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Dynamics of Component Separation in a Binary Mixture of Bose-Einstein Condensates

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We describe the first experiments that study in a controlled way the dynamics of distinguishable and interpenetrating bosonic quantum fluids. We work with a two-component system of Bose-Einstein condensates in the $|F = 1, m_f = -1\rangle$ and $|2,1\rangle$ spin states of ^{87}Rb. The two condensates are created with complete spatial overlap, and in subsequent evolution they undergo complex relative motions that tend to preserve the total density profile. The motions quickly damp out, leaving the condensates in a steady state with a non-negligible (and adjustable) overlap region. [S0031-9007(98)06974-9]

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Since its realization in dilute atomic gases [1–3], Bose-Einstein condensation (BEC) has afforded an intriguing glimpse into the macroscopic quantum world. Attention has recently broadened to include exploration of systems of two or more condensates, as realized in a magnetic trap in rubidium [4] and subsequently in an optical trap in sodium [5]. Theoretical treatment of such systems began in the context of superfluid helium mixtures [6] and spin-polarized hydrogen [7], and has now been extended to BEC in the alkalis [8–12]. Despite this long-standing and continued theoretical interest, the present paper is the first to explore directly the dynamics of interacting Bose condensates [13]. The complex structures and motional damping that we observe provide new challenges to the theoretical analysis of this problem.

The first experiments involving the interactions between multiple-species BEC were performed with atoms evaporatively cooled in the $|F = 2, m_f = 2\rangle$ and $|1, -1\rangle$ spin states of ^{87}Rb [4]. These experiments demonstrated the possibility of producing long-lived multiple condensate systems, and that the condensate wave function is dramatically affected by the presence of interspecies interactions. In this Letter, we report results from initial studies of simultaneously trapped BECs in the $|2,1\rangle$ and $|1,-1\rangle$ states of ^{87}Rb (denoted hereafter as $|2\rangle$ and $|1\rangle$, respectively). The condensates begin with a well-defined relative phase, spatial extent, and "sag"—the position at which the magnetic trapping forces balance gravity for each state. The fine experimental control of this double-condensate system permits us to study its subsequent time evolution under a variety of interesting conditions, most notably those in which there remains substantial spatial overlap between the two states.

The apparatus and general procedure we use to attain BEC in Rb are identical to those of our previous work [14] and will be reviewed here but briefly. We use a double magneto-optical trap system to load roughly 10^9 $|1\rangle$ atoms into a time-averaged, orbiting potential (TOP) magnetic trap. The atoms are magnetically compressed and evaporatively cooled for 30 s until they form a condensate of approximately 5×10^5 atoms with no noticeable noncondensate fraction (we estimate that $>75\%$ of the entire gas is in the condensate). After completion of the evaporation cycle, the magnetic trap is ramped adiabatically to various bias fields and spring constants for the subsequent experiments.

The double-condensate system is prepared from the single $|1\rangle$ condensate by driving a two-photon transition [14] consisting of a microwave photon near 6.8 GHz and a radio frequency photon of 1–4 MHz, depending on the Zeeman splitting. As in [14], we are able to transfer quickly any desired fraction of the atoms to the $|2\rangle$ state by

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selecting the length and amplitude of the two-photon pulse. The two condensates [15] are created with identical density distributions, after which they evolve and redistribute themselves for some time T. We then turn off the magnetic trap and allow the atoms to expand for 22 ms for imaging.

We selectively image the densities of either of the two states (n_1 and n_2) or the combined density distribution (n_T) by changing the sequence of laser beams applied to the condensates for probing [14]. Since the expansion and imaging are destructive processes, each image is taken with a different condensate; the excellent reproducibility of the condensates permits us to study the time evolution of the system by changing the time T. The images of the condensates do not always appear in the same absolute locations on the charge-coupled device (CCD) array detector, however, and we compensate for this shot-to-shot jitter by reconstructing the relative positions of the condensates from the images of n_1, n_2, and n_T at each time T.

The evolution of the double-condensate system, including the release from the trap and subsequent expansion [1,18], is governed by a pair of coupled Gross-Pitaevskii equations for condensate amplitudes Φ_i:

$$i\hbar \frac{\partial \Phi_i}{\partial t} = \left(-\frac{\hbar^2 \nabla^2}{2m} + V_i + U_i + U_{ij} \right) \Phi_i \,, \qquad (1)$$

where $i, j = 1, 2$ $(i \neq j)$, V_i is the magnetic trapping potential for state i, the mean-field potentials are $U_i = 4\pi\hbar^2 a_i |\Phi_i|^2/m$ and $U_{ij} = 4\pi\hbar^2 a_{ij} |\Phi_j|^2/m$, m is the mass of the Rb atom, and the intraspecies and interspecies scattering lengths are a_i and a_{ij}, respectively. In the Thomas-Fermi limit, the condensate density distributions are dominated by the potential energy terms of Eq. (1). Consequently, the expanded density distributions retain their spatial information and emerge with their gross features (such as the relative position of the condensates) intact.

The similarity in scattering lengths a_1, a_2, and a_{12} implies that the total density n_T will not change significantly from its initial configuration even though the two components may redistribute themselves dramatically during the evolution time T. In ^{87}Rb, the scattering lengths are known at the 1% level to be in the proportion a_1:a_{12}:a_2::1.03:1:0.97, with the average of the three being 55(3) Å [14,19]. The near preservation of the total density n_T can be approached theoretically by deriving from Eq. (1) the hydrodynamic equations of motion [20] for n_T and evaluating them in the limit that the fractional differences between the scattering lengths are small. The pressures that tend to redistribute n_T must also be small. A similar argument pertains if the minima of the trapping potentials V_1 and V_2 are displaced from each other (see below) by a distance that is small compared to the size of the total condensate; once again, the effects on the equilibrium distribution of the individual components may be profound but the total density should remain largely unperturbed [21].

The rotating magnetic field of the TOP trap gives rise to a subtle behavior that permits us to displace the minima of the trapping potentials V_1 and V_2 with respect to each other [22,23]. In the rotating frame, the two states see two different magnetic fields as a function of the bias field rotation frequency and sense of rotation (as well as the strengths of the bias and quadrupole fields). By adjusting these parameters, we can change the sign of the relative sag or cause it to vanish [24] while preserving (to first order) the same radial (ν_r) and axial ($\nu_z = \sqrt{8}\,\nu_r$) trap oscillation frequencies.

In the first experiment, we choose a trap that has zero relative sag ($\nu_z = 47$ Hz) and transfer 50% of the atoms to the $|2\rangle$ state with a $\sim$400 μs pulse. When $T = 30$ ms, we observe a "crater" in the image of the $|1\rangle$ atoms (Fig. 1a). The crater corresponds to a region occupied by the $|2\rangle$ atoms (Fig. 1b), indicating that the $|1\rangle$ atoms have formed a shell about the $|2\rangle$ atoms. This is consistent with the theoretical prediction that it is energetically favorable for the atoms with the larger scattering length ($|1\rangle$) to form a lower-density shell about the atoms with the smaller scattering length ($|2\rangle$) [11]. At later times the $|2\rangle$ atoms break radial symmetry and drift transversely away from the center of the cloud [25].

In order to explore the boundary between the two condensates, we perform a series of experiments in a trap in which we displace the trapping potentials such that the minimum of V_2 is 0.4 μm lower than that of V_1, or approximately 3% of the (total) extent of the combined density distribution in the vertical direction. The subsequent time evolution of the system is shown in Figs. 2 and 3.

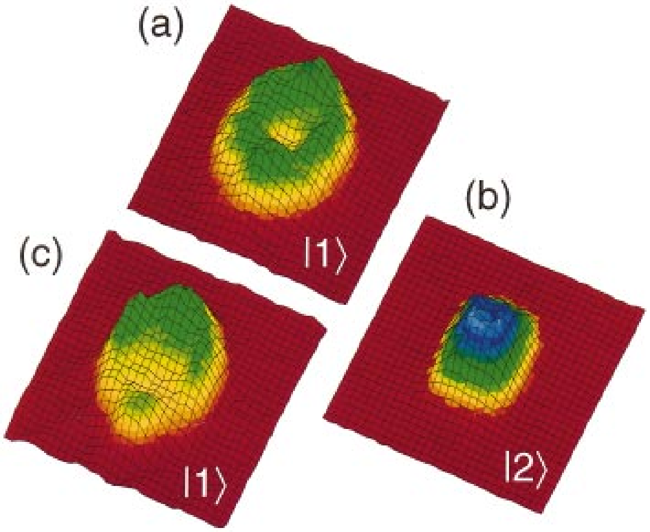

FIG. 1(color). (a) The image of the $|1\rangle$ condensate exhibits a crater, corresponding to a shell in which the $|2\rangle$ atoms (b) reside. For this trap, $\nu_z = 47$ Hz with zero relative sag. By changing the strength of the magnetic quadrupole field, we can introduce a nonzero relative sag, which shifts the location of the crater (c). (Each square in this postexpansion image is 136 μm on a side.)

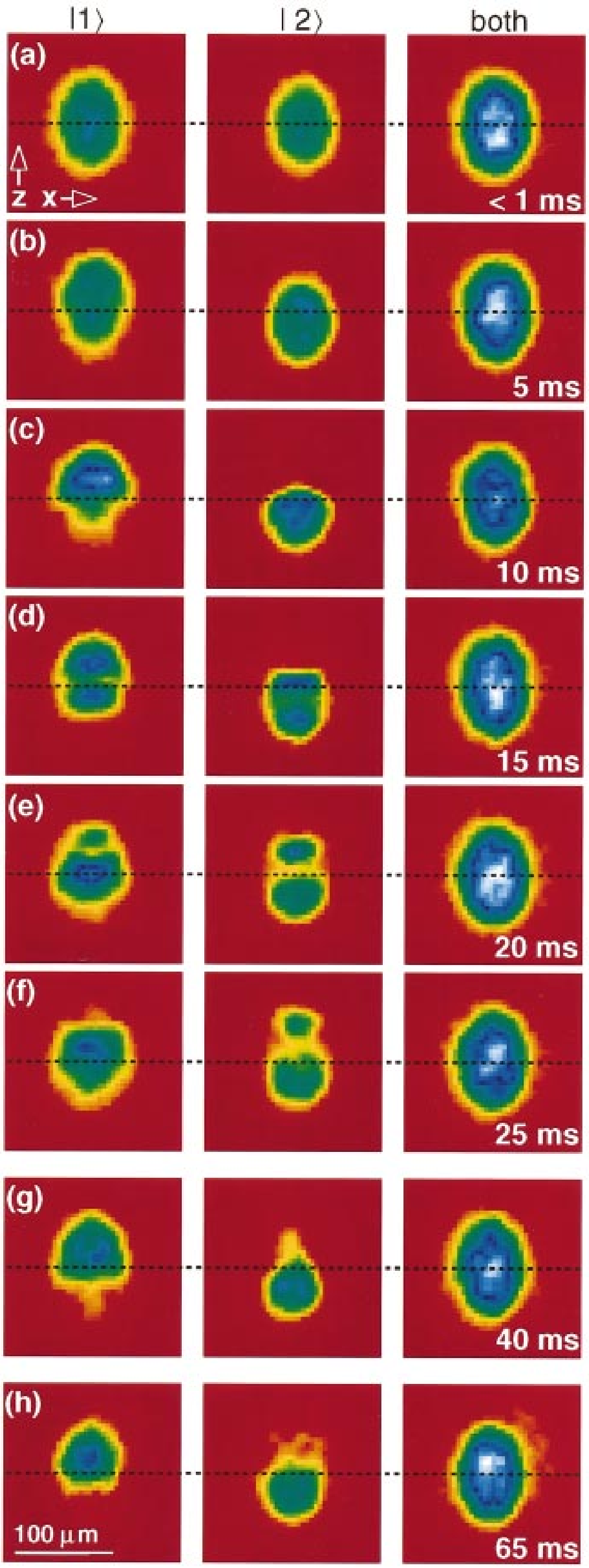

FIG. 2(color). Time evolution of the double-condensate system with a relative sag of 0.4 μm (3% of the width of the combined distribution prior to expansion) and a trap frequency $\nu_z = 59$ Hz.

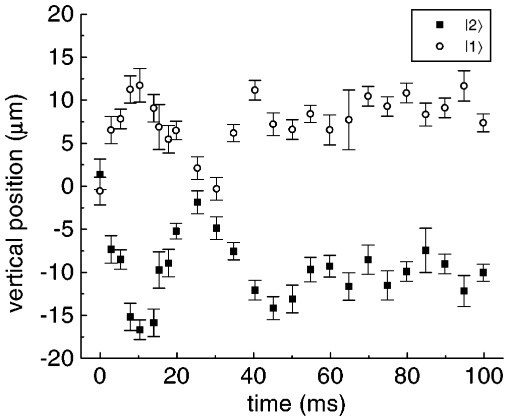

FIG. 3. The relative motion of the centers of mass of the two condensates under the same conditions as those in Fig. 2.

The two states almost completely separate (Figs. 2a–2c) after 10 ms; they then "bounce" back until, at $T = 25$ ms, the centers of mass are once more almost exactly superimposed (Fig. 3), although a distinctive (and reproducible) vertical structure has formed (Figs. 2d–2f). By $T = 65$ ms, the system has apparently reached a steady state (Figs. 2g, 2h, and 3) in which the separation of the centers of mass is 20% of the extent of the entire condensate. From these images we observe (i) the fractional steady-state separation of the expanded image is large compared

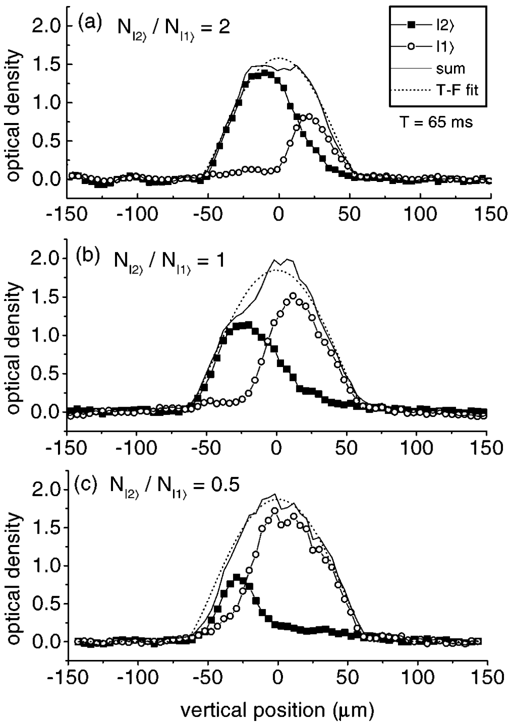

FIG. 4. Vertical cross sections of the density profiles at $T = 65$ ms for different relative numbers of atoms in the two states. The combined density distribution (solid line) is shown for comparison to the Thomas-Fermi parabolic fit (dashed line). The trap parameters are the same as those in Fig. 2.

to the fractional amount of applied symmetry breaking, as we expect for a repulsive interspecies potential; (ii) the placid total density profile (rightmost column of Fig. 2) betrays little hint of the underlying violent rearrangement of the component species; (iii) the component separation is highly damped, although it is not yet certain what mechanism [26] is responsible. With respect to the damping, the excitation is not small and may therefore be poorly modeled by theories that treat the low-lying, small-amplitude excitations [12] of double condensates.

Finally, we show the optical density as a function of relative number and position on the condensate vertical axis in order to better appreciate the amount of overlap between the two states at $T = 65$ ms (Fig. 4), which remains substantial despite the underlying separation. Each plot is averaged across a $\sim 14\ \mu$m wide vertical cut through the centers of the two condensates. From the overlap shown, one could determine the magnitude of the interspecies scattering length a_{12} by comparison to theoretical calculations conducted within the Thomas-Fermi approximation [8] and numerical solutions of the Gross-Pitaevskii [11] or Hartree-Fock [9] equations. Such calculations are beyond the scope of the present paper.

The overlap region also affords an opportunity to measure the accumulation of relative phase between the two condensates. We explore some of the experimental aspects of the phase evolution of the double-condensate system in the companion article [17].

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[16] The 6.8 GHz energy difference is a million times larger than any other relevant energy scale in the system. For example, the energy released by a *single* atom converting from a $|2\rangle$ state to the $|1\rangle$ state would, if distributed throughout the sample, be enough to drive the *entire sample* out of the condensate state.
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