Dissipation and vortex creation in Bose-Einstein condensed gases

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The existence of a critical velocity for dissipation is central to the issue of superfluidity in quantum fluids. The concept was first introduced by Landau in his famous criterion, where elementary excitations are produced above a velocity, v_c. However, much smaller critical velocities are observed in liquid ^{4}He, prompting Feynman to propose that quantized vortices may be responsible.

Bose-Einstein Condensation (BEC) of dilute alkali gases offers several advantages in studying the breakdown of superfluidity. Experimentally, these systems permit control over the temperature, number of atoms, and interaction strength, as well as allowing manipulation of the condensate using magnetic and optical forces. In a recent experiment at MIT, Raman *et al.* [1] probed a condensate using an oscillating blue-detuned laser beam. Significant heating of the cloud occurred only above a critical velocity, v_c, providing compelling evidence of a transition to a dissipative regime. In this work [2], we clarify the role of vortices in the heating process.

Our simulations employ the Gross-Pitaevskii (GP) equation for the condensate wavefunction $\Psi(\boldsymbol{r},t)$ in a harmonic trap. For convenience, we use scaled harmonic oscillator units (h.o.u.) of length, time, and energy, so that the GP equation can be written:

$$i\partial_t\Psi = (-\nabla^2 + V + C|\Psi|^2)\Psi. \tag{1}$$

The nonlinear parameter, C, is proportional to the number of condensed atoms and the interaction strength, while the potential, V, describes the combined effect of the trap and the oscillating laser beam 'object'. The oscillatory motion is similar to that in the MIT experiment [1], with a constant velocity, v, between extrema.

We find that above a critical velocity, $v > v_c$, vortex pairs are created by the object. We calculate the time-dependent condensate energy, and discover that the rate of energy transfer from the object increases sharply above v_c (see Fig. 1). This coincides with enhanced drag on the object, which is largely absent below v_c. However, energy transfer does occur below v_c due to phonon emission at the motion extrema, but this effect is much smaller.

The dependence of v_c upon the beam and condensate parameters has been investigated. In particular, we discover that v_c falls as the beam intensity increases, and rises and saturates as the condensate becomes denser. Both 2D and 3D simulations are performed, and we find that the critical velocity in 3D is significantly smaller than in 2D. This is because the critical

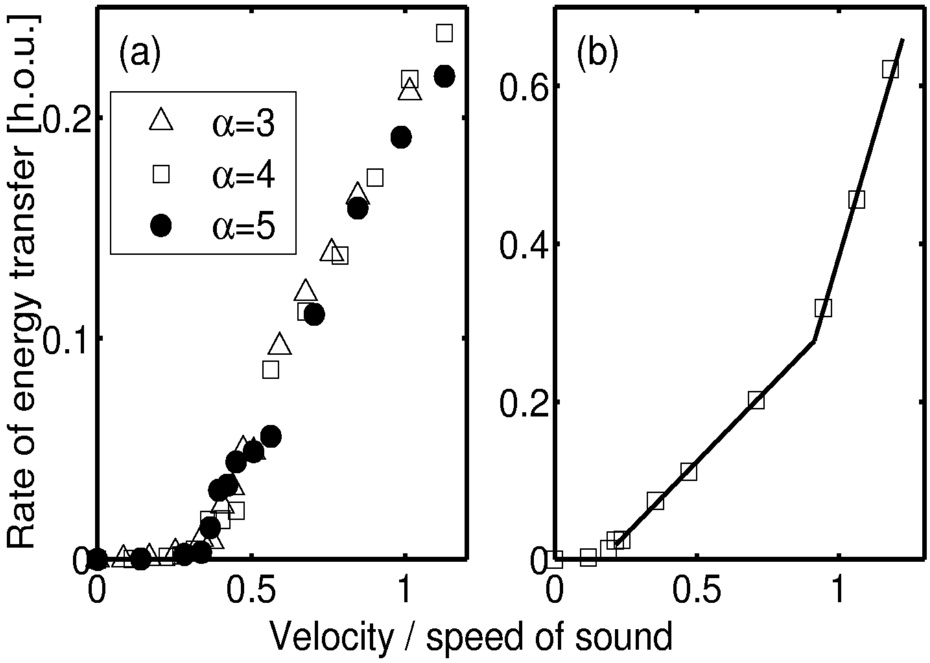

Figure 1: Mean rate of energy transfer as a function of translational velocity for (a) different oscillation amplitudes, α, in 2D, and (b) in 3D simulations. Velocities are scaled in terms of the speed of sound in the condensate centre, c_s. The plot shows a sharp transition between phonon heating (low velocities) and vortex heating at $v_c \simeq 0.4c_s$ (2D) and $v_c \simeq 0.2c_s$ (3D).

velocity scales with the speed of sound, which is proportional to the square root of the density. In 3D the laser beam passes through regions of low density so that the average sound speed is reduced. This explains the low experimental value of v_c in comparison to 2D simulations [3, 4]. In 3D we find an additional heating above the speed of sound due to enhanced phonon emission.

The vortex dynamics involve a complicated interplay between velocity fields induced by other vortices and effects arising from the condensate inhomogeneity. At finite temperatures, the vortices couple to the non-condensed thermal cloud, allowing energy transfer from the condensate to the thermal cloud and thus leading to the observed heating. We are currently extending our simulations to include finite temperature effects, and results will be presented.

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