Vortex Nucleation in Bose-Einstein Condensates due to Effective Magnetic Fields

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A spectacular property of superfluid systems is their ability to support quantized vortices. These can appear as flux lines in superconductors to which a sufficiently strong magnetic field has been applied. Alternatively, in the case of neutral superfluids subject to sufficiently fast external rotation, they exist as lines of vanishing condensate density around which the velocity field flow is quantized. These scenarios are closely linked because the equations describing a rotating superfluid, when studied in the rotating frame, mimic those of a charged superfluid (a superconductor) in a magnetic field, with the Coriolis force playing the role of the Lorentz force.

The dilute gas BEC is an extremely useful tool for probing the underlying physics of superfluid phenomena. In particular, vortex nucleation in condensates rotated by an anisotropic potential or localized stirring have attracted a lot of attention in the last years. Yet, the precise mechanism for the nucleation of vortices in these systems is still an open question.

Rotating a condensate only provides access to a limited class of problems for which the effective magnetic field is spatially homogeneous in the plane perpendicular to the rotation axis. Recent proposals to create effective magnetic fields in a more direct way open the door for more wide-ranging studies into the interaction of degenerate quantum gases with effective magnetic fields. The method considered here exploits the interaction of Λ-type three-level atoms with two laser beams possessing relative orbital angular momentum (OAM) in an electronically induced transparency (EIT) configuration. The corresponding vector potential $\mathbf{A}$ shows up in the effective equation of motion for the atoms in the following way[1]:

$$i\hbar\frac{\partial\Psi}{\partial t} = \left(-\frac{\hbar^2}{2M}\nabla^2 + \tilde{V} + g\,|\Psi|^2 + \frac{i\hbar}{M}\mathbf{A}\cdot\nabla\right)\Psi, \quad (1)$$

where $\tilde{V}(r) = V + \frac{|A|^2}{2M}$ and $g = 4\pi\hbar^2 a/Ma_z$ is the scaled strength of the two-body collisions between atoms and a_z represents the thickness of the cloud in the z-direction. If one or both beams are Laguerre-Gaussian modes carring OAM, then the induced vector potential acting on the atoms can be approximated by

$$\mathbf{A} = -\frac{\hbar\ell}{\mathbf{R}}\alpha_{\mathbf{0}}\left(\frac{\mathbf{r}}{\mathbf{R}}\right)^{\nu} \mathrm{e}_{\phi}, \quad (2)$$

An advantage of this method is that the vector potential, and consequently the effective magnetic field, can be shaped and controlled by appropriate modifications of the phase and intensity of the incident light.

In this work we study the influence of both homogeneous and inhomogeneous effective magnetic fields on the dynamics of a harmonically trapped Bose-Einstein Condensate and observe vortex nucleation for critical parameter values[2]. The exact dynamics are specific to the geometry of the trapping potential and effective magnetic field, but the the existence of unstable modes in the spectrum of elementary excitations as a precursor to vortex nucleation is a universal feature for all cases considered. Recent advances in light beam shaping technology, using for instance spatial light modulators, mean that all the potentials we consider can realistically be created in the laboratory. Fynally we show that the eventual configuration of vortices in the cloud depends on the geometry of the applied field.

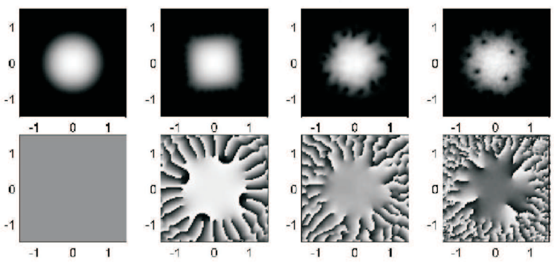

Figura 1. Snapshots of the density (top) and phase (bottom) for an inhomogeneous effective magnetic field. Time increases from left to right. The m = 4 octopole surface mode is resonantly excited, and vortex nucleation is enabled by a dynamical instability.

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