Lecture 20

Bose-Einstein condensation

Recall problem 5.29

In a gas of bosons with density ρ, there is a critical temperature

$$T_c = \frac{2\pi\hbar^2}{m k_B}\left(\frac{n}{2.612}\right)^{2/3}$$

If $T<T_c$, get macroscopic population of atoms in ground state of the potential

We do that in my lab

use gas of Rb atoms   mass = 87 amu

Density $\approx 10^{19}\ m^{-3} \approx 5\times10^{-7}\ n_{air}$

Get $T_c = 100\,nK$ ... pretty cold

Talk about how we get so cold, and what BEC is like

First, a bit about Rb:

$Z = 37$

36 electrons fill up 1s, 2s, 2p, 3s, 3p, 3d, 4s, 4p states

Last goes into 5s state

Takes a lot of energy to excite lower lying electrons

- Pretty much acts like single electron atom

Not exactly like hydrogen though

Rb levels:

6P ——— 3.0 eV

4D, 6S ——— 2.5 eV

5P ——— 1.6 eV

5S ——— 0

Hydrogenic degeneracies completely broken due to interactions with core $\bar{e}$'s

Matters because main tool we use is laser cooling

Focus on 5S - 5P:

5P

$J = \frac{3}{2}$ — $F = 3, 2, 1, 0$

$HF = 2\times10^{-6}\,eV = 5\times10^{7}\,Hz$

FS splitting $= 0.03\,eV$

$= 7\times10^{12}\,Hz$

$J = \frac{1}{2}$ — $2, 1$

5S $J = \frac{1}{2}$ — $2, 1$

HF splitting $= 3\times10^{-5}\,eV$

$7\times10^{9}\,Hz$

Not too important, but we need to know in order to set up lasers correctly... the stuff we've been talking about matters.

Laser cooling

Use laser to drive transition from 5S to 5P state

$\lambda = 780\text{ nm}$, infrared.

Atoms can only absorb light in narrow band

$$\Delta E = h\Delta\nu \approx \frac{1}{\tau} \qquad \tau = \text{lifetime of excited state}$$

$$\Delta\nu = 6\times10^{6}\text{ Hz}$$

So if laser is detuned by much more, don't get absorption

If we are on resonance, get pretty big mechanical effect.

Each photon has momentum $\hbar k \approx 8.5\times10^{-28}\ \frac{\text{kg m}}{\text{s}}$

Scatter at rate $\approx \frac{1}{\tau} \approx 6\times10^{6}$ photons/s

Gives force $\frac{\hbar k}{\tau} \approx 5\times10^{-21}\text{ N}$

acceleration $\frac{\hbar k}{\tau m} = 3.5\times10^{4}\text{ m/s}^2$ pretty big!

Use this force to slow atoms down

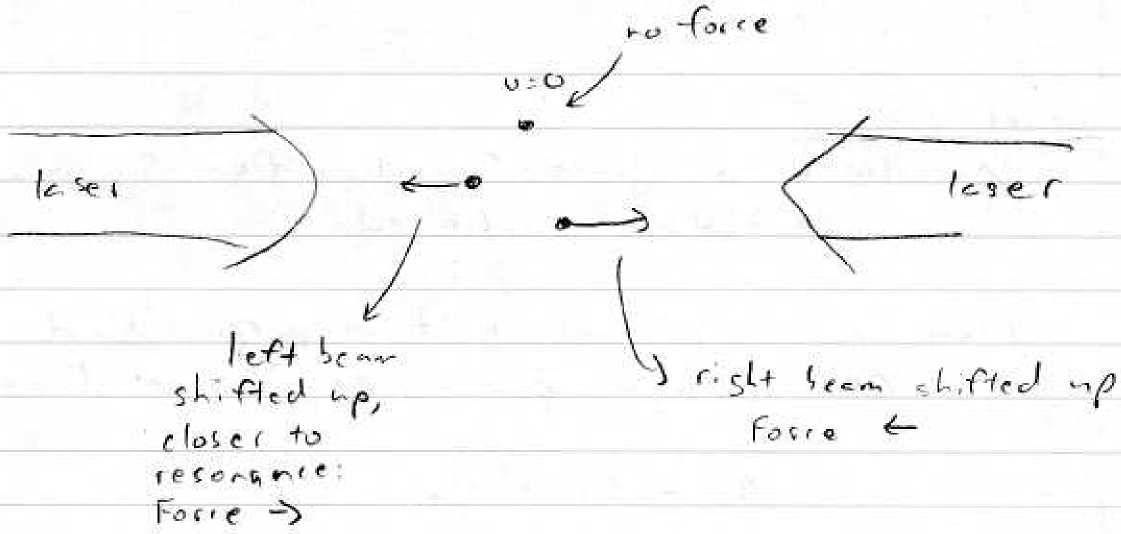
How?

Atoms in gas move everywhich way

Moving atoms have Doppler shift: $\Delta\nu = \frac{v}{\lambda}$

Send lasers in from all directions, tuned below resonance

Stationary atoms don't scatter much



No matter how atom moves, get force opposing motion

Works until $\frac{v}{\lambda} \lesssim \frac{1}{\tau}$, Doppler shift not resolved

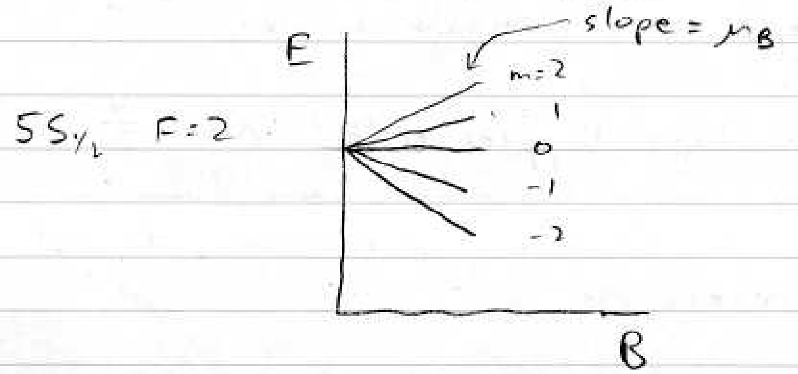
Corresponds to $\boxed{T = 100\,\mu K}$

Could get BEC here if density high enough
But at high density, gas is opaque → cooling doesn't work.

Need another way.

<u>Next step</u>: transfer atoms to magnetic trap

Recall weak field Zeeman effect:



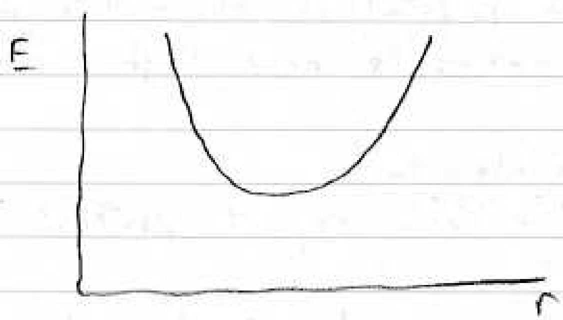
States with $m>0$ attracted to low B field
$m<0$ high B field

Turns out, Maxwell eqn's prohibit B-field maximum in free space

But minimum is allowed: get $B=0$ between two opposing magnets

(Note, spins adiabatically follow direction of $\vec{B}$, so only $|\vec{B}|$ matters)

So if we make a field with a local minimum, get trap for $m>0$ atoms:



We use $m=2$

Load trap by quickly turning lasers off and B on

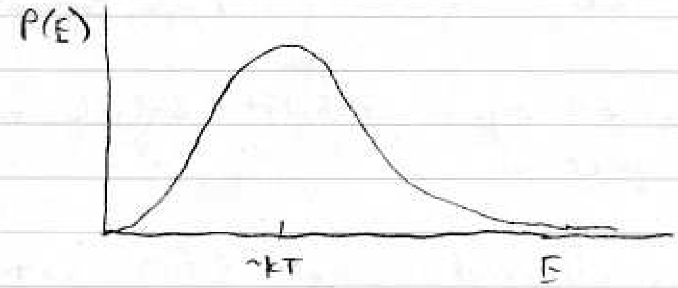
Now atoms in a conservative potential, can make them as cold and dense as we want

<u>How to cool?</u> Evaporative cooling

Basic principle: atoms in gas have range of energies

Average $E \approx kT$
Some have $E \approx 0$
Some have $E \gg kT$

Describe by energy distribution:



Can calculate using stat mech

If we remove atoms in high energy tail, take away disproportionate amount of energy

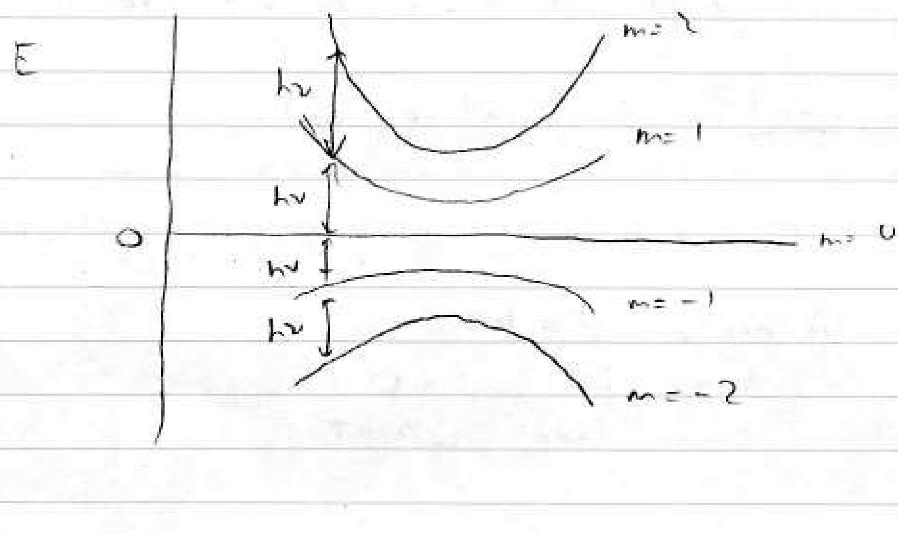
Average energy of remaining particles is lower

Best part: wait a bit, and atoms collide.
Want to reestablish thermal equilibrium, so generate new high energy atoms

$\Rightarrow$ Repopulate tail!
We can repeat process

This is nothing special: why food cools when we blow on it.

Here we can control evaporation very precisely:



Apply radiation, freq $h\nu$

Resonant when $h\nu = g_F \mu_B B$

If $\nu > \nu_{min}$, only atoms away from trap minimum, see resonance

But only energetic atoms can move far from trap minimum

So ν sets "depth" of trap: more energetic atoms driven to untrapped states.

Cool gas by gradually reducing ν
Start with 10^8 atoms, $100\,\mu K$
finish with 10^4 atoms $100\,nK$
→ obtain BEC

BEC:
Violates a lot of normal QM ideas

10^4 atoms in same ψ ≈ harmonic oscillator ground state

Can "see" ψ without disturbing it: measure 100 atoms, get good idea of state, most atoms unaffected

Condensate acts very much like purely classical wave
Don't actually need QM to describe:

Classical Particles ⟷ QM ⟷ Classical wave
BEC goes through transition