

## Observation of the Scissors Mode and Evidence for Superfluidity of a Trapped Bose-Einstein Condensed Gas

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We report the observation of the scissors mode of a Bose-Einstein condensed gas of  $^{87}\text{Rb}$  atoms in a magnetic trap, which gives direct evidence of superfluidity in this system. The scissors mode of oscillation is excited by a sudden rotation of the anisotropic trapping potential. For a gas above  $T_c$  (normal fluid) we detect the occurrence of oscillations at two frequencies, with the lower frequency corresponding to the rigid body value of the moment of inertia. Well below  $T_c$  the condensate oscillates at a single frequency, without damping, as expected for a superfluid.

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The relationship between Bose-Einstein condensation (BEC) [1] and superfluidity has been studied extensively in liquid helium [2], but only recently has it been possible to examine it in condensates of dilute alkali metal vapors [3,4]. Helium below its critical point is described by a two-fluid model and the liquid is endowed with a new degree of freedom, namely, the relative motion between the normal fluid and the superfluid. "This degree of freedom is the essence of the transport phenomena in He II known collectively as superfluidity" [5]. In the dilute alkali metal condensates various phenomena which imply the occurrence of superfluidity have been observed, e.g., collective modes of excitation [6] and demonstrations of the coherence of the wave function [7]. However in a recent theoretical paper Guéry-Odelin and Stringari [8] describe how the superfluidity of a trapped BEC may be demonstrated directly and we report the results of such an experiment. Guéry-Odelin and Stringari analyze the so-called scissors mode in which the atomic cloud oscillates with respect to the symmetry axis of the confining potential and they point out that the scissors mode has been used in nuclear physics to demonstrate the superfluidity of neutron and proton clouds in deformed nuclei [9,10].

The full theoretical analysis of the scissors mode is given in [8] and we outline only the key points here. The starting point is a BEC in an anisotropic harmonic potential with three different frequencies  $\omega_x \approx \omega_y < \omega_z$ . The scissors mode may be initiated by a sudden rotation of the trapping potential through a small angle as indicated in Fig. 1. In the subsequent motion, the cloud is not deformed provided that the change in the potential is too small to excite shape oscillations. For a thermal gas both rotational and irrotational fluid flow occur in the scissors mode and the normal fluid is predicted to exhibit two frequencies corresponding to those forms of motion. For the BEC there is only irrotational flow because of its single valued wave function and therefore it exhibits only one frequency, which is different from either of the frequencies observed for the thermal cloud.

In our experiment the trapping potential is created by a time-averaged orbiting potential (TOP) trap [11] which is

a combination of a static quadrupole field, of gradient  $B'_Q$  in the radial direction, and a time-varying field

$$\mathbf{B}_T(t) = B_r(\cos\Omega t \mathbf{e}_x + \sin\Omega t \mathbf{e}_y) + B_z \cos\Omega t \mathbf{e}_z.$$

The term  $\mathbf{B}_z(t) = B_z \cos\Omega t \mathbf{e}_z$  is additional to the usual field of amplitude  $B_r$  rotating in the  $xy$  plane. The effect of the additional term  $\mathbf{B}_z(t)$  is to tilt the plane of the locus of  $\mathbf{B} = 0$  by an angle  $\xi = \tan^{-1}(B_z/B_r)$  with respect to the  $xy$  plane. This causes the symmetry axes of the potential to rotate through an angle  $\phi \approx \frac{2}{3}\xi$  in the  $xz$  plane (this analytic result is valid only for  $\xi^2 \ll 1$ ). It is only necessary to consider the  $xz$  plane since the absorption image of the cloud is projected onto this plane. Tilting the locus of  $\mathbf{B} = 0$  reduces the oscillation frequency in the  $z$  direction from its value when  $B_z = 0$ . Thus simply switching on  $\mathbf{B}_z(t)$  also changes the cloud shape and so excites quadrupole mode oscillations. To avoid this we first adiabatically modify the usual TOP trap to a tilted trap and then quickly change  $\mathbf{B}_z(t)$  to  $-\mathbf{B}_z(t)$ . This procedure rotates the symmetry axes of the trap potential by  $2\phi$  without affecting the trap oscillation frequencies (Fig. 1).

Our apparatus for producing BEC of  $^{87}\text{Rb}$  is described in [12] and only a few relevant features are outlined below. We trap and cool the atoms in a small glass cell that forms part of a differentially pumped system with two magneto-optical traps [13], one of which is a pyramidal configuration of mirrors inside the vacuum system [14]. The Helmholtz coils which create the oscillating fields along the  $x$ ,  $y$ , and  $z$  directions are driven by audio amplifiers and it was found to be extremely important to filter out high frequency noise, especially in the coils driving the field along the  $z$  axis [15]. The  $^{87}\text{Rb}$  atoms in the  $F = 2, m_F = 2$  state were probed by a  $10 \mu\text{s}$  pulse of laser light propagating along the  $y$  axis, resonant with the  $F = 2, m_F = 2 \rightarrow F' = 3, m_{F'} = 3$  transition. The probe pulse was synchronized to the point in the rotation when the magnetic field points along the  $y$  axis and this probing scheme is not affected by  $\mathbf{B}_z(t)$ . We are restricted to probing at times which are multiples of the rotation period of the field ( $143 \mu\text{s}$ ) but this is very much smaller than the

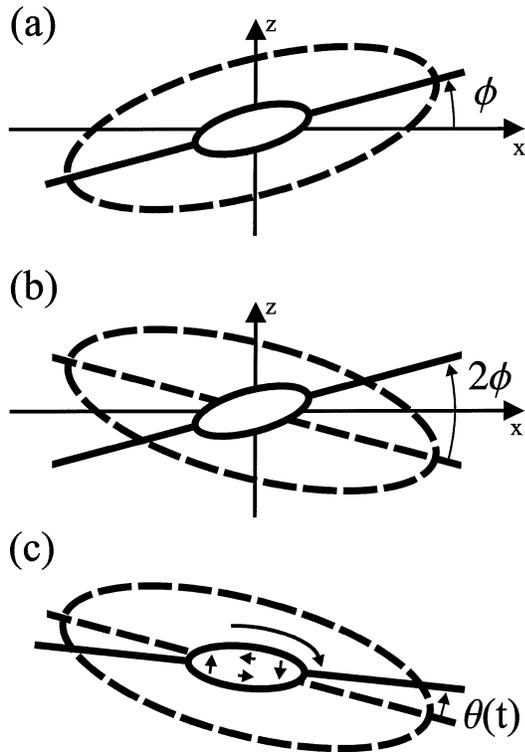


FIG. 1. The method of exciting the scissors mode by a sudden rotation of the trapping potential. The solid lines indicate the shape of the atomic cloud and its major axes. The dotted lines indicate the shape of the potential and its major axes. (a) The initial situation after adiabatically ramping on the field in the  $z$  direction, with cloud and potential aligned. (b) The configuration immediately after rotating the potential, with the cloud displaced from its equilibrium position. (c) The large arrow indicates the direction of the scissors mode oscillation and the smaller arrows show the expected quadrupolar flow pattern in the case of a BEC. The cloud is in the middle of an oscillation period. (The angles have been exaggerated for clarity.)

period of the oscillations in the trap, as it must be for the TOP trap to work.

The following experimental procedure was used to excite the scissors mode both in the thermal cloud and in the BEC. Laser cooled atoms were loaded into the magnetic trap and after evaporative cooling the trap frequencies were  $\omega_x = 90 \pm 0.2$  Hz and  $\omega_z = \sqrt{8} \omega_x$ . The trap was then adiabatically tilted in 1 s by linearly ramping  $\mathbf{B}_z(t)$  to its final value, corresponding to  $\phi = 3.6^\circ$  and a reduction of the trap frequency  $\omega_z$  by  $\sim 2\%$ . Suddenly reversing the sign of  $\mathbf{B}_z(t)$  in less than  $100 \mu\text{s}$  excites the scissors mode in the trapping potential with its symmetry axes now tilted by  $-\phi$ , as described above. The initial orientation of the cloud with respect to the new axis is  $\theta_0 = 2\phi$ , so this angle is the expected amplitude of the oscillations (Fig. 1). The angle of the cloud was extracted from a two-dimensional Gaussian fit of the absorption profiles such as those shown in Fig. 2.

For the observation of the thermal cloud the atoms were evaporatively cooled to  $1 \mu\text{K}$  which is about 5 times  $T_c$ ,

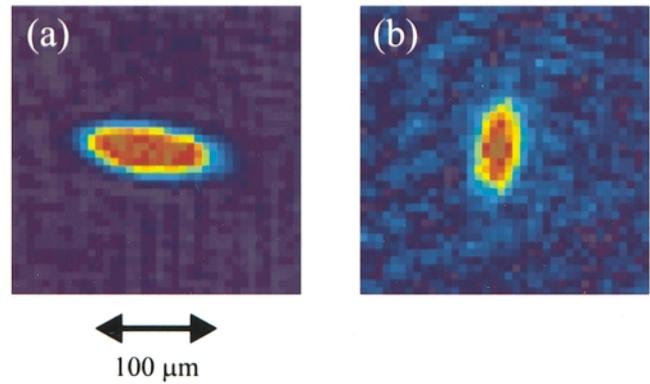


FIG. 2 (color). (a) Image of the thermal cloud in the trap. (b) Image of the condensate after 15 ms of time of flight. The condensate expands most rapidly along the direction which is initially most tightly confined, leading to a  $90^\circ$  difference in orientation as compared to the thermal cloud.

the temperature at which quantum degeneracy is observed. At this stage there were  $\sim 10^5$  atoms remaining with a peak density of  $n_0 \sim 2 \times 10^{12} \text{ cm}^{-3}$ . The scissors mode was then excited and pictures of the atom cloud in the trap were taken after a variable delay. The results of many runs are presented in Fig. 3(a) showing the way the thermal cloud angle changes with time. The model used to fit this evolution is the sum of two cosines, oscillating at frequencies  $\omega_1$  and  $\omega_2$ . From the data we deduce  $\omega_1/2\pi = 338.5 \pm 0.8$  Hz and  $\omega_2/2\pi = 159.1 \pm 0.8$  Hz. These values are in very good agreement with the values  $339 \pm 3$  Hz and  $159 \pm 2$  Hz predicted by theory [8], which correspond to  $\omega_1 = \omega_z + \omega_x$  and  $\omega_2 = \omega_z - \omega_x$ . We measured  $\omega_x$  and  $\omega_z$  by observing the center of mass oscillations of a thermal cloud in the untilted TOP trap and calculating the modification of these frequencies caused by the tilt. The amplitudes of the two cosines were found to be the same, showing that the energy is shared equally between the two modes of oscillation.

To observe the scissors mode in a Bose-Einstein condensed gas, we carry out the full evaporative cooling ramp to well below the critical temperature, where no thermal cloud component is observable, leaving more than  $10^4$  atoms in a pure condensate. After exciting the scissors mode we allow the BEC to evolve in the trap for a variable time and then use the time-of-flight technique to image the condensate 15 ms after releasing it from the trap. The repulsive mean-field interactions cause the cloud to expand rapidly when the confining potential is switched off, so that its spread is much greater than the initial size. The aspect ratio of the expanded cloud is opposite to that of the original condensate in the trap, so that the long axis of the time-of-flight distribution is at  $90^\circ$  to that of the thermal cloud as shown in Fig. 2. However this difference in the orientation does not affect the amplitude of the angle of oscillation. The scissors mode in the condensate is described by an angle oscillating at a single

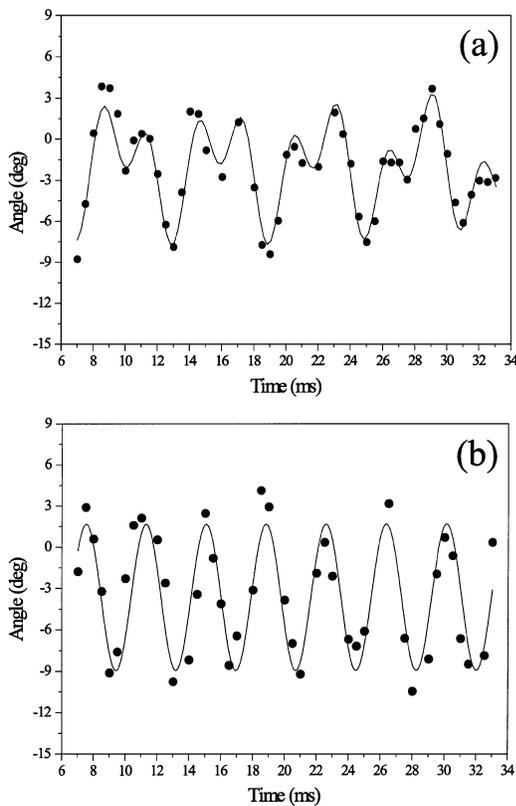


FIG. 3. (a) The evolution of the scissors mode oscillation with time for a thermal cloud. For a classical gas the scissors mode is characterized by two frequencies of oscillation. The temperature and density of our thermal cloud are such that there are few collisions, so no damping of the oscillations is visible. (b) The evolution of the scissors mode oscillation for the condensate on the same time scales as the data in (a). For the BEC there is an undamped oscillation at a single frequency  $\omega_c$ . This frequency is not the same as either of the thermal cloud frequencies.

frequency  $\omega_c$

$$\theta(t) = -\phi + \theta_0 \cos(\omega_c t). \quad (1)$$

Figure 3(b) shows some of the data obtained by exciting the scissors mode in the condensate. Consistent data, showing no damping, were recorded for times up to 100 ms. From an optimized fit to all the data for the function in Eq. (1) we find a frequency of  $\omega_c/2\pi = 265.6 \pm 0.8$  Hz which agrees very well with the predicted frequency of  $265 \pm 2$  Hz from  $\omega_c = \sqrt{\omega_x^2 + \omega_z^2}$ . The aspect ratio of the time-of-flight distribution is constant throughout the data run confirming that there are no shape oscillations and that the initial velocity of a condensate (proportional to  $\dot{\theta}$ ) does not have a significant effect.

These observations of the scissors mode clearly demonstrate the superfluidity of Bose-Einstein condensed rubidium atoms in the way predicted by Guéry-Odelin and Stringari [8]. Direct comparison of the thermal cloud and BEC under the same trapping conditions shows a clear difference in behavior between the irrotational quantum fluid and a classical gas. Another distinction is the lack of damp-

ing in the superfluid. In a thermal cloud there is damping on the time scale of collisions between the atoms. To illustrate this well-known property of a classical gas we calculated the damping in a thermal cloud using the direct simulation Monte Carlo method [16], for a mean density and temperature that are roughly the same as those of the BEC. (Since the condensate and the thermal cloud have different spatial distributions the comparison is only approximate.) The results of such a numerical calculation for a thermal cloud at a temperature of 90 nK and a peak density of  $2 \times 10^{14} \text{ cm}^{-3}$  are shown in Fig. 4 and the plot shows that the scissors mode of a classical gas is strongly damped under these conditions. Note that even for such high densities both frequency components still occur in the thermal cloud, giving behavior that is clearly different from the undamped, single frequency oscillation observed for the BEC. The results of this numerical simulation show that the amplitude of the lower frequency component is much smaller than that of the higher frequency one. The higher frequency tends towards  $\omega_c$ , the same frequency as the condensate, when the density increases so that the hydrodynamic regime is reached (where there are many collisions per oscillation period). However in this regime the damping is so strong that only a few oscillation periods would be observed as shown in [8]. We cannot reach the hydrodynamic regime experimentally because the density of the thermal cloud is 2 orders of magnitude lower than that of the condensate (the increase in phase-space density during evaporation comes mainly from the decrease in temperature).

In the near future we plan to measure the frequency of the scissors mode at finite temperatures in the condensate, i.e., where a trapped thermal cloud is present in addition to the BEC. Under these conditions the scissors mode should be damped [8] in a similar way to the quadrupole oscillations at finite temperature [17]. There is still not good agreement between the observed change in frequency of the  $m = 0$  oscillation mode of a condensate at finite

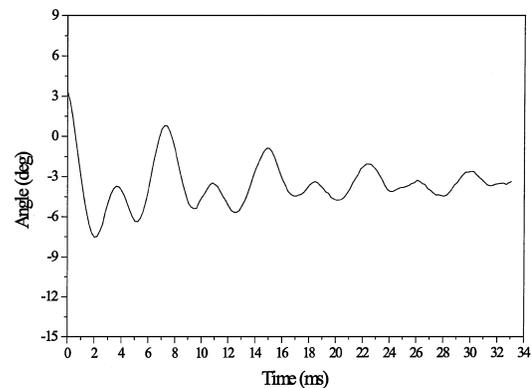


FIG. 4. A numerical simulation of the scissors mode oscillation for a thermal cloud with a temperature and density comparable to the condensate in our experiment. The two frequency components are present and the damping time is about 15 ms.

temperature and theoretical predictions [18] and therefore using the scissors mode as an alternative means of probing the interaction between the condensate and thermal cloud is important. We have found that the measurement of the angle of orientation of the cloud in the scissors mode is quite robust and could be applied in situations close to  $T_c$  where only a small proportion of the atoms is condensed. In this way the scissors mode should enable studies of the relative motion of the thermal cloud and condensate corresponding to motion of the superfluid through a normal fluid.

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