

Evidence for a Critical Velocity in a Bose-Einstein Condensed Gas

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We have studied dissipation in a Bose-Einstein condensed gas by moving a blue detuned laser beam through the condensate at different velocities. Strong heating was observed only above a critical velocity.

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Macroscopic quantum coherence and collective excitations are key features in our understanding of the phenomenon of superfluidity. The superfluid velocity is proportional to the gradient of the phase of a macroscopic wave function. Collective excitations determine a critical velocity below which the flow is dissipationless. This velocity is given by Landau's criterion [1],

$$v_c = \min\left(\frac{\varepsilon(p)}{p}\right), \quad (1)$$

where ε is the energy of an excitation with momentum p . Critical velocities for the breaking of Cooper pairs in ^3He and the generation of rotons [2] and vortices [3] in ^4He have been extensively studied.

Bose-Einstein condensed gases (BEC) are novel quantum fluids [4]. Previous work has explored some aspects related to superfluidity such as the macroscopic phase [5] and the phonon nature of low-lying collective excitations [4,6]. In this Letter we report on the measurement of a critical velocity for the excitation of a trapped Bose-Einstein condensate. In analogy with the well known argument by Landau and the vibrating wire experiments in superfluid helium [7], we study dissipation when an object is moved through the fluid. Instead of a massive macroscopic object we used a blue detuned laser beam which repels atoms from its focus to create a moving boundary condition.

The experiment was conducted in a new apparatus for the production of Bose-Einstein condensates of sodium atoms. The cooling procedure is similar to previous work [8]—the new features have been described elsewhere [9]. Briefly, laser cooled atoms were transferred into a magnetic trap in the Ioffe-Pritchard configuration and further cooled by rf evaporative cooling for 20 sec, resulting in condensates of between 3×10^6 and 12×10^6 atoms. After the condensate was formed, we reduced the radial trapping frequency to obtain condensates which were considerably wider than the laser beam used for stirring. This decompression was not perfectly adiabatic, and heated the cloud to a final condensate fraction of about 60%. The final trapping frequencies were $\nu_r = 65$ Hz in the radial and $\nu_z = 18$ Hz in the axial direction. The resulting condensate was cigar-shaped with Thomas-

Fermi diameters of 45 and 150 μm in the radial and axial directions, respectively. The final chemical potential, transition temperature T_c , and peak density n_0 of the condensate were 110 nK, 510 nK, and $1.5 \times 10^{14} \text{ cm}^{-3}$, respectively.

The laser beam for stirring the condensate had a wavelength of 514 nm and was focused to a Gaussian $1/e^2$ beam diameter of $2w = 13 \mu\text{m}$. The repulsive optical dipole force expelled the atoms from the region of highest laser intensity. A laser power of 400 μW created a 700 nK barrier resulting in a cylindrical hole $\sim 13 \mu\text{m}$ in diameter within the condensate. The laser barrier created a *soft* boundary, since the Gaussian beam waist was more than 10 times wider than the healing length $\xi = (8\pi an_0)^{-1/2} = 0.3 \mu\text{m}$, a being the two-body scattering length.

The laser was focused on the center of the cloud. Using an acousto-optic deflector, it was scanned back and forth along the axial dimension of the condensate (Fig. 1). We ensured a constant beam velocity by applying a triangular waveform to the deflector. The beam was scanned over distances up to 60 μm , much less than the axial extent

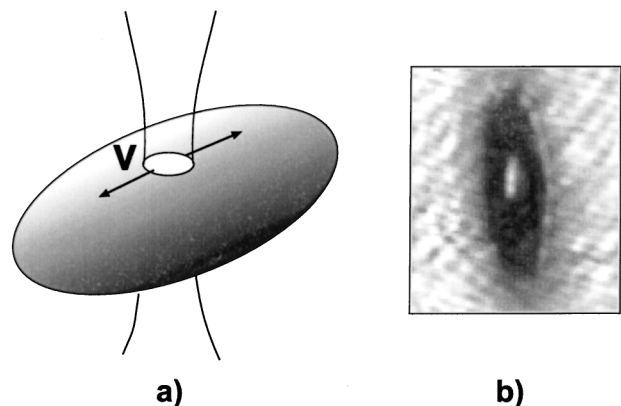


FIG. 1. Stirring a condensate with a blue detuned laser beam. (a) The laser beam diameter is 13 μm , while the radial width of the condensate is 45 μm . The aspect ratio of the cloud is 3.3. (b) *In situ* absorption image of a condensate with the scanning hole. A 10 kHz scan rate was used for this image to create the time-averaged outline of the laser trajectory through the condensate.

of the condensate of $150 \mu\text{m}$. Therefore, axial density variations were small within the scan range. The scan frequencies were varied by a factor of 3 between 56 and 167 Hz. Scan velocities close to the speed of sound required scan frequencies much larger than the axial trapping frequency ν_z .

After exposing the atoms to the scanning laser for 900 ms, we allowed the cloud to equilibrate for 100 ms, then turned off the magnetic trap and recorded the time-of-flight distribution after 35 ms on a CCD camera using near-resonant absorption imaging. The condensate fraction N_0/N was determined from fits to the bimodal velocity distribution [10]. We found that the decreasing condensate fraction was a more robust measure of the heating induced by the moving laser beam than the temperature extracted from the wings of the thermal cloud. No heating was observed when the laser beam was kept stationary for the entire 900 ms.

Figure 2 shows the effect of the moving laser on the condensate for three different scan rates $f = 56, 83,$ and 167 Hz. The heating rate is higher (larger final thermal fraction) for larger drive amplitudes d and higher scan frequencies f . When the same data are replotted as a function of the *velocity* of the laser beam $2df$ (Fig. 3), two features emerge immediately. First, all the three data sets collapse onto one universal curve, indicating that the heating of the condensate depends primarily on the velocity of the beam, and *not* on either frequency or amplitude independently. This suggests that the observed dissipation is not strongly affected by the trapping potential and discrete resonances, but rather reflects bulk properties of the condensate.

The second feature is that we can distinguish two regimes of heating separated by the dashed line in

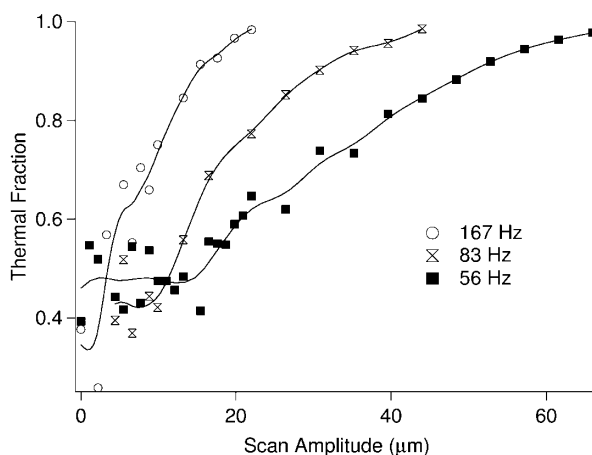


FIG. 2. Heating a condensate with a moving laser beam. The final thermal fraction increased with both the scan amplitude and the scan rate of the laser beam. The total exposure time was the same for all data points. They represent single shot measurements. Solid lines are smoothing spline fits to guide the eye.

Fig. 3. For low velocities, the dissipation rate was low and the condensate appeared immune to the presence of the scanning laser beam. For higher velocities, the heating increased, until at a velocity of about 6 mm/s the condensate was almost completely depleted for a 900 ms exposure time. The crossover between these two regimes was quite pronounced and occurred at a velocity of about 1.6 mm/s. This velocity should be compared with the speed of sound in the condensate. Since a condensate released from the magnetic trap expands with a velocity proportional to the speed of sound, we could determine its value directly from time-of-flight absorption images to be 6.2 mm/s (at the peak density), almost a factor of 4 larger than the observed critical velocity.

To rule out the possibility of heating through the non-condensed fraction, a control experiment was performed on clouds at two different temperatures above T_c , 800 and 530 nK, the latter quite close to the transition temperature. No heating of the cloud was observed in either case, for scan velocities of up to 14 mm/s; this reflects the small overlap between the scanning laser and the large thermal cloud. Since these clouds are typically not in the hydrodynamic regime of collisions, we used a single particle model for heating based on collisions with a moving wall to scale our measurements from above to below T_c . We obtained a conservative upper bound of 15% of the observed temperature rise which could be attributed to the noncondensed fraction.

What determines the critical velocity? In a quasihomogeneous dilute Bose gas near zero temperature, the critical velocity for phonon excitation is the speed of Bogoliubov

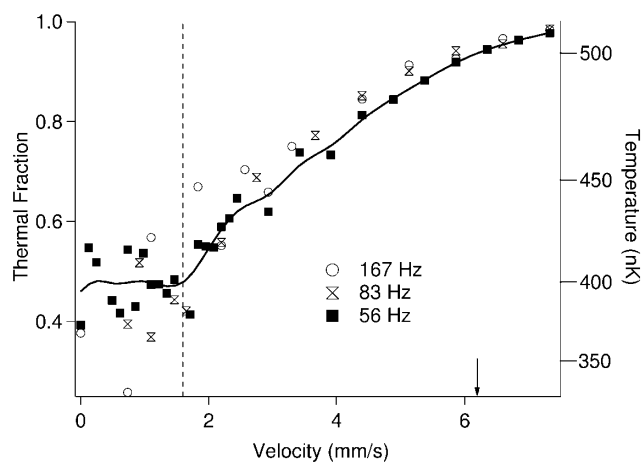


FIG. 3. Evidence for a critical velocity. The same three data sets as in Fig. 2 are replotted vs laser beam velocity and all appear to lie upon a universal curve. The dashed line separates the regimes of low and high dissipation. The right axis indicates the temperature $T = (1 - N_0/N)^{1/3}T_c$. The peak sound velocity is marked by an arrow. The data series for 83 and 167 Hz showed large shot-to-shot fluctuations at velocities below 2 mm/sec. The solid line is a smoothing spline fit to the 56 Hz data set to guide the eye.

sound, which depends on the density $n(r)$ through

$$c_B(r) = \sqrt{\frac{4\pi\hbar^2 a}{M^2} n(r)}, \quad (2)$$

where M is the atomic mass. Alternately, one may expect that the rapid flow around the laser beam generates vorticity in the fluid. For the excitation of vortex pairs in a channel of diameter D , Eq. (1) leads to a critical velocity [11]

$$v_c = \frac{\hbar}{MD} \ln\left(\frac{D}{\xi}\right). \quad (3)$$

Since this velocity scales inversely with the size of the system, it is lower than the value predicted by Eq. (2). For our situation Eq. (3) can give only an approximate estimate due to the inhomogeneous density and the different geometry. For a channel width of $15 \mu\text{m}$ and a healing length of $0.3 \mu\text{m}$ it yields a critical velocity of about 0.7 mm/s , a factor of 2 below our measurement.

The criterion given in Eq. (3) is based only on considerations of energy and momentum and provides a lower bound to v_c . In addition, one must consider how to produce the excitations dynamically. Several mechanisms for creating vortex lines have been discussed, including remanent vorticity and vorticity pinned to the surface [12]. In the latter case, the critical velocity depends on the surface roughness. The gaseous condensates are confined to magnetic traps which provide perfectly smooth boundary conditions. Therefore, we expect that the critical velocity is determined by nucleation dynamics rather than by purely energetic arguments.

The relevant criterion for the onset of dissipation in a Bose condensed gas obeying the nonlinear Schrödinger equation has been discussed in several papers. According to these theories, dissipation ensues when the relative velocity between the object and the fluid exceeds the speed of sound c_B locally [13–15]. For an incompressible flow around a cylindrical object this velocity peaks at the side, reaching twice the object's speed. The hydrodynamic equations for the compressible condensate imply that the faster the velocity of the flow field, the lower is the condensate density. This effect lowers the critical velocity for a cylindrical object even further [13]:

$$v_c = \sqrt{\frac{2}{11}} c_{\text{max}} = 0.42 c_{\text{max}}. \quad (4)$$

This result is independent of the size of the object and was corroborated by numerical simulations of the nonlinear Schrödinger equation in a homogeneous gas [13–15]. For our conditions, this estimate yields a critical velocity of 2.6 mm/s , or 1.6 times the observed threshold. However, the finite size of the condensate in our experiments [16], its inhomogeneous density distribution, and the soft boundary of the laser beam are not accounted for by the theory. All these effects should lower the critical velocity.

What happens to the condensate above v_c ? Numerical simulations of the nonlinear Schrödinger equation were used to study the flow field around an object moving through a homogeneous condensate [13,14,17]. These studies show that above a critical velocity given by Eq. (4) the superfluid flow becomes unstable against the formation of quantized vortex lines, which signals the onset of a new, dissipative regime. Pairs of vortices with opposite circulation are generated at opposite sides of the object in order to reduce the high local flow speed. The rate of heating can be estimated from the energy of vortices and the vortex shedding frequency.

The energy of a vortex pair ε_{vp} is estimated with the assumption that the vortices are separated by the object diameter $2w$ [18],

$$\varepsilon_{vp} = 2\pi D \frac{n\hbar^2}{M} \ln \frac{2w}{\xi}, \quad (5)$$

where D is the radial width of the condensate and n is the density. This yields a value of about 3.4 mK or 1.3 nK/atom . Numerical simulations [13,15] have shown that for $v > v_c$ the rate of vortex pair shedding is proportional to $v - v_c$. The proportionality constant, besides a numerical factor, is the mean field energy in frequency units divided by the speed of sound. Thus the rate of change in temperature should have the form $\dot{T} = \kappa(v - v_c)$. Using the estimate for the vortex energy, the model predicts $\kappa \approx 160 \text{ nK/mm}$, in rough agreement with our measured heating rate near the threshold which gives $\kappa = 62 \text{ nK/mm}$.

In conclusion, we have established a method for studying dissipation in a Bose condensate by implementing a scanning “hole” induced by a far-off-resonant laser beam. Both the laser beam and the trapped condensate provide clean boundary conditions. This and the simplicity of the system make it amenable to theoretical treatments of vortex nucleation and dissipative dynamics. We found evidence for a critical velocity for excitation of the condensate. Both the onset and the magnitude of the observed heating are in qualitative agreement with model calculations based on the nonlinear Schrödinger equation which predict dissipation when the flow field becomes locally supersonic. In contrast, a similar study on rotational stirring concluded that the speed of sound near the stirrer is irrelevant for vortex nucleation [19]. In further studies, we plan to vary the geometry and density in order to distinguish between different predictions for critical velocities which depend only on geometry [Eq. (3)] or only on the density [Eq. (4)]. All the calculations were done in two dimensions and at zero temperature. In the experiment, the laser beam passes through the surface of the condensate where the density vanishes. Because of this and the nonzero temperature, we expect finite dissipation even at low velocities and a smooth crossover between low and high dissipation. More precise measurements of

the heating should allow us to study these finite-size and finite-temperature effects.

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- [1] See, for example, I.M. Khalatnikov, *Introduction to the Theory of Superfluidity* (Benjamin, New York, 1965).
 - [2] D.R. Allum, P.V.E. McClintock, A. Phillips, and R.M. Bowley, *Philos. Trans. R. Soc. London A* **284**, 179 (1977); T. Ellis, C.I. Jewell, and P.V.E. McClintock, *Phys. Lett.* **78A**, 358 (1980).
 - [3] A. Amar, Y. Sasaki, R.L. Lozes, J.C. Davis, and R.E. Packard, *Phys. Rev. Lett.* **68**, 2624 (1992); O. Avenel and E. Varoquaux, *Phys. Rev. Lett.* **55**, 2704 (1985).
 - [4] See the reviews by W. Ketterle, D.S. Durfee, and D.M. Stamper-Kurn (e-print cond-mat/9904034), as well as by E.A. Cornell, J.R. Ensher, and C.E. Wieman (e-print cond-mat/9903109), in *Bose-Einstein Condensation in Atomic Gases*, Proceedings of the International School of Physics "Enrico Fermi," edited by M. Inguscio, S. Stringari, and C.E. Wieman (SIF, Bologna, to be published).
 - [5] M.R. Andrews *et al.*, *Science* **275**, 637 (1997); D.S. Hall, M.R. Matthews, C.E. Wieman, and E.A. Cornell, *Phys. Rev. Lett.* **81**, 1543 (1998).
 - [6] D.M. Stamper-Kurn *et al.*, e-print cond-mat/9906035 v2, 4 (1999).
 - [7] C.A.M. Castelijns, K.F. Coates, A.M. Guénault, S.G. Mussett, and G.R. Pickett, *Phys. Rev. Lett.* **56**, 69 (1986).
 - [8] M.-O. Mewes *et al.*, *Phys. Rev. Lett.* **77**, 416 (1996).
 - [9] R. Onofrio *et al.*, e-print cond-mat/9908340.
 - [10] Data were excluded when the total number of atoms N deviated by more than $\pm 25\%$ of the average.
 - [11] R.P. Feynman, in *Progress in Low Temperature Physics* (North-Holland Publishing Co., Amsterdam, 1955), Vol. 1, p. 17.
 - [12] J. Wilks and D.S. Betts, *An Introduction to Liquid Helium* (Clarendon Press, Oxford, 1987).
 - [13] T. Frisch, Y. Pomeau, and S. Rica, *Phys. Rev. Lett.* **69**, 1644 (1992).
 - [14] C. Huepe and M.-E. Brachet, *C.R. Acad. Sci. Paris* **325**, 195 (1997).
 - [15] T. Winiecki, J.F. McCann, and C.S. Adams, *Phys. Rev. Lett.* **82**, 5186 (1999).
 - [16] The radial extent of the condensate $D = 45 \mu\text{m}$ is only 3.5 times the laser beam diameter. This should constrict the flow around the laser beam leading to faster flow velocities.
 - [17] B. Jackson, J.F. McCann, and C.S. Adams, *Phys. Rev. Lett.* **80**, 3903 (1998).
 - [18] D. Thouless, *Topological Quantum Numbers in Non-relativistic Physics* (World Scientific, Singapore, 1998).
 - [19] B.M. Caradoc-Davies, R.J. Ballagh, and K. Burnett, *Phys. Rev. Lett.* **83**, 895 (1999).