Workshop on Topics in Quantum Turbulence

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Oscillating Bose Condensates: Generation of Vortices and Evidence for Turbulence

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Vortices, clusters of vortices and evidences of turbulence in an oscillating BEC

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Our initial goal:

**Coherent population transfer between two trapped states**

\[ V_p = V(\tilde{r}) \cos(\omega t) \]
But we forgot the vortices !!!!!!!!!!

\[ x \exp\left(-\frac{r^2}{2a_0^2}\right) \quad n_x = 1, \quad n_y = 0 \]
\[ y \exp\left(-\frac{r^2}{2a_0^2}\right) \quad n_x = 0, \quad n_y = 1 \]
\[ \exp\left(-\frac{r^2}{2a_0^2}\right) \quad n_x = n_y = 0 \]

Combination: \[ |1_x, 0_y\rangle + i|0_x, 1_y\rangle \]

Wave function:
\[ (x + iy) e^{-r^2/(2a_0^2)} = r e^{i\varphi} e^{-r^2/(2a_0^2)} \]

Vortex with a charge +1
EXPLORATORY PRESENTATION

OUTLINE

1 - GENERAL CONSIDERATIONS
2 - VORTICES FORMED BY OSCILLATIONS
3 - ROUTE TO TURBULENCE
4 - CLUSTERS OF VORTICES: TRIPOLES
5 - FRAGMENTATION
BEC OF Rb
Vapour MOT
~ $10^9$ atoms

Push beam

MOT beam

Ion pump
$P < 1 \times 10^{-9}$ Torr

Dispensers
efficient and high controllable atom source

LIAD

Combo pump
Ion pump + Ti-Sublimation pump
$P < 1 \times 10^{-10}$ Torr

UHV MOT
up to $10^9$ atoms
$T \sim 140 \mu K$

40 cm

MOT beam

Ion pump
$P < 1 \times 10^{-9}$ Torr
**Temporal Sequence**

- A full run of the BEC experiment takes 1min
- The first 35s are just for 2nd MOT loading
- The last 24s are for magnetic trapping and evaporation, which takes itself 22s
- The link between these two parts is due to a group of 5 processes that take a total of 10ms

**OUTCOME:** 3 to 8 $10^5$ condensate Atoms

$T \sim 80$ to 200 nK
Trapped Bose Condensate and superfluidity

• Investigation of Scissors Mode (rotation of the cloud around the symmetry axis)
There are many studies of vortices in BECs

- Nucleation by instabilities in the rotation PRL 86 (2001)
- Phase measurement – PRA 64 (2001)
- Dynamics of single vortex line and observation of Kelvin modes – PRL90(2003)
- Lattices – many
How are the vortices formed and how is the dynamics?

• Many experiments and many theoretical papers
• Tsubota’s group: PRA 65(2002), PRA 71(2005)
• Fetter – Rev. Mod. Phys (2008) and reference there in..
• Dalibard’s group – Theory and experiment
• Gardiner’s group – Theory
• Etc..
Oscillatory Quadrupolar external excitation

POSSIBILITY TO EXCITE VORTICES OF BOTH SIGNS:
VORTEX AND ANTI-VORTEX
Displacement
Rotation
Deformation of the potential

Larger amplitude of oscillation:
- Larger displacement
- Larger deformation of the potential
- Higher acceleration in the rotation
PRODUCING BEC (1 MIN)

EXCITATION (0 TO 70 ms)

Rest (20 ms)

TOF FOLLOWED BY ABSORPTION IMAGE
Small amplitudes and/or small times of excitation

Oscillatory banding

Equivalent to oscillations generated by sudden rotations → Scissors Mode
NEXT STEP AFTER BANDING AXIS IS THE OBSERVATION OF A DEEP IN THE ABSORPTION \( \rightarrow \) VORTEX
During oscillations there are excitation of collective Quadrupole oscillations.
Parker-Adams PRL95(2005) – Stirring BEC

1 – Quadrupolar mode breaks down, ejecting energetic atoms to form an outer cloud

2 - Turbulent cloud containing vortices is formed with a Kolmogorov energy spectrum

3 - Dissipation and crystallization
EVOLUTION WITH AMPLITUDE AND TIME OF EXCITATION

There are a large shot-to-shot fluctuation
Fixed time of excitation – 20 ms

<table>
<thead>
<tr>
<th>Axial gradient amplitude range (mGauss/cm)</th>
<th>Mean vortex number observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;40</td>
<td>0</td>
</tr>
<tr>
<td>40-90</td>
<td>1</td>
</tr>
<tr>
<td>90-190</td>
<td>3</td>
</tr>
<tr>
<td>&gt;190</td>
<td>5</td>
</tr>
</tbody>
</table>
Explosion point $\rightarrow$ proliferation of many vortices $\rightarrow$ turbulence
Vortices to tangle vortices
Average Numbers of vortices as a function of excitation time

Excitation frequency : 200Hz, Amplitude 250 mV
Tangle vortices
Observation of aspect ratio inversion of the quantum cloud- energy conversion

For a large number of vortices (turbulent?), the inversion is not observed
(Edwards, Clark, Pedri, Pitaevskii and Stringari)  
• “….since the instantaneous moment of inertia is them proportional to the asymmetry of the cross section…”  
• “…. Preventing the released condensate from attaining a circular cross section..”  

Clear the presence of angular momentum affects the expansion  

The absence of inversion in the ratio may be an indicative of Turbulence in the quantum atomic fluid, that would be a new effect in the atomic quantum fluid
Route to QUANTUM TURBULENCE

• EXCITATION IN AT LEAST TWO PLANS
• ENOUGH AMPLITUDE TO TRANSFER MANY UNITS OF ANGULAR MOMENT
• Two axis of oscillations (not equivalent)
• Tangle vortices (Feyman)
• When the vortices become tangle, the flow has a strong random element, varying rapidly from point to point (lost of inversion)
Quantum turbulence in a trapped Bose-Einstein condensate

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FIG. 1. (Color online). Schematic sketch of the rotation. The first rotation is applied along the z axis and the second rotation is applied along the x axis.
FIG. 4. (Color online). Isosurface plots of 5% of the maximum condensate density (a)–(c) and configuration of quantized vortices inside the Thomas-Fermi radius $R_{\text{TF}}$ (d)–(f). (a), (d) $t\omega = 10$; (b), (e) $t\omega = 50$; (c), (f) $t\omega = 300$. The method for identifying vortices in (d)–(f) is the same as that in Fig. 7 in Ref. [15].
CONCLUSIONS:

• EXCITATION OF VORTICES WITHOUT DIRECT ROTATION
• EVOLUTION TO TANGLE VORTICES – lost of inversion property
• FRAGMENTATION
• CLUSTER OF THREE VORTICES: TWO DIFFERENT SPATIAL STRUCTURES
THANKS