Observation of the scissors mode and evidence for superfluidity of a trapped Bose-Einstein condensed gas

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The relationship between Bose-Einstein condensation (BEC) [1] and superfluidity has been studied extensively in liquid helium, but only recently has it been possible to examine it in condensates of dilute alkali metal vapours [2]. In a recent theoretical paper Guéry-Odelin and Stringari [3] describe how the superfluidity of a trapped BEC is related to a transverse collective mode, the so-called scissors mode in which the atomic cloud oscillates with respect to the symmetry axis of the confining potential. 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 is then initiated by a sudden rotation of the trapping potential through a small angle.

In our experiment the trapping potential is created by a Time-averaged Orbiting Potential (TOP) trap which is a combination of a static quadrupole field and a time-varying field with an axial component $\mathbf{B}_z(t) = B_z \cos\Omega t\ \mathbf{e}_z$ additional to the usual field of amplitude B_r rotating in the x-y plane. The effect of the additional term is to rotate the symmetry axes of the potential through an angle ϕ in the x-z plane. After adiabatically transfer the condensate in such tilted trap, we then quickly change $\mathbf{B}_z(t)$ to $-\mathbf{B}_z(t)$. This procedure initiate the scissors oscillation for a thermal cloud or a BEC with an amplitude $\theta_0 = 2\phi$.

For the observation of the thermal cloud the atoms were evaporatively cooled to $5T_c$ (T_c being the temperature at which quantum degeneracy is observed). 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.1(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 ω_1 and ω_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 ± 3 Hz and 159 ± 2 Hz predicted by theory [3]; which correspond to $\omega_1 = \omega_z + \omega_x$ and $\omega_2 = \omega_z - \omega_x$. 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

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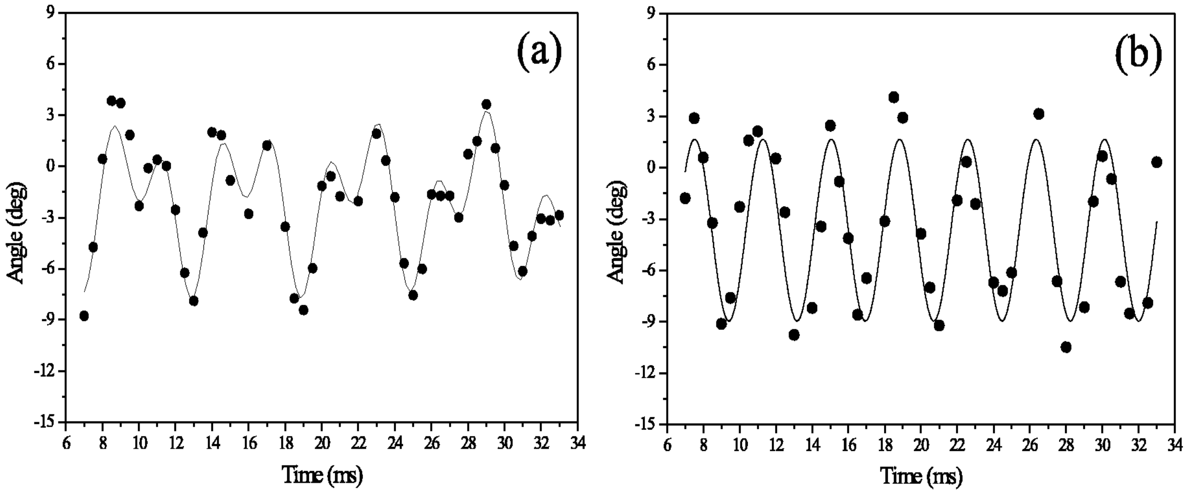

Figure 1: (a) The evolution of the scissors mode oscillation with time for a thermal cloud. For a classical gas the scissors mode is characterized by two frequencies of oscillation. (b) The evolution of the scissors mode oscillation for the condensate on the same time scales as the data in (a). For the BEC there is an oscillation at a single frequency ω_c. This frequency is not the same as either of the thermal cloud frequencies.

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. The scissors mode in the condensate is described by an angle oscillating at a single frequency ω_c. From the data in Fig. 1 (b) we deduce a frequency of $\omega_c/2\pi = 265.6 \pm 0.8$ Hz which agrees very well with the predicted frequency of 265 ± 2 Hz from $\omega_c = \sqrt{\omega_x^2 + \omega_z^2}$.

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 [3].

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