Dynamics of vortices in a dipolar Bose-Einstein condensate with an oscillating potential

S. Sabari *

Abstract
We study the dynamics of quantized vortices in a dipolar Bose-Einstein condensate excited by an oscillating Gaussian potential. Above the critical velocity, the oscillating potential keeps nucleating vortex pairs with opposite rotations. This leads to teaming dynamics of vortices in a dipolar Bose-Einstein condensate.

Introduction
The experimental realization of Bose-Einstein condensates (BECs) of ^{52}Cr, ^{164}Dy and ^{168}Er with long-range dipole-dipole interaction superposed on the short-range two-body contact interaction marks a major development in ultra cold quantum gases [**?**]. Because of the long-range nature and anisotropic character of the DD interaction, the dipolar BEC possesses many distinct features and new exciting phenomena including solitons and quantized vortices. Recently, studying dynamics of vortices in an atomic BEC subject to an oscillating Gaussian potential should open up a research area [**?**]. The first reason is that an atomic BEC is a clean system free of remnant defects and impurities, it is possible to study the intrinsic nucleation of topological defects. Second, the oscillating potential leads to synergy dynamics of quantized vortices and solitons. Linear motion of the potential results in vortex dipoles with fixed charge, whereas oscillatory motion leads to vortex dipoles with alternating charges, causing rearrangement of dipoles and a metamorphosis between vortices and solitons. Third, the oscillation introduces another important parameter, namely frequency, into quantum hydrodynamics. A few works on oscillating potentials in atomic BECs have already been reported. However, dipolar interactions were not considered in any of these studies [**?**, **?**, **?**]. Therfore, in this work, we study the dynamics of the vortices in a dipolar BEC.

Theoretical model
A dipolar BEC at absolute zero temperature can be described by the following dimensionless Gross-Pitaevskii equation as,

$$i\frac{\partial\psi}{\partial t} = \Big[\frac{1}{2}(-\nabla^2_{2D} + \gamma^2x^2 + \nu^2y^2) + \Lambda \mathrm{e}^{-\frac{[(x-x_0(t))^2+y^2]}{d^2}} + g|\psi|^2 + g_{dd}\int\frac{d\mathbf{k}_\rho}{(2\pi)^2}e^{-i\mathbf{k}_\rho\cdot\rho}n(\mathbf{k}_\rho,t)h_{2D}(\sigma)\Big]\psi, \quad (1)$$

where $g = 4\pi a_s N/(\sqrt{2\pi}d_z)$, $g_{dd} = 4\pi a_{dd}N/(\sqrt{2\pi}d_z)$, $\gamma = \omega_x/\bar{\omega}$, $\nu = \omega_y/\bar{\omega}$ and Λ is the amblitude of the Gaussian potential, $x_0(t)$ $(= \sin(\omega t))$ is the x-coordinate of the center of the Gaussian potential and d is its radius.

*S. Sabari is with Department of Physics, Savitribai Phule Pune University, Pune 411007, Maharashtra, India, email:ssabari01@gmail.com

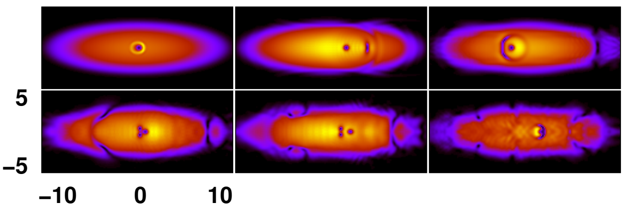

Figure 1: Density profile for nucleation of vortices for ^{52}Cr BEC. Upper row (from left to right) $t = 0\ ms$, $t = 1.60\ ms$, $t = 3.92\ ms$, and lower row (from left to right) $t = 4.72\ ms$, $t = 5.36\ ms$, and $t = 6.0\ ms$, respectively.

Result and Discussion
In Figure 1, we show the destiny of vortices nucleated by the oscillating potential for dipolar BEC with $a_s = 50\,a_0$, $a_{dd} = 15\,a_0$ (^{52}Cr), and $N = 20000$. If the velocity of the Gaussian potential ($V_p = \epsilon\ \omega$) is larger than the critical velocity, V_c, vortices are nucleated in the BEC. Otherwise, vortices are not nucleated for $V_p \leq V_c$. First figure in the upper row is the initial state in the static Gaussian potential, which is obtained by an imaginary time step of the nonlocal, Gross-Pitaevskii equation. Above the critical velocity a vortex pair is nucleated behind the Gaussian potential in second panel. Then the oscillating potential nucleates vortex pairs whose impulses alternately change direction. They reconnect with each other to make new vortex pairs, leaving the potential. Accordingly, the condensate surface becomes filled with vortices with opposite rotation, which leads to the nucleation of solitons and the migration of vortices which have not been previously reported in a Bose-Einstein condensate with dipole-dipole interactions.

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