# Quantized Vortices in a gaseous Bose-Einstein condensate

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The discovery of Bose-Einstein condensation of atomic gases [1, 2, 3, 4] has led to a new impulse in the physics of quantum gases. Among the several questions that can be studied in these systems, superfluidity is one of the most intriguing and fascinating. Evidence for such a superfluid character of gaseous BEC's has been brought by a recent experiment aiming to study the energy deposited in the condensate by a moving "object" (*i.e.* the hole created by a blue detuned laser)[5].

The rotational properties of the quantum gas which are studied in the present work [6] also give a direct access to its superfluid character as illustrated by the famous "rotating bucket" experiment (for related studies see also [7, 8]). When an ordinary fluid is placed in a rotating container, the steady state corresponds to a rotation of the fluid as a whole together with the vessel. Superfluidity, first observed in liquid HeII, changes dramatically this behavior [9]. For a small enough rotation frequency, no motion of the superfluid is observed; while above a critical frequency, lines of singularity appear in its velocity field. These singularities, referred to as vortex filaments, correspond to a quantized circulation of the velocity ($nh/m$ where $n$ is an integer, and $m$ the mass of a particle of the fluid) along a closed contour around the vortex.

In this presentation we will report the observation of such vortices in a stirred gaseous condensate of atomic rubidium. Our experiment is directly analogous to the rotating bucket experiment. The atoms are confined in a static, cylindrically-symmetric Ioffe-Pritchard magnetic trap (longitudinal and transverse frequencies 11.7 Hz and 219 Hz) upon which we superimpose a non-axisymmetric, attractive dipole potential created by a stirring laser beam. The combined potential leads to a cigar-shaped harmonic trap with a slightly anisotropic transverse profile. The transverse anisotropy is rotated at angular frequency $\Omega$ as the gas is evaporatively cooled to Bose-Einstein condensation. The evaporation is pushed to a point at which the thermal fraction is nearly undetectable, the number of condensate atoms being $\sim 140000$.

The possible presence of vortices in the condensate is probed by shadow imaging after a time-of-flight, during which the transverse size of the condensate expands by a factor $\sim 40$. For the trap parameters given above, we have found that no singularity appears in the cloud image as long as the stirring frequency is smaller than 149 Hz. However, for a stirring frequency slightly above $\Omega_c/(2\pi) = 150$ Hz, a density dip systematically appears at the center of the cloud. Figure 1 illustrates this transition by showing two pictures of the condensate after expansion; the first with a stirring frequency $\Omega = 145$ Hz (Fig.1a) below and the second $\Omega = 152$ Hz (Fig.1b) above the critical frequency.

When the stirring frequency is increased notably above the value $\Omega_c$, multiple dips appear in the absorption image of the cloud, corresponding to a vortex array as shown in Fig. 1c. This picture was obtained with a less confining trap (transverse frequency equal to 169 Hz), which is found experimentally to allow the formation of vortex arrays up to 11 vortices.

We will also report on very recent measurements of the angular momentum $L_z$ of the gas as a function of the stirring frequency. This measurement is performed by the excitation of the transverse quadrupolar mode of the condensate. The angular momentum $L_z$ is directly related to the angular precession of the eigenaxes of the mode [10]. We find that for a stirring frequency below $\Omega_c$ no detectable angular momentum is deposited in the condensate. When $\Omega$ reaches $\Omega_c$, the measured angular momentum jumps to a value of the order of $\hbar$. Above $\Omega_c$, $L_z$ is a smooth and increasing function of $\Omega$. This direct measurement of the angular momentum of a quantized vortex is the analog, for quantum gases, of the Vinen experiment, which showed the quantization of circulation in rotating superfluid helium [11].

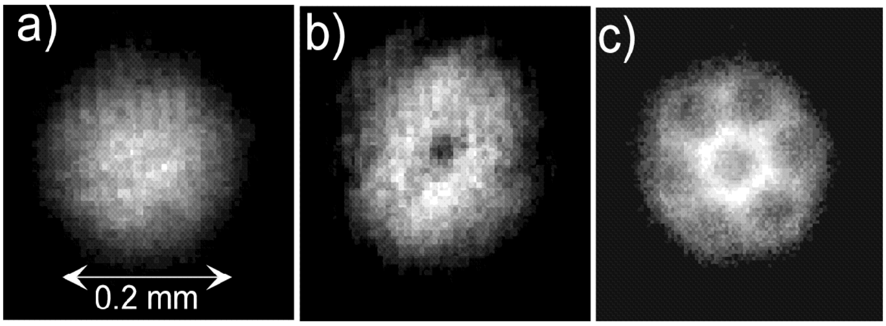


Figure 1: Condensate with 0, 1, and 7 vortices.

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