EXPERIMENTAL MEASUREMENT OF THE MOMENTUM STRUCTURE OF AN ATOMIC BOSE-EINSTEIN CONDENSATE

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Abstract For more than 50 years, quantized vorticity has been investigated, both theoretically and experimentally with great success. A more modern interest has developed for chaotic systems of vorticity and turbulence in quantum fluids. Until recently, all experiments on turbulence were performed in one of the two helium isotopes, which has led to a stagnation of experimental progress. As a result of the difficulty associated with cryogenic experiments, the theoretical understanding of quantum turbulence (QT) has vastly outpaced experimental efforts to understand the effects of quantization on fluid flow. However, with the discovery of trapped atomic Bose Einstein Condensates (BECs) [1], a new class of experiments is within reach. Turbulence in an atomic BEC was recently produced by Henn *et. al* [3], opening the door for further investigations in this new and accessible system. In BECs, as opposed to superfluid helium, a large variety of techniques are available to directly visualize the superfluid flow. The structure of turbulent ^{87}Rb condensate was explored by an optical absorption technique which produces a two dimensional density profile of the atomic density. In recent work [3], successive images of similarly created expanding clouds shows the time evolution of the turbulent cloud during a free expansion from a magnetic trap and allows the investigation of the dynamic properties. The behavior observed is unique from both a Thomas-Fermi and Maxwell-Boltzmann distributions, implying the presence of different energy structure and a presence of turbulence. From these data, the internal and kinetic energy distributions are calculated as a function of time during the expansion, kinetic energy spectrum of the *in situ* condensate is measured, and a phase diagram for various vortex states are explored as a function of the perturbation strength of the confining magnetic trap.

ENERGY STRUCTURE

The energy distribution for a turbulent BEC in a magneto-optical trap (MOT) is calculated with a Lagrangian formulation simulating the velocity field for a system containing entangled vorticity [2]. With this, a generalized hydrodynamic equation is developed to describe the free expansion of a turbulent BEC after being released from its trap. Of particular interest in this calculation are the relative magnitudes of the internal atomic interaction and the kinetic energies, which show that after the turbulent cloud is released the kinetic energy rapidly dominates the distribution. In a system where the interaction energy is less than kinetic, the atoms are expected to expand ballistically with their initial velocity. Therefore the overall density distribution after a time of flight, τ, can be used as a measure of the velocity distribution of a trapped turbulent condensate.

MOMENTUM STRUCTURE

The density distribution of the atoms, after a time of flight, is measured with an absorption imaging technique. The contrast of this image is used to determine the momentum distribution of the *in situ* condensate. Data showing the expansion of a thermal cloud, a BEC, and a turbulent BEC after the same time of flight are shown in Fig. 1. In each case the the atoms expand differently, implying separate internal velocity structures of the trapped cloud. These data are analyzed to show a power law dependence of $E(k) \sim k^{-1\pm0.3}$ for the energy dispersion across multiple realizations of the turbulent system.

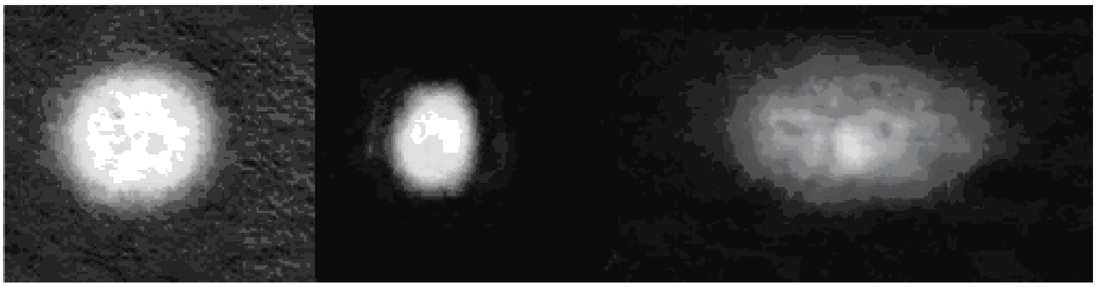

Figure 1. Three images of expanded clouds which were released from the same cigar shaped optical trap oriented along the x-axis. After a time of flight, τ, a Maxwell-Boltzmann cold gas, Thomas-Fermi condensate, and turbulent BEC are displayed respectively from left to right. Each image exhibits the typical expansion characteristics for the state of the system: a Maxwell gas will tend to isotropy, a Thomas-Fermi condensate conducts aspect ratio inversion, and the turbulent condensate shows a large occupation of high momentum states. These data can be analyzed to determine the internal energy structure of a trapped gas.

The scaling behavior is measured for wave-numbers ranging from the vortex core size to the maximum detectable value in each system investigated. This spectrum is consistent with the presence of Kelvin modes on the vortex lines [5].

PHASE DIAGRAM

In addition to studying the profile of individual turbulent systems, the production of vortex states in BECs was also studied. The number and structure of vortices were examined as a function of amplitude and duration of the perturbation field on the MOT. Four separate regions were discovered with alteration of the excitation fields. The transitions between them is an ongoing area of research. In order of increasing energy, the regions are described by a Thomas-Fermi cloud with zero vorticity, the formation of regular vortices, a quantum turbulent state, and the granulation of the super and thermal components of the condensate [4]. Each region has a unique set of dynamics and properties which are being investigated.

References

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