

Vortex Nucleation in a Stirred Bose-Einstein Condensate

Dissipation and turbulence in superfluid flow often involves the creation and subsequent motion of quantized vortices. Since vortices are topological defects they may only be created in pairs, or can enter a system individually from its boundary. The nucleation process has been a subject of much theoretical interest [1]. Experiments with Bose-Einstein condensates in atom traps are well suited to test theories of nucleation because the boundary of the condensate is well controlled, and vortices can be directly imaged.

In previous work, we had observed vortex lattices in stirred Bose-Einstein condensates [2]. By varying the stirring parameters we explored different mechanisms for vortex nucleation [3]. A large stirrer, with a beam waist comparable to the condensate radius showed enhanced vortex generation at discrete frequencies. The figure shows the number of vortices versus the frequency of rotation of the laser beam using 2-, 3- and 4-point patterns for the stirring beams. These resonances were close to the frequencies of excitation for surface modes of different multipolarity. This observation confirms the role of discrete surface modes in vortex formation.

However, when we used a tightly focused (beam waist $5\ \mu\text{m}$) laser beam as stirrer, we observed a broad response as a function of the frequency of the stirrer's motion, and no resonances (see figure). Furthermore, vortices could be generated well below the critical rotation frequency for the excitation of surface modes. This suggests a local mechanism of vortex generation involving hydrodynamic flow and local turbulence.



Discrete resonances in vortex nucleation (left). The number of vortices created by multi-point patterns is shown. The arrows below the graph show the positions of the surface mode resonances. The stirring times were 100 ms for the 2- and 3-point data, and 300 ms for the 4-point data. Inset shows 2-,3-, and 4-point dipole potentials produced by a $25\ \mu\text{m}$ waist laser beam imaged onto the CCD camera.

Non-resonant nucleation using a small stirrer (right). Average number of vortices created for different stirring times using a 2-point pattern positioned at the edge of the condensate.

1. A.L. Fetter and A.A. Svidzinsky, *Vortices in a trapped dilute Bose-Einstein condensate*, J. Phys.: Condens. Matter **13**, R135 (2001).
2. J.R. Abo-Shaeer, C. Raman, J.M. Vogels, and W. Ketterle, *Observation of Vortex Lattices in Bose-Einstein Condensates*, Science **292**, 476-479 (2001).

3. C. Raman, J.R. Abo-Shaeer, J.M. Vogels, K. Xu, and W. Ketterle, *Vortex Nucleation in a Stirred Bose-Einstein Condensate*, Phys. Rev. Lett. **87**, 210402 (2001).