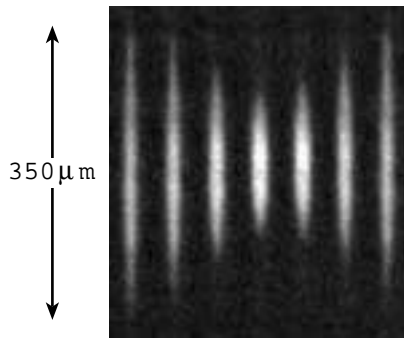


Sound at non-zero temperature: collisionless and hydrodynamic excitations of a Bose-Einstein condensate

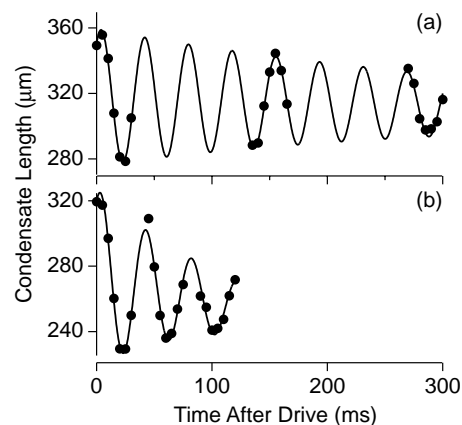
Collective excitations are the fingerprints of a system and reveal many of its dynamic properties. We extended earlier work on collective excitations of a Bose-Einstein condensate by studying them at non-zero temperature and at high density where they become analogous to first and second sound in superfluid helium [1]. The existence of such two modes is characteristic of a superfluid system.

Our study focused on the lowest-lying shape oscillation. This oscillation was probed above and below the Bose-Einstein condensation temperature. The temperature dependencies of the frequency and damping rates of condensate oscillations indicate significant interactions between the condensate and the thermal cloud. First sound, which constitutes hydrodynamic oscillations of the thermal cloud, was observed. An antisymmetric dipolar oscillation of the thermal cloud and the condensate was also studied. This excitation represents the bulk flow of a superfluid through the normal fluid and has similarities to second sound. The detailed theoretical description of these results is currently a challenge for many-body theorists.



Damped quadrupolar condensate oscillations at low (a) and high (b) temperature. Points show the axial condensate length determined from fits to phase-contrast images (such as shown in the figure above). The oscillation at high temperature has a slightly lower frequency, and is damped more rapidly than at low temperature.

In situ images of the $m=0$ quadrupolar condensate oscillation near 30 Hz. A Bose-Einstein condensate with no discernible thermal component was imaged every 5 ms by phase-contrast imaging. The evident change in the axial length of the condensate was used to characterize the oscillation.



1. D.M. Stamper-Kurn, H.-J. Miesner, S. Inouye, M.R. Andrews, and W. Ketterle, Phys. Rev. Lett. **81**, 500 (1998).