Bose-Einstein condensates in optical lattices

Creating number squeezed states of atoms

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Overview

• What is a BEC?
• What is an optical lattice?
• What happens to a BEC in an optical lattice?
• Experiments
  • Mott insulator
  • Collapse and revival of matter waves
• Other interesting bits
• Summary
Bose-Einstein condensation

- Definition: Macroscopic occupation of a single quantum level (usually ground state).
- Due to saturation of excited states of system

\[ n\Lambda_{dB}^3 \geq 2.612 \]

- Created for the first time in 1995 in atomic Rb
- More than 30 groups have now observed BEC
BEC features

- Made by first laser cooling, then evaporative cooling a sample of trapped atoms.
- Occurs at ultracold temperatures $\sim 100 \text{ nK}$.
- Typically consist of $10^4$–$10^7$ atoms of eg Rb, Na.
- Best thought of as a *matter wave*, analogous to laser light.
- All atoms are phase coherent i.e. widely spaced atoms can form an interference pattern.
- *Quantum mechanics on a macroscopic scale*
Phase transition
Optical dipole force

- **Stark effect**: Shift of atomic energy levels in static electric field.
- **AC Stark effect**: Shift of atomic energy levels due to time-varying electric field of laser.
- In the limit of large detuning from resonance (avoid spontaneous decay)

\[
\Delta E(x) \propto \frac{I(x)}{(\omega - \omega_0)^2}
\]

- Remember \( F(x) = -dE(x)/dx \), so atoms in a laser beam experience force proportional to gradient of intensity of laser beam
Optical lattices

- Definition: Standing waves of light
- Atoms see series of potential wells (hills).
- If cold enough, atoms can be trapped in single well.
- Blue-detuned: atoms trapped at nodes
- Red-detuned: atoms trapped at anti-nodes
- *Depth of potential easily controlled via laser intensity*
Loading BEC into lattice

- Increase intensity adiabatically

$$V(x) = E_R(t) \cos^2\left(kx/2\right), \quad k = 2\pi/\lambda$$
The physics

Initially . . .

- Atoms can tunnel between wells
- Each well is approximately a coherent state.
- Variance in atom number is equal to mean.
- System is superfluid.

As laser intensity increases . . .

- Wells become isolated (longer tunnelling time).
- Number fluctuations supressed.
- Heisenberg says — *phase fluctuations increase*.
Quantum phase transitions

- Classical phase transitions driven by thermal fluctuations.
- Quantum phase transitions driven by quantum fluctuations.
- Occur at $T=0$ by changing parameters of Hamiltonian.
- Mott insulator: Energy minimised by number states in each well.
- How? — reduce tunnelling rate by increasing lattice depth.
Experiments

Turn on lattice adiabatically, then switch off suddenly
Superfluid to Mott insulator . . .

Images after 18 ms of expansion

Momentum distribution for different potential depths of a 3D lattice:
... and back to superfluid

Adiabatic ramp to 22 $E_R$ (80 ms)

Hold (20 ms)

Release to 9 $E_R$ (t ms)
... and back to superfluid II
Theory: Bose-Hubbard model

\[
\hat{H} = -J \sum_{\langle i, j \rangle} \hat{b}^\dagger_i \hat{b}_j + \sum_i \epsilon_i \hat{n}_i + \frac{U}{2} \sum_i \hat{n}_i (\hat{n}_i - 1)
\]

\(J\): tunneling matrix element. Decreases with \(E_R\).
\(U\): interaction matrix element. Increases with \(E_R\).

**Mott insulator transition:** \[\frac{U}{nJ} > 5.8 \times z\]

\(n\): number of atoms per site
\(z\): number of nearest neighbours
More theory

- Recent results show that disappearance of interference is not a signature of MI phase (Roth and Burnett, condmat/0209066).

- However excitation spectrum was also studied.

- Energy gap appears above lattice depth of $13 E_{\text{recoil}}$.

- Thus an insulating state was acheived.
Collapse and revival

Coherent state: superposition of number states

\[ |\alpha\rangle = e^{-|\alpha|^2/2} \sum_n \frac{\alpha^n}{\sqrt{n!}} |n\rangle \]

Ground state Hamiltonian of single well

\[ \hat{H} = \frac{U}{2} \sum_i \hat{n}_i (\hat{n}_i - 1) \]

Evolution:

\[ |\alpha\rangle(t) = e^{-|\alpha|^2/2} \sum_n \frac{\alpha^n}{\sqrt{n!}} e^{-i \frac{1}{2} Un(n-1)t/\hbar} |n\rangle \]
Revival

- All phases match up at times $t_c = U/h$

- Can be realised by sudden switch to Mott insulator state!
Time scales

Revivial time is *independent* of atom number variance.

Collapse time is *dependent* on initial variance of atom number.
Other interesting bits

- Proposal (and experiments) on controlled cold collisions. Two different internal states, each see different lattice. Move lattices together — interactions dependent on state. Quantum computing???

- Proposal to form Mott insulator with $n = 2$. Then photoassociate and melt $\Rightarrow$ molecular BEC.

- Why is this interesting? Wednesday physics seminar tomorrow, 1pm Conference room 2.32D, Physics Annexe (Building 6). PAIR CORRELATED ATOM LASER BEAMS Dr Karen Kheruntsyan.
Summary

- Introduction to BEC
- Introduction to optical lattices
- Quantum phase transitions
- Superfluid to Mott insulator
- Bose-Hubbard model.
- Collapse and revival of matter waves
- Other proposals for BECs in lattices.

No Microsoft products were used in the making of these slides

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