Anderson Localization and Damping of Superfluid Transport by Disorder and Defects

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Outline

Party Line: Bose condensates are tunable, defect free, and clean

Deliberately mess that up by imposing randomness on a $^7$Li BEC

- Extreme tuning of interactions
  - weak – magnetic dipolar interactions
  - strong – beyond mean-field

- Effects of random disorder
  - slower dynamics – Anderson localization
  - dynamics – Ohmic damping of superfluidity
Tunable Interactions: Feshbach Resonance

Hyperfine sublevels of $^7\text{Li}$ (Bosons)

Coupled channels calculation of the scattering length of $^7\text{Li}$ $|1,1\rangle$ state

$2S_{1/2}$ Ground State of $^7\text{Li}$

$|1,1\rangle$

$|2,2\rangle$

Energy (MHz)

Magnetic Field (G)

$a < 0$

$0.1 \, a_o / \text{G}$

zero-crossing slope:

$a(a_o)$

Magnetic Field (G)
Scattering Length vs. Field

\[ a = (-24.5a_0) \left( 1 + \frac{192.3G}{B - 736.9G} \right) \]

3D regime

Quasi 1D regime

\( na^3 \gg 1 \)

>7 decades

Pollack et al., PRL 102, 090402 (2009)

Solitons

e.g. Khaykovich et al., Science 296, 1290 (2002) (ENS)
and Strecker et al., Nature 417, 150 (2002) (Rice)
Superfluid/Insulator Transition

Disorder–induced transition to an insulator (P.W. Anderson, 1958)

- Interplay between disorder and interactions is very subtle and still poorly understood
- Relevant to granular superconductors, superfluid helium in porous media, high-$T_c$, …
- Cold atoms → new insight (Florence, Orsay/Palaiseau, Hannover, Rice …)
Anderson predicted that electrons are localized by coherent scattering from disorder.

Destructive interference leads to exponential localization when \( k \ell < 1 \).

For a BEC with correlated disorder, we need

\[
\xi = \frac{1}{(8\pi na)^{1/2}} > \sigma \quad \text{(disorder correlation length)}
\]

L. Sanchez-Palencia et al. PRL 98 210401 (2008)

\( \rightarrow \) need small \( a, n, \) and/or \( \sigma \)

Tunable interactions enables systematic investigation.
Controlled Disorder: Optical Speckle

Laser light (671 nm)

\[ k = \frac{1}{\sigma} = 1.8 \, \mu m^{-1} \]

Distance (\( \mu m \))

Relative Intensity

\[ \langle I \rangle \]

Power Spectrum

\[ k_D = \frac{1}{\sigma} = 1.8 \, \mu m^{-1} \]
1D Expansion in Disorder

- Evaporate in crossed beam trap
- Turn off cross beam - expand in 1-D in presence of disorder
  \( \omega_z \approx (2\pi) 0.7 \text{ Hz} \)
- Expansion momentum \( k_{\text{max}} \) depends on interactions:

\[
E_{\text{total}} = E_{\text{trap}} + E_{\text{int}}
\]

Free expansion:

\[
\frac{\hbar^2 k^2}{2m}
\]

Crossover from exponential to algebraic localization

![Graph showing the relationship between scattering length and \( k_{\text{max}} \) with a crossover from exponential to algebraic localization.](image)
Slow Expansion - Anderson Localization

Slow: \[ \frac{2k_{\text{max}}}{k_D} = 0.34 \]
Weak disorder: \[ \frac{V_D}{\mu} = 0.4 \]

Each shot average of 10 disorder realizations

Faster Expansion - Algebraic Localization

\[ \frac{2k_{\text{max}}}{k_D} = 1 \]

Weak disorder: \[ \frac{V_D}{\mu} = 0.4 \]

linear scale

log scale

log-log scale
Fastest - Classical Localization

Fast expansion: \( \frac{2k_{\text{max}}}{k_D} = 2.2 \)  \( \rightarrow \) \( \xi < \sigma \)

Atoms trapped by large disorder peaks

Similar results observed at Orsay/Palaiseau, Florence, and Hannover
Comparison with Theory
Sanchez-Palencia et al.

Localization length:

\[ L_{loc} = \frac{\hbar^4 k_{max}^2 k_D}{2\pi m^2 V_D^2 \left( 1 - \frac{2k_{max}}{k_D} \right)} \]

Possible break-down of theory at large \( k \)
Dipole Oscillations in Disorder

- Start with BEC in a harmonic trap
- Suddenly offset trap
- Impose speckle

Y. Chen et al., PRA 77, 033632 (2008)
Damping of Dipole Motion

How does damping depend on velocity?

See also work of Florence group: Lye et al., PRL 95, 070401 (2005)

Y. Chen et al., PRA 77, 033632 (2008)

\( a \approx 200 \ a_0 \)

dissipation even for small \( V_D \)

overdamped for \( V_D > \sim 0.3 \ \mu \)

global superfluidity lost
Velocity Dependence of Damping

\[ v_{\text{max}}(t) = z_0(t) \omega \]

\( v \) decreases with amplitude

\( a \sim 25 a_0, \quad \mu = 470 \text{ Hz} \)

\( c_s = (\mu/m)^{\frac{1}{2}} = 5.2 \text{ mm/s} \)

= Landau critical velocity

Damping peaks at \( v \approx c_s \)

\[ \frac{\beta}{\omega} \]

\[ \frac{v}{c_s} \]

Functional form from Radouani, PRA 70, 013602 (2004)

Fit a range of oscillations to an underdamped oscillator:

\[ z(t) = Ae^{-\beta t} \cos t \sqrt{\omega^2 - \beta^2} + \varphi \]
“Phase Diagram” - Damping vs. \( v \) and \( V_D \)

\[ a = 183 \, a_0 \]

Theory: Albert et al, PRL 100, 250405 (2008)
Simpler Problem - Single Defect

Disorder is a collection of many defects – what about a single one?

**dip**

**barrier**

1D non-interacting simulations

blue-detuned light sheet  red-detuned light sheet
Barrier Dip

Damping Phase Diagram for Single Defect

Local Landau critical velocity is less for a barrier than for a dip:

\[ v_c = c = \sqrt{\frac{n_0 U}{m}} \]

\[ \frac{v_c}{c} = (1 + \delta n)^{5/2} \]
Compare with 1D Theory

Single defect:

Disorder:

Albert et al., PRL 100, 250405 (2008)

$\gamma = \text{“fluidity factor”}$
What Causes Dissipation?

time of flight images

Strong interactions

Single defect

- For strong interactions, condensate is excited upon crossing defect
- Numerical calcs suggest that damping due to emission of solitons and linear excitations (Albert et al.)

see also Fort et al., PRL 95, 170410 (2005); Engels and Atherton, PRL 99, 160405 (2007)
Summary

- Anderson Localization of expanding BEC
  - depends strongly on $k/k_D$
  - continuously vary $k$ using Feshbach resonance

- Ohmic damping scales with $v/c$ and $V_D/\mu$
  - onset at Landau critical velocity
  - damping coincides with observed excitations