A tunable Bose-Einstein condensate in disordered potentials

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Motivations

Ultracold atoms as quantum simulator ??

- Superfluidity: atomic BEC <-> Helium (critical velocity, vortices, QT regime, ...)
- Single order parameter: macroscopic coherence (interference, Josephson junctions..)
- Quantum Statistics at demand: Fermi & Bose systems
- Interactions at demand: weakly and strongly correlated regimes
- BCS-BEC crossover: connecting superfluidity and superconductivity
- Designing crystals with light: perfect lattices (Bloch oscillations, band insulators...)
- Implementing quantum hamiltonians: quantum phase transitions (Mott, Tonks, BKT, quantum magnetism)

YeS, atomic gases are a definitively nice tool for simulating nature...

But, so far, only a pretty perfect nature....
An example:

Real crystals are not standing waves, so full of vacancies and impurities and of course electrons like to interact a lot.

In fact, nature is not so perfect as we like to pretend...

Disorder is ubiquitous in nature, since nature is disordered !!!
And many phenomena depends critically by the presence of disorder.

High Tc granular superconductors
(image from J. C. Davis, Berkeley USA)
Anderson model: weakly interacting electrons hopping on a lattice with random on-site energies

Single particle tight binding model with random on-site energies

The eigenstates are spatially localized with exponentially decreasing tails.
- localization of waves in a random medium
- extended states become localized in the presence of disorder
- general phenomenon, from condensed matter (electrons)...


...to:

- light waves

- microwaves

- sound waves

- matter waves (BECs)
Still, this is an “approximate” model: in fact electrons are highly interacting quantum objects!

..and many phenomena, as superfluidity and superconductivity, rely on the interactions between the particles.

-> interactions vs disorder

Despite many efforts, the interplay between interactions and disorder remains a challenging task (very difficult to control interactions and disorder at will!!)

Nature of the superconductor–insulator transition in disordered superconductors

ARTI GARG1,2, MOHT RANDERA3,4 AND NANDINI TRIVE21

LETTERS

Strong correlations make high-temperature superconductors robust against disorder
¿Quantum gases: quantum simulators?

J. E. Lye et al. PRL 95, 070401 (2005)
D. Clément et al. PRL 95, 170409 (2005)
C. Fort et al. PRL 95, 170410 (2005)
T. Schulte et al. PRL 95, 170411 (2005)

J. Billy et al., Nature 453, 891 (2008)


Our approach is to use a tunable BEC trapped into disordered potentials:

- BEC into an optical trap
- Transfer into a fully **controllable** disordered quasi-periodic lattice
- Manipulating the scattering length between the atoms (disorder vs interactions)
- Mapping out the condensate wave-function with and w/o disorder

- A tunable 39 Potassium BEC
- Our disordered potential: the bichromatic lattice
- One word on the non-interacting, system: observing **Anderson** localization.
- From an uncorrelated glass to a coherent state
Cooling potassium to BEC

Sympathetic cooling of $^{39}\text{K}^\text{87}\text{Rb}$:

BEC of 100000 atoms below 50 nK

Tuning the interactions via a magnetic Feshbach resonance in a potassium condensate ($^{39}\text{K}$)

Feshbach tuning of the interactions (mag. field stability 50 mG -> 0.03 $a_0$ !!)

$U < 10^{-4}$ J

Evaporative+sympathetic cooling in a magnetic trap down to $T \sim 1 \mu K$

Loading in a crossed beam dipole trap at $\lambda = 1030$ nm, $P = 10$ W.

$N_{\text{Rb}} = 1.5 \times 10^6$ and $N_{\text{K}} = 6 \times 10^5$ atoms @1.8 $\mu$K

Selective evaporation in the dipole trap

Homogeneous magnetic field: $B \sim 0-1000$ G, $\Delta l/l < 10^{-4}$
Potassium BEC

$T=1.8 \, \mu K$
$N_K=6 \times 10^5$
$\alpha_{kRb} = 28 \, \alpha_0$
$\alpha_{kK} = -33 \, \alpha_0$

$T=0.25 \, \mu K$
$N_K=3.4 \times 10^5$
$\alpha_{kRb} = 150 \, \alpha_0$
$\alpha_{kK} = -33 \, \alpha_0$

$T_c=0.10 \, \mu K$
$N_K=1 \times 10^5$
$\alpha_{kK} = 180 \, \alpha_0$

Tuning the interactions

- $B > 398.5 \, \text{G} \rightarrow$ 3-body losses due to Feshabach resonance: $K_3 \propto \alpha^4$
- $350.2 \, \text{G} < B < 398.5 \, \text{G} \rightarrow$ stable BEC with tunable positive interactions
- $B < 350.2 \, \text{G} \rightarrow$ BEC with negative interactions

Stable BEC with negative interactions $(N, \alpha)$
Collapse: $\alpha_c = \alpha_{ho}/ N$
$a_K = 0 \rightarrow$ ground state of the harmonic oscillator. $E_{\text{rel}}$ pure kinetic energy $a_{ho} = \sqrt{\frac{\hbar}{m\bar{\omega}}} = 1.84 \, \mu\text{m}$
Observation of the dipolar interactions in 39K

Quasi-periodic lattice ($\alpha=0$)  


\[
\hat{H} = -J \sum_{i,j} \hat{b}_i^\dagger \hat{b}_j + \Delta \sum_j \cos(2\pi \beta j) \hat{n}_j
\]

Metal-insulator (exp. localized) transition even in with 1D disorder for $\Delta_c = 2J$

The competition between $J$ (main lattice) and $\Delta$ (disorder) defines the physics

$\lambda_1 = 1064.42\ \text{nm}$  
$\lambda_2 = 866.3\ \text{nm}$

Extended states

Localized states

Spatial distribution

Momentum distribution

Narrow peaks in $p(k)$

Broad peaks in $p(k)$
\[ \langle r^2 \rangle(t) \propto t^2 \]

\[ \langle r^2 \rangle(t) \propto \langle r^2 \rangle(0) \]

Universal behavior with $\Delta/J$
Adding interactions the momentum distribution becomes narrower: transition from a localized to extended state!
1) \( F^{-1}(f(k)^{1/2}) \) = average local shape of the wavefunction

\[
\sum_{i=1,2} A_i \exp\left(-|z - z_i|/L\right) \cdot \left[1 + B \cos(k_1(z - z_i) + \phi_i)\right]
\]

2) \( F^{-1}(f(k)) \) = correlations (@ 4.4 lattice sites) (Wiener-Khintchine theorem): spatially averaged correlation function

\[
f(k) \sim F^{-1} \int G(x', x' + x)dx'
\]
Many copies of the same experimental realization: measuring phase correlation:

\[ \Delta/J = 12 \]

1. Uncorrelated states: low contrast, random phase ("glassy" regime)

2. Extended single state: maximum contrast and locked phase (coherent regime)

3. "Partially correlated" states: some contrast and not completely random phase (a "fragmented" regime)
independent exponentially localized states

formation of fragments

single extended state

Mean-field calculations by M. Modugno (in preparation)

Damski et al., PRL 91, 080403 (2003)
Lugan et al., PRL 98, 170403 (2007)
SIT transition

P.W. Anderson demonstrated that superconductivity is stable against some disorder (no magnetic) ("Anderson theorem").

but... 2D disordered superconductors show a transition from a superconducting to an insulator phase (SIT). The nature of this transition is still under debate.

Disorder “fragments” the order parameter:

-> Islands of superconductivity with defined $\Delta$

-> The system behaves as a bulk superconductor as long as $\Delta \neq 0$, and the phases of $\Delta (r)$ on two sides of the sample are correlated. The correlations are guaranteed by coherent tunnelling of Cooper pairs between the islands


Future plans

I. Strongly correlated bosons (1D) in presence of disorder:
   a. Expected transition from a SF to Bose glass phase (U, Δ >> J)
   b. Probing the excitation spectra (Bragg spectroscopy)
   c. Compressibility measurements (Mott vs Bose glass)

II. Fermions in disordered potentials: closer connection to condensed matter problems
   a. Competition between EF and disorder strength
   b. Fermions in 2D disordered potential (superfluidity vs disorder, MIT)
Exploring Correlated 1D Bose Gases from the Superfluid to the Mott-Insulator State by Inelastic Light Scattering

D. Clément, N. Fabbri, L. Fallani, C. Fort, and M. Inguscio
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(Received 23 December 2008; revised manuscript received 10 February 2009; published 13 April 2009)

We report the Bragg spectroscopy of interacting one-dimensional Bose gases loaded in an optical lattice across the superfluid to the Mott-insulator phase transition. Elementary excitations are created with a nonzero momentum and the response of the correlated 1D gases is in the linear regime. The complexity of the strongly correlated quantum phases is directly displayed in the spectra which exhibit novel features. This work paves the way for a precise characterization of the state of correlated gases in optical lattices.

Recent observations of confinement induced resonances

Observation of an Efimov spectrum in an atomic system


ERC starting grant: heteronuclear molecules

39K all optical: work in progress

Ytterbium: work in progress