Bose-Einstein Condensation in Bumpy Potentials

**EXPERIMENT**

U. Arizona BEC group

- Brian P. Anderson
- Tyler Neely (PhD student)
- Chad Weiler (PhD student)
- David Scherer (PhD March 2007)

**THEORY partners**

Condensation dynamics

- Matthew Davis (UQ)
- Ashton Bradley (UQ)
Vortices in BECs

Various methods exist for making a BEC rotate...

First BEC vortex (JILA)

Research question:
Can bumps in a trapping potential induce vortex formation (fluid rotation) during condensation?
Motivation

Vortices in superfluids
- Formation and trapping mechanisms

BECs in rough and disordered potentials
- Atom chips, fragmentation
- Quantum phase transitions (Bose glass)
- Properties of other superfluids

Quantum fluid mixing & merging
- Atom-optical elements (beam combiners)
- Quantum-state engineering
  - Superfluid turbulence
  - Kibble-Zurek mechanism

Dynamics of condensation in bumpy potentials
Experiments

I. BEC in a 3-well trap
D R. Scherer, C.N. Weiler, T.W. Neely, and B.P. Anderson,

[Simulations underway by P. Kevrekidis (UMass) and R. Carretero (SDSU)]

II. BEC in a toroidal trap

III. BEC in a spatially smooth trap

Common element: examining the process of condensation, rather than manipulation of a BEC

Partnering with M. Davis, A. Bradley to understand the dynamics of condensate formation in these experiments.
I. BEC in a 3-well trap

Intensity of optical barrier in BEC plane

BEC held in TOP trap

Blue-detuned Optical Barrier Beam

Imaging beams

Chrome mask

Phase dots

CCD

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The 3-well trap

Magnetic potential (TOP trap) + Optical Potential = 3-Well Potential

Top-down view

Isolated BECs start forming in 3 wells during evaporative cooling
BECs merge during growth

(1) 3 independent BECs start forming from common thermal cloud.

Barrier energy $E_B$

Single-particle ground-state energy $E_0 \ll E_B$

(2) BECs grow during continued evaporative cooling.

Chemical potential $\mu < E_B$

(3) BECs merge together. Interference between matter waves leads to directional fluid flow.

Final chemical potential $\mu > E_B$

Interference region

Fluid flow? Depends on phase gradients and relative phases.
Fluid flow

Slow merging of two condensates

Neglect phase gradients, assume constant phase profiles:

\[ \Psi(\vec{r}, t) = \sqrt{n_1(\vec{r}_1, t)} + \sqrt{n_2(\vec{r}_2, t)} e^{i\delta \phi} \]

Current density:

\[ J(x) = \frac{\hbar}{2im} \left[ \Psi^* \frac{\partial \Psi}{\partial x} - \frac{\partial \Psi^*}{\partial x} \Psi \right] \]

\[ J(x = 0) \propto \sin(\delta \phi) \]

Direction of fluid flow at overlap depends on relative phase.

Not known \textit{a priori}!
Vortices from slow BEC merging

Given random relative phases, conditions for vortex nucleation can occur up to 25% of the time.

Clockwise Circulation
- $\Phi_3 - \Phi_2 < \pi$
- $\Phi_2 - \Phi_1 < \pi$
- $\Phi_1 - \Phi_3 < \pi$

Counter-Clockwise Circulation
- $\Phi_3 - \Phi_2 > \pi$
- $\Phi_2 - \Phi_1 > \pi$
- $\Phi_1 - \Phi_3 > \pi$

Probability of a vortex forming: $P_v = 0.25$

denotes relative phase
Fast Merging: interference fringes

Interference fringes from quickly merged but still trapped BECs.

Estimate of fast merge time: ~500 ms.

Nonlinear dynamics ("snake" instability): fringes decay to vortices and antivortices in a trapped BEC.

$P_v > 0.25$ for fast merging. ($P_v = 0.25$ for slow merging)

Simulations

2D GPE, no damping. Model of growth of BEC’s physical size by increasing scattering length with time (only a simple approximation!).

2\pi/3 relative phases (ideal case)  Fast merging, with non-ideal phases
Experiment sequence

With no Optical Barrier:
- $4 \times 10^5$ atoms in $\sim 7$ Hz (radial) x $14$ Hz (axial) trap
- $\mu \sim k_B \times 8 \text{nK}$

1. Turn on barrier beam
2. Make BECs by evaporative cooling
3. BECs merge
4. Turn off trap, cloud expands (vortex cores expand)
5. Image cloud (by absorption)

Test #1:
**Strong barrier**
- $170 \mu W$, $k_B \times 26 \text{nK}$
- Merge by lowering barrier

Test #2:
**Weak barrier**
- $45 \mu W$, $k_B \times 7 \text{nK}$
- BECs merge during growth
Test #1: Merge 3 BECs by lowering barrier

Example images:

Data:

$F_v$: fraction of images that have at least one vortex. $F_v \sim P_v$?

$\tau$: Time to ramp down barrier after BECs created

$F_v > 0.25$, as expected for fast merging.

$F_v \sim 0.25$, as expected for slow merging.
Multiple vortices

200 ms barrier ramp to zero: multiple vortices and (presumably) antivortices in final BEC.
Average # of vortex cores per image: 2.1

Add extra 100-ms hold time after ramp, but before expansion.
Average # of vortex cores per image: 0.7

Vortex-antivortex annihilation?

Single vortices observed for at least 5 s extra hold time: relatively long vortex lifetime.

3D, T=0 GPE modeling for 3 BEC merging underway by P. Kevrekidis (UMass) and R. Carretero (SDSU).
Test #2: merge during growth

Do vortices form during BEC growth in a bumpy potential?

YES! Vortices seen in single BECs created in a bumpy potential.

\[ F_v \sim 0.6 \]

Condensate growth rate is “fast”.
II. BEC in toroidal potential

Instead of 3-armed Optical Barrier, use tightly focused Gaussian beam (optical plug).

Toroidal trap in the limit of large beam intensity.

Remove beam + expand + image
Measuring the angular momentum

Squeeze trap, induce quadrupolar oscillations of BEC.

Strobe the oscillations (90 ms period). Precession of shape if BEC has angular momentum.

(prev. used at ENS, JILA, Oxford, …)

Slope = angular momentum
Angular momentum measurements

**Full data set**

![Graph of Angular momentum measurements for Full data set](image)

**Rotations only**

![Graph of Angular momentum measurements for Rotations only](image)

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What’s going on?

Kibble-Zurek mechanism in a toroidal trap (spontaneous persistent currents)?
- defect trapping in a quenched phase transition

Kibble, J Phys A 9, 1387(1976),
Zurek, Nature 317, 505 (1985),
Anglin and Zurek, PRL 83,1707 (1999)

SGPE simulations by Matt Davis and Ashton Bradley, U. Queensland

Movie:
3D SGPE with Optical plug
Evaporative cooling in a smooth trap

Harmonic trap: optical barrier beam is absent.

Spontaneous formation of vortices in BEC during evaporative cooling:
- Marshal, New, Burnett, and Choi, PRA 59, 2085 (1999),
- Drummond and Corney, PRA 60, R2661 (1999).
- Spin vortices, experiment: Stamper-Kurn group (Nature, 2006)

Kibble-Zurek mechanism in a smooth trap?

Something else altogether (ie, turbulence)?
TOP trap is *dynamic*. Our TOP trap has an instantaneous radial harmonic potential (due to gravitational sag).

Rotating bias field shifts trap center around a circle.

2 kHz rotation frequency.

Time-averaged potential (harmonic)
Do vortices depend on TOP?

**TOP CCW**

- $L_z$ CW [against TOP]
- $L_z$ CCW [with TOP]
- $L_z \sim 0$
- Lz CW [against TOP]
- Lz CCW [with TOP]

**TOP CW**

- $L_z$ CW [with TOP]
- $L_z$ CCW [against TOP]
- $\hbar$ per particle
- Lz CW [with TOP]
- Lz CCW [against TOP]
TOP does bias angular momentum of vortices!

TOP CCW

TOP CW
Summary

I. 3-well experiments

1. Single Vortices created via slow merging of BECs.
2. Multiple Vortices (vortex pairs?) created via fast merging of BECs.
3. Vortices created simply by making a single BEC in a 3-well potential

II. Toroidal trap

4. Persistent currents are created by condensing in toroidal potential.
   Can also be seen in SGPE simulations.

III. Smooth TOP trap

5. Vortices appear after condensation in smooth TOP trap, with
direction strongly biased in TOP rotation direction, though not all
are in TOP direction.