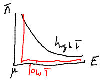
Boson gas (e.g. same atoms)

$$\bar{n} = \frac{1}{e^{(E-\mu)/kT} - 1}$$



as $T \to 0$, there is a sharp upturn in average occupancy approaching the ground state

ground state ends up with all the particles

Bose-Einstein condensate

e.g. He-4 is a spin-0 atom

as it cools, a large proportion of atoms "condense" into same ground state – quantum! indistinguishability matters

Superfluidity

– no viscosity

near-perfect thermal conductivity

Photons are spin-1 bosons

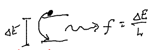
$$\bar{n} = \frac{1}{e^{E/kT} - 1} \qquad \mu = 0$$

photons don't have a fixed number

created or destroyed at will

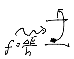
Lasers

spontaneous emission

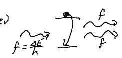


how normal light is created

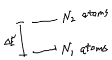
absorption



stimulated emission



Light Amplification by Stimulated Emission of Radiation



$Y(E)$ = # of photons around with energy E

$$R_{spon} = A_{spon} N_2$$

$$R_{abs} = B_{abs} N_1 Y(\Delta E)$$

$$R_{stim} = B_{stim} N_2 Y(\Delta E)$$

In equilibrium

$$R_{abs} = R_{spon} + R_{stim}$$

$$A_{spon} N_2 + B_{stim} N_2 Y(\Delta E) = B_{abs} N_1 Y(\Delta E)$$

$$Y(\Delta E) = \frac{A_{spon}/B_{abs}}{\frac{N_1}{N_2} - \frac{B_{stim}}{B_{abs}}}$$

Boltzmann statistics

$$\frac{N_1}{N_2} = \frac{e^{-E_1/kT}}{e^{-E_2/kT}} = e^{\Delta E/kT}$$

$$Y(\Delta E) = \frac{A_{spon}/B_{abs}}{e^{\Delta E/kT} - \frac{B_{stim}}{B_{abs}}}.$$

should be Bose-Einstein distribution

$\to B_{stim} = B_{abs}$

in equilibrium, a photon is just as likely to be absorbed as to stimulate emission

That's a problem: avg photons out = avg photons in

Solution: put crystal out of equilibrium

if $N_1 << N_2$

fewer atoms to absorb photons

& more to emit photons

then we get lasing

population inversion

optical pumping