interactions have a profound influence on most of the properties of Bose-Einstein condensation (BEC) in dilute alkali gases. These interactions are well described in a mean-field model by a self-interaction energy that depends only on the density of the condensate ( $n$ ) and the s-wave scattering length ( $a$ ) [1]. Strong repulsive interactions produce stable condensates with a size and shape determined by the self-interaction energy. In contrast, attractive interactions ( $a < 0$ ) lead to a condensate state where the number of atoms is limited to a small critical value determined by the magnitude of  $a$  [2]. The scattering length also determines the formation rate, the spectrum of collective excitations, the evolution of the condensate phase, the coupling with the noncondensed atoms, and other important properties.

In the vast majority of condensate experiments the scattering length has been fixed at the outset by the choice of atom. However, it was proposed that the scattering length could be controlled by utilizing the strong variation expected in the vicinity of a magnetic-field-induced Feshbach resonance in collisions between cold ( $\sim \mu\text{K}$ ) alkali atoms [3]. Recent experiments on cold  $^{85}\text{Rb}$  and Cs atoms and Na condensates have demonstrated the variation of the scattering length via this approach [4–7]. However, extraordinarily high inelastic losses in the Na condensates were found to severely limit the extent to which the scattering length could be varied and precluded an investigation of the interesting negative scattering length regime [8]. These findings prompted the subsequent proposal of several exotic coherent loss processes that remain untested in other alkali species [9–11].

Here we report the successful use of a Feshbach resonance to readily vary the self-interaction of long-lived condensates over a large range. In  $^{85}\text{Rb}$  there exists a Feshbach resonance in collisions between two atoms in the  $F=2$ ,  $m_f=-2$  hyperfine ground state at a magnetic field  $B \sim 155 \text{ Gauss(G)}$  [4,12]. Near this resonance the scattering length varies dispersively as a function of magnetic field and, in principle, can have any value between  $-\infty$  and  $+\infty$  (see inset in Fig. 1). This has allowed us to reach novel regimes of condensate physics. These include producing very large repulsive interactions ( $n_{pk}|a|^3 \simeq 10^{-2}$ ), where effects beyond the mean-field approximation should be readily observable. We can

also make transitions between repulsive and attractive interactions (or vice-versa). This now makes it possible to study condensates in the negative scattering length regime, including the anticipated “collapse” of the condensate [13], with a level of control that has not been possible in other experiments [14]. In fact, this ability to change the sign of the scattering length is essential for the existence of our  $^{85}\text{Rb}$  condensate. Away from the resonance the large negative scattering length ( $\simeq -400 a_0$  [4,15]) limits the maximum number of atoms in a condensate to  $\sim 80$  [2]. However, we have produced condensates with up to  $10^4$  atoms by operating in a region of the Feshbach resonance where  $a$  is positive.

The experimental apparatus was similar to the double magneto-optical trap (MOT) system used in our earlier work [16]. Atoms collected in a vapor cell MOT were transferred to a second MOT in a low-pressure chamber. Once sufficient atoms have accumulated in the low-pressure MOT, both the MOT’s were turned off and the atoms were loaded into a purely magnetic, Ioffe-Pritchard “baseball” trap. During the loading sequence the atom cloud was compressed, cooled and optically pumped, resulting in a typical trapped sample of about  $3 \times 10^8$   $^{85}\text{Rb}$  atoms in the  $F=2$ ,  $m_F=-2$  state at a temperature of  $T = 45 \mu\text{K}$ . The lifetime of atoms in the magnetic trap due to collisions with background atoms was  $\simeq 450$  s.

Forced radio-frequency evaporation was employed to cool the sample of atoms. Unfortunately,  $^{85}\text{Rb}$  is plagued with pitfalls for the unwary evaporator familiar only with  $^{87}\text{Rb}$  or Na. In contrast to those atoms, the elastic collision cross section for  $^{85}\text{Rb}$  exhibits strong temperature dependence due to a zero in the s-wave scattering cross section at a collision energy of  $E/k_B \simeq 350 \mu\text{K}$  [17]. This decrease in the elastic collision cross section with temperature means that the standard practice of adiabatic compression to increase the initial elastic collision rate does not work.  $^{85}\text{Rb}$  also suffers from unusually high inelastic collision rates. We recently investigated these losses and observed a mixture of two and three-body processes which varied with  $B$  [18]. The overall inelastic collision rate displayed several orders of magnitude variation across the Feshbach resonance, with a dependence on  $B$  similar to that of the elastic collision rate. However, the inelastic rate increased more rapidly than the elastic rate towards the peak of the Feshbach resonance, and was found to be

significantly lower in the high field wing of the resonance than on the low field side. This knowledge of the loss rates, together with the known field dependence of the elastic cross section [4,15], has enabled us to successfully devise an evaporation path to reach BEC. This begins with evaporative cooling at a field ( $B = 250$  G) well above the Feshbach resonance. To maintain a relatively low density, and thereby minimize the inelastic losses, a relatively weak trap is used. The low initial elastic collision rate means that about 120 s are needed to reach  $T \simeq 2 \mu\text{K}$ , putting a stringent requirement on the trap lifetime. As the atoms cool, the elastic rate increases and it becomes advantageous to trade some of this increase for a reduced inelastic collision rate by moving to  $B = 162.3$  G where the magnitude of the scattering length is decreased. The remainder of the evaporation is performed at this field (with a radial (axial) trap frequency of 17.5 Hz (6.8 Hz)). In contrast to field values away from the Feshbach resonance, the scattering length is positive at this field and stable condensates may therefore be produced.

The density distribution of the trapped atom cloud was probed using absorption imaging with a  $10 \mu\text{s}$  laser pulse 1.6 ms after the rapid ( $\simeq 0.2$  ms) turn-off of the magnetic trap. The shadow of the atom cloud was magnified by about a factor of 10 and imaged onto a CCD array to determine the spatial size and the number of atoms. The emergence of the BEC transition was observed at  $T \simeq 15$  nK. Typically, we were able to produce “pure” condensates of up to  $10^4$  atoms with peak number densities of  $n_{pk} \simeq 1 \times 10^{12} \text{cm}^{-3}$ . The lifetime of the condensate at  $B = 162.3$  G was about 10 s [19]. This lifetime is consistent with that expected from the inelastic losses we have measured in cold thermal clouds [18]. It is notable that our evaporation trajectory suffered a near-catastrophic decline prior to the observation of the BEC transition. We approached the required BEC phase space density at 100 nK with about  $10^6$  atoms, but then lost a factor of about 50 in the atom number before the characteristic two-component density distribution was visible. Over this part of the trajectory, the cooling efficiency has become low (and the phase space density remain approximately constant). This is because the mean free path is comparable to the cloud size and the high density results in high losses. This situation improves when the number of

atoms becomes sufficiently low, and we are then able to obtain a significant fraction of the atoms in a condensate. The number of atoms in the condensate after we reach this favorable low-density regime is obviously a delicate balance between the elastic (cooling) and inelastic (loss) collision processes in the cloud. Both of these are strongly field dependent near the Feshbach resonance. Although we are able to decrease the loss rate by moving to higher fields, the ratio of elastic to inelastic collisions actually decreases and it becomes harder to form condensates. For example, at  $B = 164.3$  G we can only produce condensates of a few thousand atoms. Conversely, moving to lower fields does not help because we reach the favorable low-density cooling regime at smaller numbers of atoms. This restriction together with the larger loss rate means that at  $B = 160.3$  G, for example, we are unable to form condensates.

One of the features of the high inelastic loss rates reported in the Na experiments was an anomalously high decay rate when the condensate was swept rapidly through the Feshbach resonance [8]. In light of this work, it was essential to determine to what extent the  $^{85}\text{Rb}$  condensate was perturbed in being swept across the Feshbach peak during the trap turn-off. These measurements also provide an additional test of coherent loss mechanisms such as those in references [9–11]. We applied a linear ramp to the current in the baseball coil to sweep the magnetic field experienced by the atoms from  $B = 162.3$  G across the Feshbach peak to  $B \simeq 132$  G and then immediately turned off the trap and imaged the atom cloud. From the images we determined the fraction of condensate atoms lost as a function of the inverse ramp speed (Fig. 2). The loss for the fastest ramp, which corresponds to the direct turn-off of the magnetic trap, is less than 9%. This was determined in a separate experiment where the condensate was imaged directly in the magnetic trap both before and after the ramp. For comparison, the experiment was repeated using a cloud of thermal atoms much hotter than the BEC transition temperature. The results for the thermal atoms are consistent with the known inelastic loss rates in the vicinity of the Feshbach resonance [18]. The strong and poorly characterized temperature dependence of these known loss rates near the Feshbach peak makes it difficult to determine what fraction of the observed condensate

loss can be attributed to the usual inelastic loss processes and we cannot, therefore, rule out a coherent aspect to the loss process. There have been several models of coherent loss processes put forward to explain the corresponding sodium results [9–11]. However, these calculations are based on the Timmermans theory [9] of coupled atomic and molecular Gross-Pitaevskii equations which is unlikely to be applicable to the conditions of the present experiment [20].

We also changed the self-interaction energy by varying the magnetic field and observed the resulting change in the condensate shape. By applying a linear ramp to the magnetic field we have varied the magnitude of  $a$  in the condensate by almost three orders of magnitude. The duration of this ramp was sufficiently long (500 ms) to ensure that the condensate responded adiabatically. Fig. 3 shows a series of condensate images for various magnetic fields. They illustrate how we are able to easily change  $a$  over a very wide range of positive values. Moving towards the Feshbach peak the condensate size increases due to the increased self-interaction energy. The density distribution approaches the parabolic distribution with an aspect ratio of  $\lambda_{TF} = \omega_z/\omega_r$  expected in the TF regime [21]. Moving in the opposite direction the cloud size becomes smaller than our 7 micron resolution limit shortly before we reach the noninteracting limit where the condensate density distribution is a Gaussian whose dimensions are set by the harmonic oscillator lengths ( $l_i = (\hbar/m\omega_i)^{1/2}$  where  $i = r, z$ ) [21]. We took condensate images similar to those shown at many field values between 156 and 166 G. From the images the full widths at half-maximum (FWHM) of the column density distributions were determined. The scattering length was then derived by assuming a TF column density distribution with the same FWHM ( $\propto (Na)^{1/5}$ ). In Fig. 1 we plot the scattering length derived in this manner versus the magnetic field. It shows that these values agree with the predicted field dependence of the Feshbach resonance.

The ability to tune the atom-atom interactions in a condensate presents several exciting avenues for future research. One is to explore the breakdown of the dilute-gas approximation near the Feshbach peak. The lifetime of the condensate decreases with larger  $a$ , but for a lifetime of about 100 ms, which is sufficient for many experiments, we have created

static condensates with  $n_{pk}|a|^3 \simeq 10^{-2}$ . For such values, effects beyond the mean field approximation, such as shifts in the frequencies of the collective excitations [22], are about 10%.

A second avenue is the behavior of the condensate when the scattering length becomes negative. When we increased the magnetic field beyond  $B = 166.8$  G, where  $a$  was expected to change sign, a sudden departure from the smooth behavior in Figs. 1 and 3 was observed. As  $a$  was decreased the condensate width decreased and then about 5 ms seconds after the change in sign there was a sudden explosion that ejected a large fraction of the condensate. This left a small observable remnant condensate surrounded by a “hot” cloud at a temperature on the order of 100 nK. These preliminary results on switching from repulsive to attractive interactions suggest a violent, but highly reproducible, destruction of the condensate. The ability to control the precise moment of the onset of  $a < 0$  instability is a distinct advantage over existing methods for studying this regime which rely on analyzing ensemble averages of “post-collapse” condensates [14]. The dynamical response of the condensate to a sudden change in the sign of the interactions can now be investigated in a controlled manner, probing the rich physics of this dramatic condensate “collapse” process.

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- [19] This is in dramatic contrast to the very short lifetimes obtained with Na condensates anywhere near the vicinity of a Feshbach resonance [8]. We believe that the primary difference is that we have three orders of magnitude lower density.
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## FIGURES

FIG. 1. Scattering length in units of the Bohr radius ( $a_0$ ) as a function of the magnetic field. The data are derived from the condensate widths. The solid line illustrates the expected shape of the Feshbach resonance using a peak position and resonance width consistent with our previous measurements [4,18]. For reference, the shape of the full resonance has been included in the inset.

FIG. 2. Fraction of atoms lost following a rapid sweep of the magnetic field through the peak of the Feshbach resonance as a function of the inverse speed of the field ramp. Data are shown for a condensate ( $\bullet$ ) with a peak density of  $n_{pk} = 1.0 \times 10^{12} \text{ cm}^{-3}$  and for a thermal cloud ( $\circ$ ) with a temperature  $T = 430 \text{ nK}$  and a peak density of  $n_{pk} = 4.5 \times 10^{11} \text{ cm}^{-3}$ .

FIG. 3. (color) False color images and horizontal cross sections of the condensate column density for various magnetic fields. The condensate number was varied to maintain an optical depth (OD) of  $\sim 1.5$ . The magnetic field values are (a)  $B = 165.2 \text{ G}$ , (b)  $B = 162.3 \text{ G}$ , (c)  $B = 158.4 \text{ G}$ , (d)  $B = 157.2 \text{ G}$ , (e)  $B = 156.4 \text{ G}$ .





