Expanding Atomic Quantum Gases

with tunable interaction and disorder

---emulating dynamics and fluctuations in superfluids ... and nuclear matter?

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My question

How can we design condensed matter experiments to emulate nuclear/high energy physics phenomena? (esp. those difficult to test in real NP/HEP experiments, i.e. accelerators)

Promising systems (studied in my lab):
• Graphene --- Dirac/chiral fermions: Coulomb collapse, Klein paradox…..

• Ultracold quantum gases (Bose-Einstein condensates; degenerate fermions/BEC-BCS; Bose-fermi mixtures;….)

Advantages: Tunable system parameters (customer-designed Hamiltonians):
You can watch the system (probe both density and phase) to evolve!

Emulational physics?
Talk outline

• Brief review of cold atoms & BEC
  ---examples of NP/HEP connection
• Tunable interaction and expanding BEC
• Disordered BEC:
  superfluid to insulator transition
  evolution of quantum and density fluctuations

Please stop me for questions!
Quantum Gases

- Quantum regime $n \Lambda^3 \geq 1$
  \[ n = \text{density} \]
  \[ \Lambda = \text{de Broglie wavelength} \]

Identical particles!

- Gas phase $n \approx 10^{12} \text{ cm}^{-3}$
- Low temperature $T \approx 100 \text{ nK}$
  \[ \Rightarrow \Lambda \approx 1 \mu\text{m} \]

- Phase transitions
  - Bosons ($^7\text{Li}$): Bose-Einstein condensation
  - Fermions ($^6\text{Li}$): BEC-BCS crossover
Meet Our Atom: Lithium-7

$^7\text{Li} -- \text{boson} \quad (3p^+, 4n) + 3e^-$

$^6\text{Li} -- \text{fermion} \quad (3p^+, 3n) + 3e^-$

Bose-Einstein Condensation

$2^2S_{1/2}$

$E$

$F=2$

(1)

(0)

(-1)

$F=1$

(-2)

(-1)

(0)

(1)

$^{(m_F=2)}$

Tunable Interaction
(Feshbach Resonance)
of $^7\text{Li}$ in (1,1) state

“mean field” interaction $\propto a_0$

Scattering length ($a_0$)

Magnetic field (G)
Experimental Creation of BEC

Zeeman Slowing $\rightarrow$ MOT $\rightarrow$ optical pumping

laser cooling:  
(671nm)  
$\omega$  
$F=-k\nu$  
$\nu$  
$\omega$

$N \sim \text{few } 10^{10}$  
$T \sim 1 \text{mK}$

rf evaporation

$N \sim \text{few } 10^{6}$  
$T \sim 10 \mu K$

BEC!
How to Experimentally Probe an Atomic Gas

“sit”
• in-situ imaging of cloud
  -- probe ground state wavefunction

“fly”
• free expansion: momentum space translates into real space
  --- probe phase coherence/fluctuation
  • ("restricted-fly") evolution dynamics in selective potentials

“kick”
• excite and collective mode
A golden decade of quantum gases of cold atomic quantum gases --- some highlights

- Bose-Einstein Condensate (BEC) [1995] now in most alkali, H, He* and Yb, Cr
  (Nobel prize, 2001)

- Fermionic Condensate/BCS-BEC crossover [2004-2005]

2-body Inter.

\[ \text{BEC (bosonic molecules)} \]

\[ \text{BCS (cooper pairs)} \]

\[ k_F|a| > 1 \]

“Feshbach Resonance”

(from Ketterle’05)
• Atoms in optical lattices (e.g., BEC/superfluid-Mott insulator) [2002-]

Optical Lattices

Periodic potentials produced by interfering laser beams
1D, 2D, 3D, incommensurate, variable lattice parameter,
 disorder, ...

• Atoms in optical disorder potential [2005-]

M. Greiner et al., (2002)

(Mott insulator)

(Anderson insulator)
Tunable System Parameters

• interaction (repulsive, attractive, short range, long range, isotropic/anisotropic)
• random and period potentials
• dimensionality (1-3D) and spatial structure
• quantum and density fluctuations
• time-dependent perturbations

Emulator for Quantum Systems
[Feynman/DARPA]
NP/HEP Connections?

• Expansion of quantum gases and hydrodynamics [Thomas, Grimm, ...]
• Instabilities due to interaction ---- condensate collapse: “Bosenova”; dipolar collapse
• Bose-Fermi mixture and supersymmetry, “Goldstino” modes (K.Yang’08); models for string theory (Stoof’05)...
• Sound wave propagation: models for cosmology
Interaction and Expansion of BEC

Interactions – Generic Discussion

\[ V(R) \]

2-body potential

\[ \Lambda_{dB} \sim 1 \, \mu m \]

\[ \Rightarrow \text{detailed shape of } V(R) \text{ unimportant} \]

Characterize interaction by s-wave scattering length \( a \):

- mean-field interaction energy \( nU_0 = 4\pi\hbar^2n_0am \)

\[ a < 0 \text{ attractive} \quad \quad \quad \quad a > 0 \text{ repulsive} \]
What Determines $a$?

$^7\text{Li}$  

$^6\text{Li}$  

$\alpha = -27\ \alpha_0$ \quad $\alpha = -2300\ \alpha_0$

See Notes!

**Answer:** The last bound state!
Li-7 in (1,1) state

(b) $B = 717G$

(c) $B = 551G$

(d) $B = 544G$
551G: $a \approx 1a_B$

TOF images

544G: $a < 0$

TOF images
Dipolar Interaction and Dipolar Collapse at $a>0$

- Cr-52 BEC: a dipolar BEC (Pfau’05)
Disordered BEC, fluctuations

Collaborators: James Hitchcock, Dan Dries, Mark Junker, Chris Welford and Randy Hulet (Rice Univ.)

Yong P. Chen et al., PRA 77, 233632 (2008)
From Superfluids and Superconductors to Insulators..
What is the essence of superfluidity and superconductivity?

*understanding by (temporarily) “escaping”...*

**Insulators:**
- technologically important
- intellectually important to understand conductors and superconductors/superfluids

How to get an insulator?

Way#1: no carriers

*band insulator* (no carriers)

BUT...

Conductor (metal)
Interaction and Disorder

Festkörperfysik ist Schmutzphysik!
(“Solid State Physics is Dirty Physics”)

fundamental themes in condensed matter physics

Andersen insulator

disorder+interaction?

Mott insulator

metal [superfluid/superconductor]

(interaction)
Superfluid/Superconductor to Insulator Transition (SIT)

See also: “dirty” superfluid, random J-junction arrays etc. – “dirty bosons”

**Disordered Superconductor**

Example: Thin film superconductors (e.g., Bi)

- “granular superconductor”: local superconductor
  - global insulator
  - \((E_c > E_J)\)
- “homogeneous”: any local superconductivity?

**Simulate by disordered quantum gas**

(both bosons & fermions)

- How does disorder destroys superconducting order parameter \(|\Psi|e^{i\theta}\)
- superfluidity and phase coherence
- “Bose glass”?
- Dissipation mechanism? intermediate metallic phase? (“Bose metal”)
- Is (dirty) boson-picture sufficient (SC)?
BEC: Coherent and Superfluid

Coherence = Superfluidity?

Disordered BEC:
$^7$Li: us (Rice, 2006-)


(coherent matter wave: $\Rightarrow$ atom laser)

(from W. Ketterle website)

Anderson insulator

Mott insulator

(a nanoscience “simulator”)

Bose glass ?

transition to insulator $\sim$ loss of coherence

[superfluid/BEC]

(interaction)
How to Generate Optical Disorder: \textit{Laser Speckle}

- Diffusive plate (rough glass, CNT film etc)
- IR (1030nm)

\textbf{laser speckle is a} \textbf{coherent} phenomenon

\textbf{(incoherent lights won’t give speckle)}

\textbf{Potential Energy} vs distance

\textbf{Δz} and \textbf{2V_D}

\textbf{<V(r)V(r')>:
- Disorder Strength}
\textbf{V_D} tunable from 0 to few kHz

\textbf{Disorder correlation length}
(speckle size) \textbf{Δz} down to ~15 μm (limited by diff. plate/geometry)

\textbf{BEC radial size ~ Δz}

\textbf{===>} effective 1D disorder!
How to Probe it?

“sit”
• in-situ imaging of cloud
  -- probe ground state wavefunction

“push”
• excite and collective mode --- (damping)
• slow push (transport)

“fly”
• free expansion (after experiencing disorder)
  --- probe phase coherence/fluctuation
  • (“restricted-fly”) evolution dynamics in disorder
    --- rate of expansion /transport

Typical (Interacting) BEC:
[Part 1 of Talk (SIT)]

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N~10^5-10^6 atoms
axial size(z)~1mm
radial size ~10 μm
Interacting a~200a_B
chemical μ~kHz
T<100nK

Experimental sequence:
- optical trap: on
- disorder: off
- trap + disorder
- μ
- <~1s

- on
Transport Experiment 1: **Trap offset slowly --- “Dragging BEC through disorder”**

- **BEC**
- **Trap**
- **Disorder**

**Initial:** \( V_D = 0 \)
- \( V_D \approx 0.3 \mu \)
- \( V_D \approx \mu \)

- \( d = 1.4 \text{mm} \)
- \( \tau_{offset} \approx 1 \text{s} \)
Pinning of BEC by disorder

Strong disorder pins BEC

Cloud Center ($\mu$m)

$V_D / \mu$

$d$

- 1400 $\mu$m
- 900 $\mu$m
- 500 $\mu$m
- 300 $\mu$m
Transport Experiment 2: Trap offset abruptly --- dipole excitation

\[ V_D = 0\text{Hz} \quad V_D = 60\text{Hz} \quad V_D = 300\text{Hz} \]

\[ \tau_{\text{evolve}} = 75\text{ms} \]

Evolution of cloud following abruptly “shaking” trap (in ~5msec)
Damping of Dipole Excitations

(a) Dissipation/damping sets in at very small $V_D$

(b) Overdamped for $V_D \geq 0.3\mu$

Cloud moving speed
~ BEC sound speed (center)!

Exciting phase slips (vortices), phonons etc
Summary of transport properties

• We measure global transport
  <different from local-insulator probe such as Greiner>

Apparently 3 different regimes of transport:

• **High** $V_D$ : inhibition of transport (global **insulator**)
  “pinning point” (0.7-1µ) not universal value (dep on disorder realization
  and measurement type) --- probably sensitive to high peaks in disorder?

• **Small** $V_D$ damps dipole excitation
  dissipation or dephasing? “metallic” regime? (cf: on lattice, DeMarco’07)
  dissipation mechanism --- “phase slips”, vortices ...??
  where does the energy go?

• **Medium** $V_D$ : overdamped transport
  what’s the transport mechanism? tunneling assisted?
  fate of this regime at T=0? --- “semiconductor” regime?
Time of Flight (TOF) Free Expansion

BEC

trap

disorder

TOF free expansion time ($\tau$) [few ms]

Time of Flight probes phase coherence
Time of Flight (TOF) Free Expansion

disorder:
off

on

optical trap:
on

<~1s

imaging cloud
off

TOF free expansion time ($\tau$) [few ms]
$V_D$ 0 Hz

note: color scale all relative! $\tau_{\text{TOF}}$
$V_D \sim 0.3 \mu$

0.1 ms

0.5 ms

1.5 ms

3 ms

5 ms

8 ms

$\tau$

stripes pattern:

- not exactly periodical (not interference)

- not scalable from beginning cloud
$V_D \sim \mu$
increasing disorder...

$V_D$

0 Hz 200 Hz 700 Hz

0ms 1ms 2ms 3ms 6ms 8ms

note: color scale all relative!

(Random) interference “stripes”

chemical potential $\mu \sim 1$ kHz

$\tau_{TOF}$

Yong P. Chen et al., PRA(2008)
Density Fluctuations: In-situ vs TOF

$t_{TOF} = 0$ ms (in-situ)

$V_D/\mu = 0$

$V_D/\mu \approx 0.3$

$V_D/\mu \approx 0.5$

$V_D/\mu \approx 1.0$

$t_{TOF} = 8$ ms

Random but reproducible interference fringes

Phase coherence
Features of the interference pattern

Vd=500 Hz

• not correspond to in situ disorder (though does vary with disorder realization)
• can be reproduced from shot-shot!
• not sensitive to “hold time”
  -- unlikely from random quantum fluctuation (in phase)

Numerics (GPE) show can be derived and evolved from initial density fluctuation & phase coherent ground state (Clement & Sanchez-Palencia’07)

\[ \frac{\partial}{\partial x} (e^{ikx}) = ik e^{ikx} \]

\[ n(r) = |\Psi(r)|^2 \]

\( \phi \): BEC phase fluctuation at \( t=0 \) ----> density fluctuation (\( t=\tau \))
Disorder-induced Phase fluctuation in BEC?

\[ n(r) = |\Psi(r)|^2 \]

\[ \frac{\partial}{\partial x} (e^{ikx}) = ike^{ikx} \]

(phase \sim velocity)

free expansion

phase fluctuations also observed in elongated interacting BEC at finite \( T \)
S.Dettmer et al., (W.Ertmer, Hanover), PRL2001

in our case: (quantum) phase fluctuation due to disorder instead of heating!

\[ L_\phi = L_\phi(T, <V_d>, B[a]) \]
(Reproducible) Random Interference: Matterwave Speckle

Coherence

“interference” stripes <--- coherence
- reproducible
- only BEC (not seen with thermal gas)
- 1D modulation<--1D disorder


Random potential+reproducible “fluctuation” pattern=>coherence--mesoscopic physics

Note: in periodic potential (lattice), interference pattern (one-shot) occurs even w/o coherence
Digression: Speckle and Mesoscopic Physics

conductance through small conductors (wires, rings etc.):

\[ \Rightarrow \text{Universal Conductance Fluctuation (UCF)} \]

--- phase coherence transport

and analog of speckle for electron wavefunction

- **mesoscopic:** phase coherence \( L \sim \) sample size
- cold atoms/BEC excellent lab to study mesoscopic effects!

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Universal Conductance Fluctuations in Silicon Inversion-Layer Nanostructure

W. J. Skocpol, P. M. Mankiewich, R. E. Howard, L. D. Jackel, and D. M. Tennant

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(Received 9 April 1986)

We measure the conductance variations of submicrometer inversion-layer segments in silicon devices, systematically changing the length, width, inelastic diffusion length, gate voltage, magnetic field, and temperature. Results agree with the theory of universal conductance fluctuations, demonstrating that random quantum interference causes rms conductance changes \( \Delta G = e^2/h \) in each phase-coherent subunit of each segment. The random quantum interference is extremely sensitive to change of a single scatterer.
**Strong Disorder:**

- VD/\(\mu\) (all 6ms TOF)
- B~720G (interacting)
- 8ms TOF
- 0Hz
- B~720G (interacting)

**Insulator without phase coherence**

- "tight binding" limit (random Josephson) [also in Rb exp]

- "granular" condensate/superfluid (global insulator)
  - each (superfluid) "grain": number certain; (relative) phase random
  - ==> no macroscopic phase coherence

- [BEC/superfluid (coherent)]

- Lattice (Mott)
  - M. Greiner et al., (2002)

- Loss of phase coherence
**Medium Disorder: SIT and Phase Coherence**

Medium disorder:
- during superfluid-insulator transition
- system not yet “granular”
- (global) superfluidity compromised [losing phase rigidity]
- still has phase coherence

**disorder**

$\frac{V_d}{\mu}$

- 8ms TOF
- $B \approx 720$G
- (interacting)

[0 ms (in-situ)
- (cloud still connected)
- (not granular)]

[BEC/superfluid (coherent)]

How is (global) **superfluid order parameter** suppressed? [mean field th broken down?/role of quantum fluctuations]
Exp#4: Fall/Flow in Disorder

Experimental Procedure

- Turn off the optical trap
- Allow the condensate to evolve inside the disorder
- Turn off the disordered potential
- (immediately) Image the cloud
Results

• We Qualitatively compare the disordered TOF images to a free expanding BEC

(no disorder)

5 ms

(with disorder)

[at this disorder strength strong stripes were observed in the free TOF experiment]

10 ms
Localized confinement (trapping)?

- We see localized confinement few areas of the BEC
- Parts are confined for very long times (~20ms)
- Majority of the cloud “flows” away

10ms evolution in disorder

17ms evolution in disorder
Quantum Coherence may be important even in insulators --- especially if you get them from a superfluid/superconductor

And what about superfluidity & superconductivity?

3 steps:
• “Bosonization” (eg. pair)
• Phase Coherence
• **Phase Rigidity**
what’s the global phase diagram for a disordered & interacting Bose (or Fermi) gas? (free space or trapped)
Quantum/Phase fluctuations are interesting in Physics...

- drive *quantum phase transition* (cf. Q.Si and D.Natelson, NPA radio show) relevant for High Tc, heavy fermions materials, superfluid-insulator transition, nuclear matter.....
- even our fate ... : **Quantum Emulator?**

(from http://map.gsfc.nasa.gov/)