Ultracold Atoms in Optical Lattices

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Overview

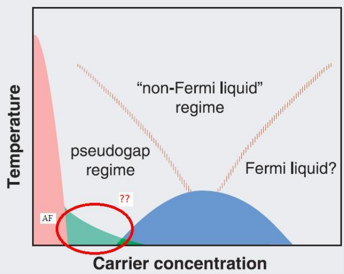
1. Motivation
2. Cooling
   - Laser Cooling
   - Doppler Cooling
   - Evaporative Cooling
3. Optical Lattice
4. Applications
   - Superfluid to Mott Insulator Transition

Problems with Real Systems

Unnecessary Distractions??

- Real systems have many distractions -
  - Impurities
  - Sample Quality - Hard to achieve single crystals
  - Other effects like band structure, etc.
- May hide the real cause of a phenomenon of interest
- A model can include only a fraction of these

Cuprates



Orenstein 2000

How to find the real cause for a physical phenomenon and test whether a model is correct? - Go to low temperatures !

Cold Atoms

What are Cold Atoms?

- Super-cooled gas (T$\sim 10^{-7}$ K) of atoms trapped on a periodic lattice formed by lasers (optical lattice)

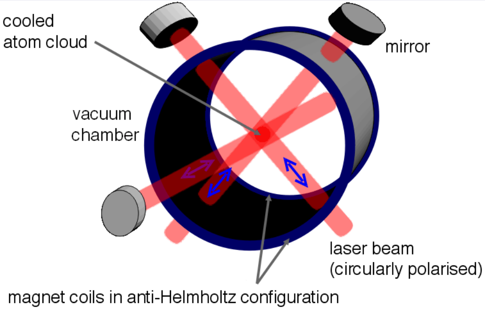
Why Cold Atoms?

- Free of impurities
- Low temperatures - Enable us to study various quantum phases
- Easy and Fast tuning of experimental parameters like underlying lattice periodicity, interaction between particles etc.

Steps involved in Cooling

- *Magneto-optical Trap* (MOT) - Laser Cooling, Doppler Cooling
- Magnetic Trap with Evaporative Cooling

Experimental Setup of MOT



wikipedia

Laser Cooling

- Idea - Atoms absorb light and emit spontaneous - In the process gets “cooler”
- In each emission, atom kicking out a photon gets a recoil which reduces its speed
- On repetition, mean velocity and thus, mean kinetic energy of the atom gets reduced - Temperature gets reduced!
- It is important to use laser of right frquency (color) to match atomic resonance

Doppler Cooling

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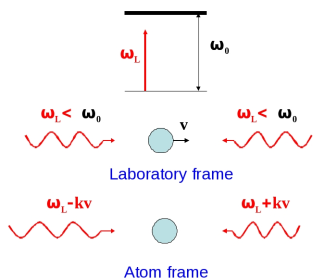
- Atom moving towards laser with see it bluer in color. If we start with laser with frequency slightly less than resonance frequency, then only faster atoms ($\omega_0 = \omega_L + kv$) will be affected

Doppler Effect



C. Salomon, SIGRAV School, Firenze, Sep 2006

Doppler Cooling

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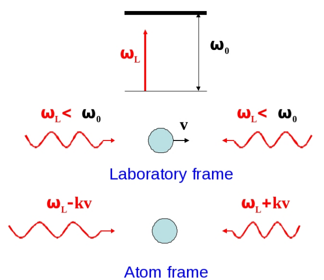
- Atom moving towards laser with see it bluer in color. If we start with laser with frequency slightly less than resonance frequency, then only faster atoms ($\omega_0 = \omega_L + kv$) will be affected
- It is getting harder - We have to keep adjusting the laser color as atom cools

Doppler Effect



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Magneto-Optical Trap (MOT)

- How to trap cooler atoms to the center of container and not let them hit container's wall and get heat up?

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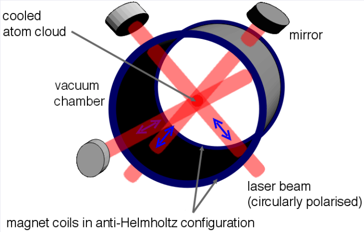

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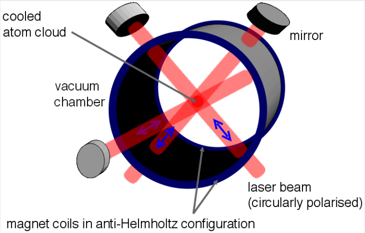
- How to trap cooler atoms to the center of container and not let them hit container's wall and get heat up?
- A small magnetic field is applied which is minimum at the center of container and increases towards the edges (Anti-Helmholtz Configuration)

Experimental Setup of MOT



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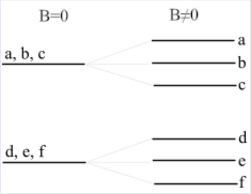
- How to trap cooler atoms to the center of container and not let them hit container's wall and get heat up?
- A small magnetic field is applied which is minimum at the center of container and increases towards the edges (Anti-Helmholtz Configuration)
- This leads to Zeeman splitting of levels - Resonance frequency decreases - Doppler cooling possible - Cooler atoms can be further slowed if trying to move out - MOT

Experimental Setup of MOT



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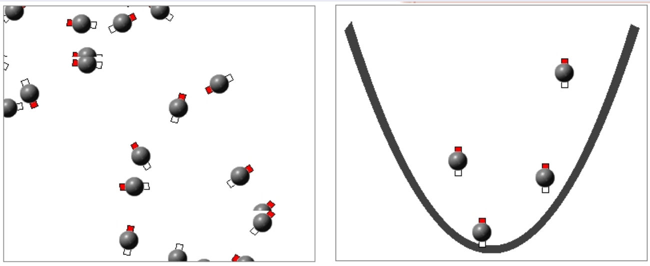
Limitations

- *Doppler Cooling Limit* - When an opposite moving photon is absorbed, atom's speed decreases - On emission, an extra random momentum is added to the atom which, on an average, give positive contribution
- *Maximum Concentration* - If concentration of atoms increases, collision may increase and the energy of emitted photon may go into collision heat
- *Atomic Structure* - Difficult to generate the laser power needed at wavelengths much shorter than 300 nm. Also, more hyperfine structure (related to nucleus - electron spins interaction), more the number of ways to emit photon without returning to ground state - dark states - do not contribute in cooling further

Evaporative Cooling

Magnetic Trap

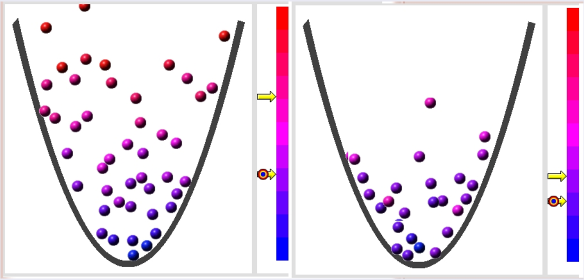


$B = 0$ $\quad$ $B \neq 0$

Physics 2000 website (Colorado)

- Strong magnetic field in form of potential well for the atomic moments.

Evaporative Cooling



$t = 0$ $t > 0$

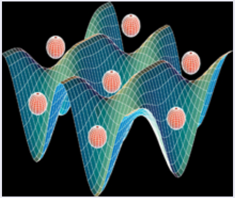
Physics 2000 website (Colorado)

- The most energetic molecules are allowed to escape. They take more than their share of heat - atoms left behind are colder now - Same as tea cooling in a cup

Optical Lattice

- An artifical crystal of light - a periodic intensity pattern formed by interference of two or more laser beams

Optical Lattice



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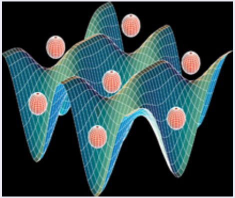
Optical Lattice

- An artifical crystal of light - a periodic intensity pattern formed by interference of two or more laser beams
- In 1-d, if two oppositely moving laser beams with same wavelength interfere - Standing waves - Regions of dark and bright stripes - $V(x) = V_0 \sin^2 x$ - Atoms trapped at 1-d lattice sites

Optical Lattice



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Optical Lattice

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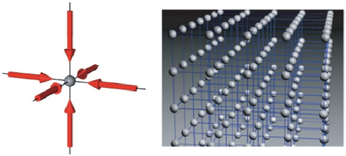
- If 3 such standing waves are superimposed - an optical cubic lattice !

Optical Lattice



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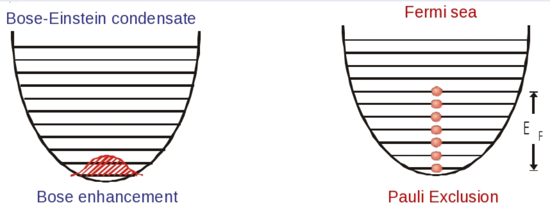
Optical dipole potentials

- An electric dipole moment is induced in neutral atoms in an Electric field
- Interaction between dipole moment and Electric field modifies atom energy ($\sim -\vec{d} \cdot \vec{E}$)
- Two cases arises -
  - $\omega_L < \omega_0$ - Atoms are pulled to regions of maximum field
  - $\omega_L > \omega_0$ - Atoms are pushed away from maxima
- Either way atoms can be trapped in a minima or a maxima

Bose Einstein Condensation



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- Fermions obey Pauli Exclusion priciple - no two fermions can occupy same quantum level
- Bosons obey Bose-Einstein statistics - all bosons can occupy same quantum state at absolute zero - *Bose-Einstein condensation*

Interacting Bosons in Periodic Potential

$$\mathcal{H} = -J \sum_{\langle ij \rangle} a_i^\dagger a_j + \frac{U}{2} \sum_i n_i (n_i - 1)$$

Ground state of Bose Hubbard Model

$\frac{U}{J} << 1$

- All the particles occupying $\mathbf{k} = 0$ state - each atom spread over entire lattice
- Atom number at each site - uncertain - follows Poisson distribution
- Wavefunction has a fixed phase - Atoms loses their individual identity - moves as a coherent unit - *Superfluid*

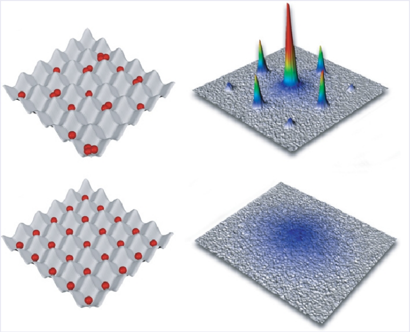
$\frac{U}{J} >> 1$

- Fluctuations in atom number at a site becomes costly - Ground state - Localized wavefunctions at each site
- For commensurate filling - equal number of particles at each site
- Phase coherence is lost in this state

Superfluid to Mott Insulator Transition

- U/J can be controlled by changing depth of potential, V_0
- On increasing V_0, atomic wave packets become more and more localized - U increases and J decreases
- Possible to change J/U from 0 to as high as 2000 in cold atoms experiment
- Can we see this transition experimentally ?

Superfluid to Mott Insulator Transition



Bloch 2005

- Top Panel - When BEC is released from periodic potential - due to phase coherence - peak in momentum distribution of particle number
- Bottom - Mott Insulator - No phase coherence - No peak