Rapidly rotating two-dimensional BEC in quadratic plus quartic potential

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Trap potential has quadratic and quartic terms

$$V_{\rm tr} = \frac{1}{2}M\omega_\perp^2\left(r^2 + \lambda\frac{r^4}{d_\perp^2}\right)$$

where λ fixes quartic admixture and $d_\perp = \sqrt{\hbar/M\omega_\perp}$ is oscillator length

In rotating system, additional centrifugal potential

$$V_{\rm cent} = -\frac{1}{2}M\Omega^2 r^2$$

acts to cancel harmonic confinement

Quartic term permits study of regime $\Omega \geq \omega_\perp$

Recent experiments of

Bretin, Stock, Seurin, and Dalibard, PRL **92**, 050403 (2004)

use additional axial laser beam to create a weak effective quartic potential ($\lambda \approx 0.001$) with renormalized effective radial trap frequency $\omega_\perp/2\pi \approx 64.8$ Hz

See vortex lattice for $\Omega \lesssim \omega_\perp$

See disordered vortices for $\omega_\perp \lesssim \Omega$

Near $\Omega \approx 1.05\,\omega_\perp$, system appears to break up

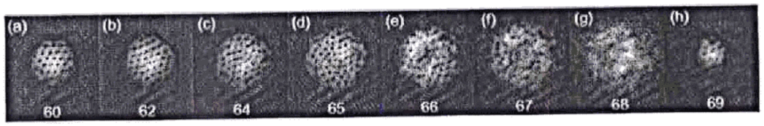


FIG. 1. Pictures of the rotating gas taken along the rotation axis after 18 ms time of flight. We indicate in each picture the stirring frequency $\Omega_{\rm stir}^{(2)}$ during the second stirring phase ($\omega_\perp/2\pi = 64.8$ Hz). The vertical size of each image is 306 μm.

In TF limit, theory predicts reduced density at center for $\Omega \geq \omega_\perp$

This behavior is seen in ENS experiments

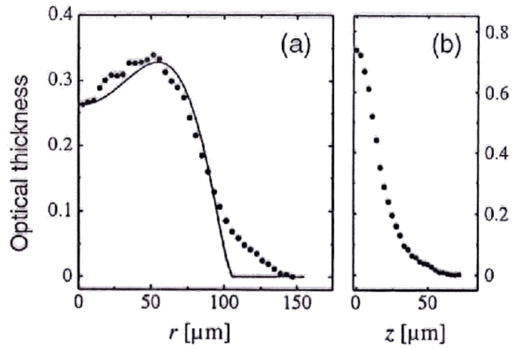
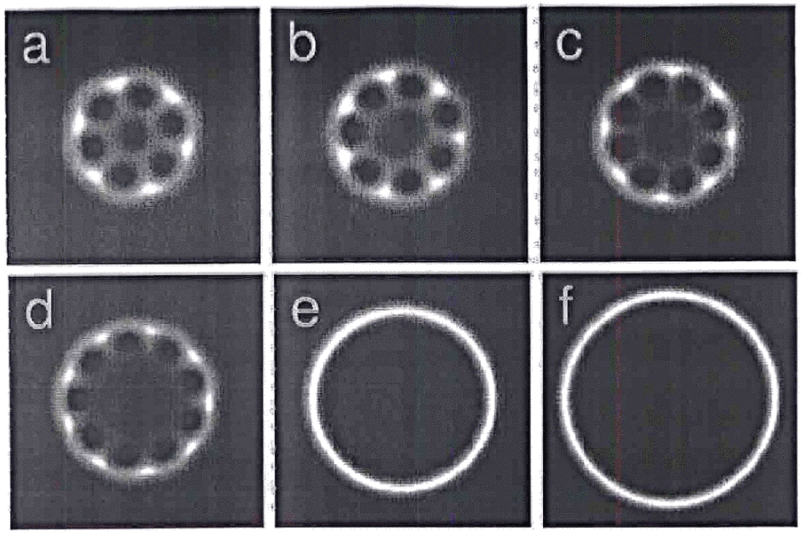


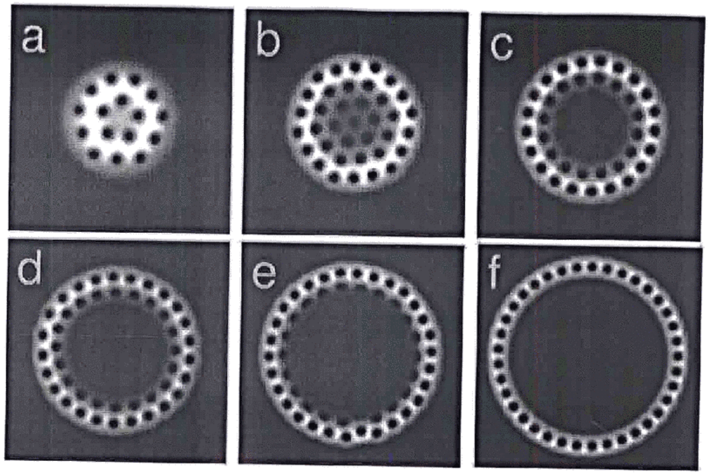
FIG. 2. Optical thickness of the atom cloud after time of flight for $\Omega^{(2)}_{\rm stir}/2\pi = 66$ Hz. (a) Radial distribution in the xy plane of Fig. 1(e). Continuous line: fit using the Thomas-Fermi distribution (3). (b) Distribution along the z axis averaged over $|x| < 20\ \mu$m (imaging beam propagating along y).

Analytical and numerical work with GP equation indicates system remains stable for large values of $\Omega/\omega_\perp \gg 1$

1. In TF limit with $\langle \mathbf{v}_s \rangle \approx \mathbf{\Omega} \times \mathbf{r}$, find a dense vortex lattice for
$$\omega_\perp \leq \Omega \leq \Omega_h$$
2. Ω_h is the critical value for formation of central hole (appearance of annular condensate)
3. Here, Ω_h is known function of
   - the admixture of quartic potential λ, and
   - interaction strength $g = 4\pi Na/Z$, where N/Z is the density per unit length in the z direction
4. For $\Omega > \Omega_h$, annular condensate expands radially and annular gap becomes narrow
5. Eventually, vortices disappear and flow becomes purely irrotational ("giant vortex")
6. Theoretical estimates of the transition to giant vortex require treatment of individual vortices; they do not agree with numerical simulations



Two-dimensional numerical studies for $\lambda = \frac{1}{2}$ and small interaction parameter $g = 4\pi Na/Z = 80$ (*not in TF limit*) confirm the qualitative features of analytical results



Two-dimensional numerical studies for $\lambda = \frac{1}{2}$ and large interaction parameter $g = 1000$ (*in TF limit*) confirm the general features of analytical results (except for the onset of the giant vortex)

Why do theory and experiment differ so greatly?

- ENS rotating condensate is nearly spherical for $\Omega \approx \omega_\perp$; do three-dimensional effects dominate observations?
- ENS paper suggests repeating experiment for tightly confined quasi-two-dimensional geometry
- Is there some fundamental failure of GP for $\Omega \gtrsim \omega_\perp$? Is there some dynamical instability of the vortex lattice?
- Stringari suggests that $T = 0$ hinders transfer of more angular momentum to condensate; is there a better way (as in JILA experiment)