A double species $^{23}\text{Na}$ and $^{87}\text{Rb}$ Bose–Einstein condensate with tunable miscibility via an interspecies Feshbach resonance

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Abstract

We have realized a dual-species Bose–Einstein condensate (BEC) of $^{23}\text{Na}$ and $^{87}\text{Rb}$ atoms and observed its immiscibility. Because of the favorable background intra- and inter-species scattering lengths, stable condensates can be obtained via efficient evaporative cooling and sympathetic cooling without the need for fine tuning of the interactions. Our system thus provides a clean platform for studying inter-species interactions–driven effects in superfluid mixtures. With a Feshbach resonance, we have successfully created double BECs with largely tunable inter-species interactions and studied the miscible–immiscible phase transition.

Keywords: double BEC, interspecies Feshbach resonance, tunable interaction

(Some figures may appear in colour only in the online journal)

1. Introduction

Degenerate quantum gas mixtures have been a subject of intensive study in recent years. First realized with two hyperfine states of $^{87}\text{Rb}$ atoms [1], such mixtures were soon extended to Bose–Bose [2–6], Bose–Fermi [7] and Fermi–Fermi [8] combinations of two different atoms. Many important properties of these mixtures, such as miscibility, are determined by the relation between the inter- and intra-species interactions [9–12] which can be controlled with Feshbach resonances [4, 13].

The marriage of a heteronuclear quantum gas mixture with a Feshbach resonance is also a promising gateway toward a quantum degenerate gas of ground-state ultra cold polar molecules, which can introduce the long-range, anisotropic dipolar interaction to the playground [14, 15]. This has been successfully demonstrated with $^{40}\text{K}^{87}\text{Rb}$, where weakly-bound Feshbach molecules were created first and then transferred to the lowest energy level with a stimulated Raman process [16]. To address the KRb molecule’s large chemical reaction–induced loss [17, 18] and relatively small electric dipole moment [19], other mixtures [5, 6, 20–22] are now being studied intensively. Very recently, ground-state RbCs [23] and NaK molecules [24] were successfully produced.

$^{23}\text{Na}$ and $^{87}\text{Rb}$ are the first two atomic species to be Bose condensed and their mixture is among the first to be investigated theoretically [9, 11, 25]. The Na–Rb system is a nice candidate for pursuing an ultracold polar molecule as the NaRb molecule has a large permanent electric dipole moment [19] and is stable against two-body chemical reactions [26]. In addition, compared with several other popular Bose–Bose mixtures, the Na–Rb system has the advantage that each individual species’ background interaction can support its stable condensate. Feshbach resonances can thus be applied to tune the inter-species interaction at will for a range of interesting studies, such as non-equilibrium dynamics with quenched miscibility [27–29] and binary spinor condensates [30–32].
In this paper, we describe our work on the production of a double BEC of $^{23}$Na and $^{87}$Rb in a simple hybrid quadrupole + optical dipole trap setup. While the two condensates are immiscible with their background interactions, with an inter-species Feshbach resonance, we demonstrate miscibility tuning over a large range. These experimental results are well accounted for by numerical solutions of the coupled Gross–Pitaevskii (G–P) equations with interaction parameters derived from our previous Feshbach resonance work [33].

The rest of this paper is organized as follows. In section 2, we present the coupled G–P equations and apply them to the $^{23}$Na and $^{87}$Rb double BEC system. This is followed by the description of how we prepare the double BEC in section 3. In section 4, we show the main experimental results and their comparison with numerical simulations. Section 5 concludes the article.

2. Theory

In the mean-field formalism, the ground-state wavefunctions $\psi_i$ ($i = 1$ for Na and 2 for Rb) of two overlapped BECs with particle numbers $N_i$ can be obtained from a pair of coupled time-independent G–P equations

$$\left(-\frac{\hbar^2 \nabla^2}{2m_i} + V_i + N_i g_{11} |\psi_1|^2 + N_2 g_{12} |\psi_2|^2 \right) \psi_1 = \mu_1 \psi_1,$$

$$\left(-\frac{\hbar^2 \nabla^2}{2m_2} + V_2 + N_2 g_{22} |\psi_2|^2 + N_1 g_{12} |\psi_1|^2 \right) \psi_2 = \mu_2 \psi_2.\tag{2}$$

Here $m_i$, $V_i$, and $\mu_i$ are the mass, external trap potential, and chemical potential for the $i$th atomic species, respectively. The two-body intra- and inter-species interactions are determined by the corresponding scattering length $a_{ij}$ via the interaction constant $g_{ij} = 2\pi \hbar^2 a_{ij}/M_i$, with $M_i$ the reduced mass. The miscibility is determined by the relation between $g_{12}^2 g_{11}$ and $g_{22}$. In the Thomas–Fermi limit with the kinetic energy terms ignored, phase separation happens when $g_{12} > \sqrt{g_{11}g_{22}}$.

The two condensates are trapped with the same 1070 nm optical dipole trap (ODT). Due to the very different polarizabilities and masses between Na and Rb, their trap frequencies $\omega_i$ are different. Contributions from gravity are thus included to take into account the differential sagging caused by center-to-center separation between the two condensates. The overall trap potential can be expressed as $V_i = \frac{1}{2}m_i \omega_i^2 r^2 + m_i g_y$, with gravity along the y-direction. Here $g$ is the gravitational acceleration.

The scattering lengths for $^{23}$Na ($a_{11} = 54.5$ $a_0$) [34] and $^{87}$Rb ($a_{22} = 100.4$ $a_0$) [35] are well known. Here $a_0$ is the Bohr radius. With the recently measured $a_{12} = 73$ $a_0$ [33], we find that $g_{12}^2 g_{11}/g_{22} > 1$, which indicates that the inter-species interaction is strong and double $^{23}$Na and $^{87}$Rb BEC with their background scattering lengths should be immiscible. The three positive but moderate magnitude scattering lengths support stable condensates. They also ensure fast elastic collisions for efficient evaporative and sympathetic cooling without causing many inelastic three-body losses, and are thus quite ideal for double BEC production. This is a big advantage over several other systems [4–6], in which Feshbach resonances had to be employed to control the scattering length of one of the species in order to achieve the double BEC. Tuning inter-species interactions simultaneously is thus difficult for those cases. Here, we can use inter-species Feshbach resonances at will for investigating inter-species interaction–driven effects.

Near a Feshbach resonance, $a_{12}$ varies as a function of the $B$ field as

$$a_{12} = a_{bg} \left(1 + \frac{\Delta}{B - B_0} + \ldots \right),\tag{3}$$

where $a_{bg}$ is the background scattering length in the vicinity of the resonant field $B_0$, and $\Delta$ is the resonance width defined as the field difference between the zero crossing point and the resonance. To make fine tuning of interaction with realistic $B$ field resolution and stability, it is desirable to have a large $\Delta$. In principle, all resonances in the same channel should be included here for an accurate calculation of $a_{12}$.

As illustrated in figure 1, the 347.8 G s-wave resonance between $^{23}$Na and $^{87}$Rb atoms [33] in their lowest-energy states has a width $\Delta = -4.9$ G. Thus $a_{12}$ and the interspecies interactions can already be changed over a large range without going too close to the resonance where three-body loss becomes large. Near the zero crossing point and the nominal miscible–immiscible transition point, $a_{12}$ varies with very small slopes. It is thus quite feasible to experimentally control $a_{12}$ with a resolution $\ll a_{12}$ around these magnetic field regions for studying non-interacting mixtures and miscibility-related problems with high precision.

3. Double BEC production in a hybrid trap

Our single-vacuum chamber apparatus has been described previously [33, 36]. Here we present the major modifications only. The most important one is on the configuration of the hybrid trap based on a better understanding of its operation principle. Different from the original implementation [37], which had the ODT focus displaced vertically, the displacement of our ODT focus is along the horizontal (radial) direction of the magnetic quadrupole trap (QT). As illustrated in figures 2(a) and (b) for $^{23}$Na atoms with the same ODT and QT parameters, our configuration provides a higher potential wall from the potential minimum to the QT center. This potential wall is essential in preventing Majorana loss from happening. While this modification makes little difference during the initial stage of the evaporation, it becomes more important when the clouds become colder where Majorana loss is severe.

Another important change we put forward is on the QT. As shown in figure 2(c), now we decompress it by ramping the gradient from 160 G cm$^{-1}$ down to 64 G cm$^{-1}$ in 2 s after
BEC undergoes a miscible to immiscible transition. The potential walls from the potential minimum to the center of the clouds are cooled adiabatically during this process; meanwhile the aforementioned potential wall is increased by 50%, which suppresses Majorana loss further. With these two improvements we have been able to produce a $^{23}$Na cloud cold enough for an efficient crossed ODT loading. The microwave frequency scan continues during the decompression and keeps going on in the decompressed QT.

As our Na MOT contains only $5 \times 10^6$ atoms, sympathetic cooling is necessary for double BEC production. Thanks to the favorable $\alpha_{12}$ and the much larger number of Rb atoms ($3 \times 10^9$ atoms), sympathetic cooling is still rather efficient even in the decompressed QT. This is evident from the fact that the same microwave evaporation protocol optimized for Rb BEC production can be used for the two-species evaporation without further tuning.

Evaporation in the decompressed QT stops at 6833.98 MHz with only $4.7 \times 10^5$ $^{87}$Rb left together with $4.2 \times 10^5$ $^{23}$Na atoms. At this point, the $^{23}$Na($^{87}$Rb) temperature is 2.5 $\mu$K (2.3 $\mu$K) and the calculated phase-space density (PSD) is 0.058(0.006) for $^{23}$Na($^{87}$Rb). We note that sympathetic cooling has already stopped when the coolant $^{87}$Rb atoms are less than $^{23}$Na atoms at about 6833.75 MHz. The further removal of $^{87}$Rb atoms is for the benefit of the pure ODT loading and evaporation. In the same 1070 nm ODT, the trap depth $U_{Na}$ for $^{23}$Na is $\sim 3$ times less than the $U_{rb}$ of $^{87}$Rb. Thus when we ramp down the ODT power, $^{23}$Na always evaporates faster and it becomes the coolant while $^{87}$Rb is sympathetically cooled. With an excessive amount of $^{87}$Rb atoms as the thermal load, we have found that it is impossible to create the double BEC.

The atoms are then loaded into the crossed ODT by simultaneously lowering down the magnetic field gradient to zero and ramping up a second laser beam in 500 ms, as illustrated in figure 2(c) in between the two shaded regions. The waist is 65 $\mu$m for both beams and they intercept each other with an angle of $62^\circ$. A 16 G homogeneous magnetic field is applied at the end of the loading to provide a quantization axis for the spin polarized atoms. Typically, about 70% of the $^{23}$Na atoms and almost all $^{87}$Rb atoms can be loaded into the crossed ODT. The PSDs are improved to 0.19 (0.02) for $^{23}$Na($^{87}$Rb), due to the trap geometry deformation and also continuous evaporation during this loading procedure [37]. In the crossed ODT, the trap frequencies $\omega_{Na} : \omega_{Rb} = \sqrt{U_{Na}/m_{Na}} : \sqrt{U_{Rb}/m_{Rb}} \approx 1.1$. Assuming thermal equilibrium, the sizes of the two clouds $\sigma_{Na} : \sigma_{Rb} \approx 1.8$. Thus using $^{23}$Na as the coolant is advantageous for sympathetic cooling because $^{87}$Rb atoms are always immersed in the $^{23}$Na bath. Indeed, a high sympathetic cooling efficiency of 3.4 is observed for $^{87}$Rb.

Continuous evaporation in the crossed ODT leads to a bimodal distribution first in $^{23}$Na which signifies its BEC phase transition, while that for $^{87}$Rb always lags behind. We attribute this to the lower transition temperature $kT_c \approx 0.94h\omega N^{1/3}$ of $^{87}$Rb because of its smaller atom number $N$ and lower trap frequency $\omega$. Here $k$ is the Boltzmann’s constant. In the end, we are able to produce a quasi-pure double BEC with $2.4 \times 10^4$ ($1.0 \times 10^4$) $^{23}$Na($^{87}$Rb) atoms. The whole ODT evaporation lasts for 4.3 s. The typical final trap frequencies measured with parametric resonances are $2\pi \times (124, 143, 74)$ and $2\pi \times (112, 129, 66)$ Hz for $^{23}$Na and $^{87}$Rb, respectively. We can also produce a single-species $^{23}$Na.
BEC with $1.5 \times 10^5$ atoms, if we remove all $^{87}$Rb atoms at the microwave evaporation step.

4. Results and discussions

Immiscibility of the two simultaneously condensed samples shows up clearly in the time-of-flight (TOF) absorption images taken from the horizontal direction. Figure 3 demonstrates this with two very different atom number ratios. The images in figure 3(a) contain $3.5 \times 10^5(3.2 \times 10^4)$ $^{87}$Rb $(^{23}$Na) atoms, while those in figure 3(c) have $8.5 \times 10^5(1.3 \times 10^5)$ $^{87}$Rb($^{23}$Na) atoms. It is apparent that the presence of $^{87}$Rb will always repel $^{23}$Na atoms away, in agreement with the inter- and intra-species interaction ratios.

We note that the two clouds are not concentric to each other because of the differential gravitational sag in the crossed ODT. For the typical final vertical trap frequencies, this effect makes the $^{87}$Rb cloud center-of-mass (COM) locate 2.8 $\mu$m below that of $^{23}$Na. Taking the samples in the upper images as examples, the calculated single species Thomas–Fermi radius is 5.5 $\mu$m for $^{23}$Na and 2.6 $\mu$m for $^{87}$Rb. Thus the $^{87}$Rb cloud can only overlap and repel the lower part of the $^{23}$Na one, consistent with the crescent shape $^{23}$Na images and the optical density (OD) cross sections in figures 3(b) and (d).

This qualitative understanding is supported by numerical simulations. Depicted in figure 4(a) are in-trap density profiles obtained by numerically solving the coupled G–P equations with the corresponding experimental conditions for producing the images in figure 3(a). The overall experimentally observed density patterns are qualitatively captured by the simulation. One of the main features, the notch at the lower part of the Na cloud due to the repulsive Na–Rb interactions, is well reproduced. From the vertical cross section in figure 4(b), the displacement between the center of the two clouds is determined to be 3.5 $\mu$m. The additional 0.7 $\mu$m compared with the differential gravitational sag reflects the repulsive nature of the inter-species interaction. We note that the experimentally measured vertical displacements are much larger due to the expansion [10].

Limited by optical access, our setup does not have the capability to take images from the vertical direction. Judging from symmetry and the horizontal images, we can reasonably conjecture that the two images should be concentric with each other in that direction, with the smaller size $^{87}$Rb cloud totally wrapped around by $^{23}$Na atoms. This is supported by the simulated density patterns and cross sections in figures 4(c) and (d), respectively. It is interesting to notice that as a result of the interspecies interaction, the $^{23}$Na BEC density becomes flat-topped. In future investigations, besides improving the observation capability, it may also be worth using another laser wavelength for the ODT to eliminate the differential sag so that the two clouds can be concentric in all three directions. Such a ‘magic wavelength’ has been calculated to be 946.66 nm for $^{23}$Na and $^{87}$Rb [38].

Since fine tuning of the interaction is not needed at the double BEC creation stage, Feshbach resonance can be used solely for studying interspecies interaction–induced effects. Here we study the miscible–immiscible phase transition with the 347.8 G inter-species resonance. We first prepare both atoms in their $|1, 1\rangle$ hyperfine levels with an adiabatic rapid passage after loading the atoms into the crossed ODT. The magnetic field is then brought up to a range of values near the 347.8 G Feshbach resonance while ODT evaporation is performed. Once the final ODT power is reached, both the ODT and the magnetic field are turned off abruptly and

Figure 3. Absorption images after 10 ms TOF which show immiscibility of the double BEC with their background interaction. (a) and (c) are pairs of a $^{87}$Rb and a $^{23}$Na condensates with different atom number ratios. Field of view: 210 $\mu$m × 210 $\mu$m. (b) and (d) are the center cross sections along the vertical direction for the images in (a) and (c), respectively.

Figure 4. Simulated in-trap column density profiles with the same experimental conditions as those in figure 3(a). The probing directions are horizontal for (a) and vertical for (c). Field of view: 20 $\mu$m × 20 $\mu$m. The contrasts of the Na images are adjusted to enhance the visibility. (b) and (d) are the corresponding cross sections with the blue solid curve for Na and the red dashed curve for Rb.
under each corresponding

2, 12, 12, 12. B

resonance. The simulation conditions for each image are the same as the corresponding experimental ones in interaction strengths due to three-body losses.

for even larger positive a12, the mutual attraction pulls the two clouds together and greatly increases their overlap. For more negative a12, we observe inter-species attraction–induced collapsing (images not shown). As a12 increases, the center-to-center separation between the two condensates becomes larger. The remaining atom numbers also become fewer due to increasing three-body losses. For even larger positive a12, these losses and the accompanying heating become too severe to perform the measurement. The observed miscibility character agrees qualitatively with the simulated ones, as presented in figure 5(b).

At the critical inter-species scattering length a12 ≈ 60 aB, we cannot identify obvious signatures of miscible–immiscible transition from the images. To characterize the miscibility versus a12 more quantitatively, we extract the vertical COM separation between each pair of clouds from figure 5(a). Illustrated in figure 6 are the separations normalized to the Rb condensate size. The normalization is necessary to partially cancel out the atom numbers’ variation effect. There is a noticeable kink near a12, below which the separation decreases with a steep slope. From the column density profiles in figure 5(b), the simulated COM separation versus a12 is also plotted in figure 6 in the same manner. The simulation agrees qualitatively with our measurement; in particular, the transition point is clearly reproduced.

5. Conclusions

To conclude, we have successfully created a double BEC of 87Rb and 23Na atoms with widely tunable inter-species interactions. The miscible–immiscible phase transition is observed, but the transition is not very sharp. This indicates that the kinetic energy terms are important in double BECs, especially for the relatively small atom number situation here.

In future works, it will be interesting to study the same phenomena with much larger condensates when the Thomas–Fermi approximation is more valid. In situ detection methods may also be developed to extract more information necessary for investigating dynamics during the miscible–immiscible phase transition [28, 29]. The capability of creating miscible double BECs also makes it possible to use condensates as a starting point for magneto-association to achieve the highest molecule conversion efficiency [39].

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