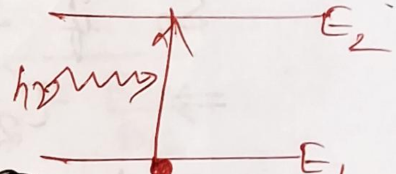
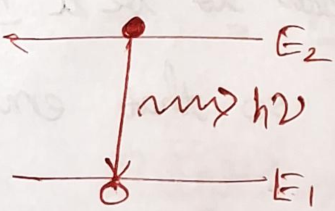
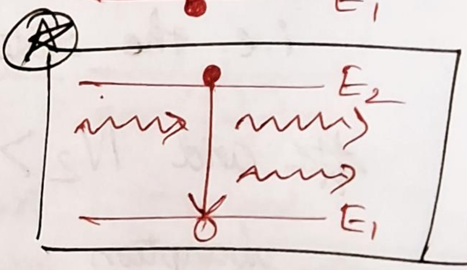
29th December, 2025

LASER

- Light Amplification through Stimulated Emission of Radiation
- Einstein predicted the possibility of lasing in 1916 by introducing concept of stimulated emission
- Charles Townes developed the lasing mechanism in microwave region (MASER) in 1954

Light - Matter interaction - Three Quantum Processes.

	Spontaneous	Stimulated
Absorption	X	
Emission		

Spontaneous absorption : X

Stimulated absorption : atom + $h\nu$ → atom*

Spontaneous emission : atom* → atom + $h\nu$

Stimulated emission : atom* + $h\nu$ → atom + $2h\nu$

Rate of transitions (R)

① $R_{12}^{spontaneous} = 0$

② $R_{12}^{stimulated} \propto \rho_{photon}$ (photon density)

$\propto N_1$ (# of electrons in E_1)

$\Rightarrow R_{12}^{stimulated} = B_{12} N_1 \rho_{photon}$

③ $R_{21}^{spontaneous} \propto N_2$ (# of electrons in E_2)

$\Rightarrow R_{21}^{spontaneous} = A_{21} N_2$

④ $R_{21}^{stimulated} \propto \rho_{photon}$

$\propto N_2$ (# of electrons in E_2)

$\Rightarrow R_{21}^{stimulated} = B_{21} N_2 \rho_{photon}$

Here A_{21}, B_{12}, B_{21} are called **Einstein coefficients**

Comparison of transitions at thermal equilibrium

- The relation between transitions is dependent on relation between Einstein coefficients

① At thermal eq^m, **Net absorption = Net emission**

② Radiation is identical to black body radiation and given by **Planck's radiation law**

③ The occupation of levels follows **Boltzmann distribution**

(1) $\Rightarrow$ $B_{12}\rho N_1 = A_{21}N_2 + B_{21}\rho N_2$

$$\rho(B_{12}N_1 - B_{21}N_2) = A_{21}N_2$$

$$\rho = \frac{A_{21}N_2}{B_{12}N_1 - B_{21}N_2}$$

$$= \frac{A_{21}/B_{12}}{\left(\frac{N_1}{N_2} - \frac{B_{21}}{B_{12}}\right)}$$

(3) $\Rightarrow$ $$\frac{N_2}{N_1} = \exp\left[-\frac{E_2 - E_1}{K_B T}\right]$$

$\because$ $E_2 - E_1 = h\nu$

$$\frac{N_2}{N_1} = \exp\left(-\frac{h\nu}{K_B T}\right)$$

$$\Rightarrow \frac{N_1}{N_2} = \exp\left(+\frac{h\nu}{K_B T}\right)$$

$$\therefore \rho = \frac{A_{21}}{B_{12}} \cdot \frac{1}{\exp\left(\frac{h\nu}{K_B T}\right) - \frac{B_{21}}{B_{12}}}$$

(2) ~~upon~~ $\Rightarrow$ $$\rho(\nu) = \frac{8\pi h\nu^3}{c^3}\frac{1}{\exp\left(\frac{h\nu}{K_B T}\right) - 1}$$

$\therefore$ $\frac{A_{21}}{B_{12}} = \frac{8\pi h\nu^3}{c^3}$ $\Rightarrow$ spont emission $\gg$ stimulated absorption

and $\frac{B_{21}}{B_{12}} = 1 \Rightarrow B_{21} = B_{12}$

} Einstein relations

↓

~~sp~~ stimulated emission = stimulated absorption

At thermal equilibrium spontaneous emission dominates stimulated emission.

Conditions for Lasing Action

We need stimulated emissions to dominate spontaneous emission for <u>lasing action</u>

* $\frac{\text{Stimulated emission}}{\text{Spontaneous emission}} = \frac{B_{21} N_2 \rho(\nu)}{A_{21} N_2}$

Three conditions for lasing action = $\frac{B_{21}}{A_{21}} \rho(\nu) > 1$

1. High photon density
2. Larger lifetime
3. $N_2 > N_1$

$\Leftrightarrow$ $\rho(\nu)$ is high or $\frac{B_{21}}{A_{21}} > 1$

Rate vs lifetime

$$\text{Rate} \propto \frac{1}{\text{Lifetime}}$$

Just as rate is the number of transitions occuring out of the level, lifetime is the time the electron stays in the level.

So if $B_{21} > A_{21}$

$\Rightarrow \tau_2 > \tau_1$

i.e. the state needs to be a <u>metastable state</u>

and $N_2 > N_1$ so that emission dominates absorption

$\Rightarrow N_2 > N_1$

This condition is called <u>population inversion</u> and cannot occur under equilibrium.

Lasing action is defined as condition when the stimulated emission dominates the spontaneous emission

~~A Met~~

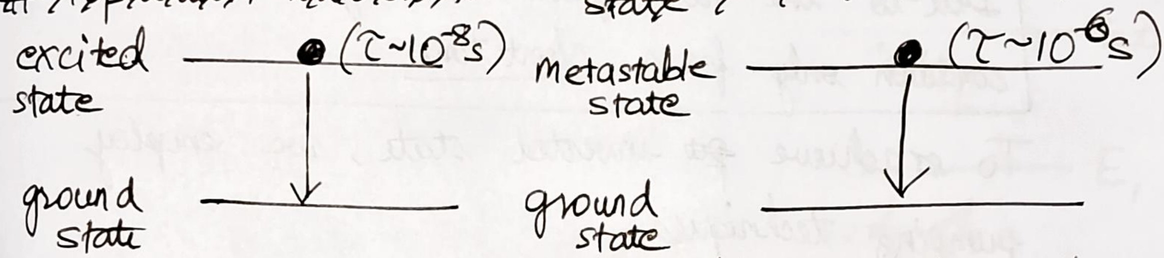
Meta stable state (to achieve condition ②)

~~A~~ Typical excited state lifetime is of the order of $10^{-8}s = 10\,ns$.

However, some states can have larger lifetime due to various reasons. These are called metastable state. These states are in between excited and ground ~~metastable~~ ~~states~~. The lifetime of these states is of the order of $10^{-3} - 10^{-6}\,s$ i.e. ms to μs.

~~Population inversion.~~

~~excited state~~

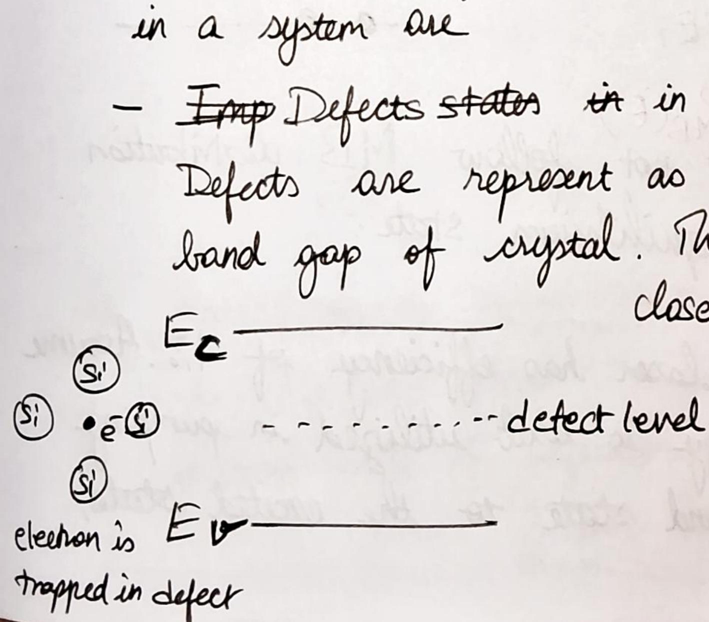


So the electron in a metastable state does not transition to ground state so easily

Some of the ways to introduce meta stable states in a system are

- ~~Imp~~ Defects ~~states~~ ~~in~~ in a crystal.

  Defects are represent as levels in the forbidden band gap of crystal. These levels generally lie closer to the midgap.



These are also called <u>trap levels</u>.

If lifetime of electron in ~~the~~ metastable state is 10^{-3} s to 10^{-6} s, then the electron stays nearly 10^{2} to 10^{5} times longer in metastable state than in excited state

To understand the timescale difference of lifetimes, if we consider lifetime of excited state as 1 sec then lifetime of metastable state as 100 s to 100,000 s

i.e. 2 min to 1 day.

$\frac{1000}{3.6} \approx \frac{100}{4} = 25$

Winter season:

- ——— cold shower
- ——— blanket
- ——— Shavasana

Analogy of excited state vs metastable state vs ground state

~~# Population Inversion.~~

~~So if we create a situation of~~

Population inversion (to achieve condition ③)

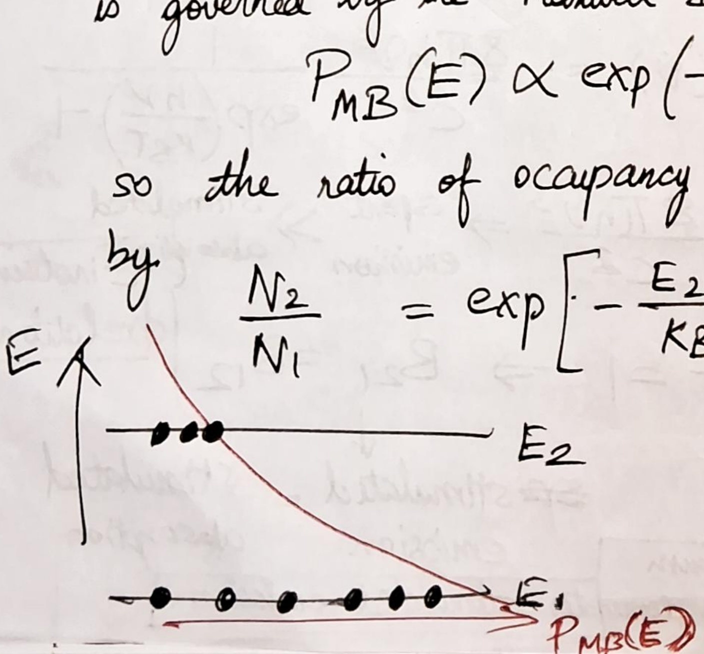
Normal state

At thermal equilibrium, the occupancy of levels is governed by the Maxwell Boltzmann distribution

$$P_{MB}(E) \propto \exp\left(-\frac{E}{K_B T}\right)$$

so the ratio of occupancy of levels E_1 & E_2 given by

$$\frac{N_2}{N_1} = \exp\left[-\frac{E_2 - E_1}{K_B T}\right]$$



So population N_2 at excited level E_2 is smaller than population N_1 at ground level E_1.

This is the typical condition of system at thermal equilibrium also called <u>equilibrium condition</u>. It is also called ~~inverted state~~ normal state.

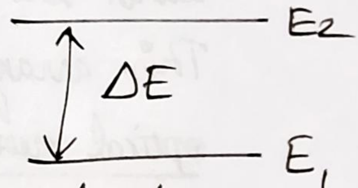
For typical values of E_1 and E_2, ~~N_2~~ N_1 ~~exceeds~~ is nearly ~~N_2 by~~ 10^{30} times N_2.

<u>Problem:</u>

Find the ratio of populations of the two states in a He-Ne laser that produces light of wavelength 6328 Å at 27°C.

<u>Solution:</u>

$$\frac{N_2}{N_1} = \exp\left(-\frac{E_2 - E_1}{k_B T}\right)$$



But $E_2 - E_1 = \Delta E$ is given $\bar{c}$ wavelength

So $\Delta E = \dfrac{1.24}{\lambda\ (\mu m)}$

$\lambda = 6328\text{Å} = 0.6328\,\mu m$

$\Rightarrow \Delta E = \dfrac{1.24}{0.6328} = 1.96\,eV$

$T = 27°C = 300K$

$\Rightarrow k_B T = 26\,meV$

$$\therefore \frac{N_2}{N_1} = \exp\left(-\frac{1.96}{0.026}\right) = \exp(-75.38) \approx 10^{-32}$$

— Time scale of equilibrium condition.

The system stays in ~~ground state~~ for equilibrium condition forever if not disturbed

e

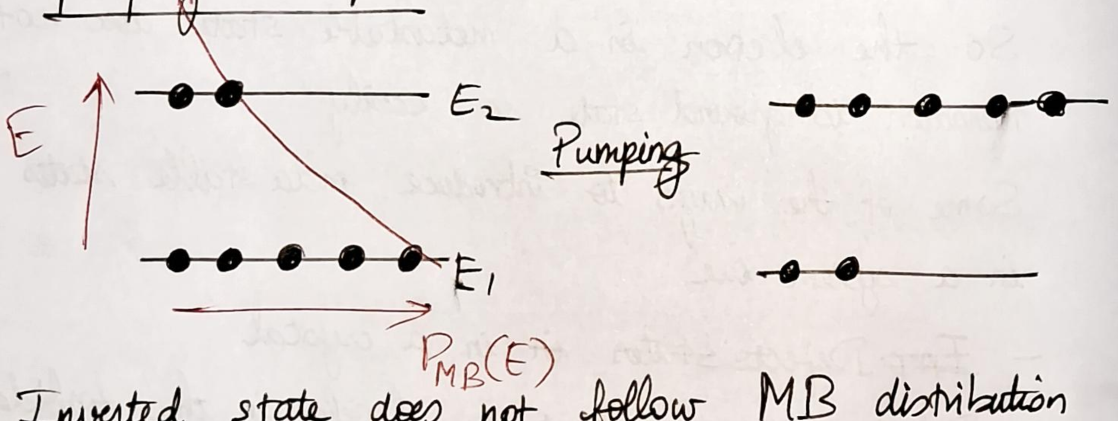
Inverted state

However,
if we create a situation in which the population of upper energy levels N_2 far exceeds the population of lower energy level N_1, such a condition is called population inversion and state of system is called inverted state.
This is an atypical condition and therefore is a not a equilibrium condition, also called non-equilibrium condition.

- Time scale of non-equilibrium condition

Due to the non-equilibrium, system exists in this condition only for a short time

To achieve inverted state, we employ pumping techniques

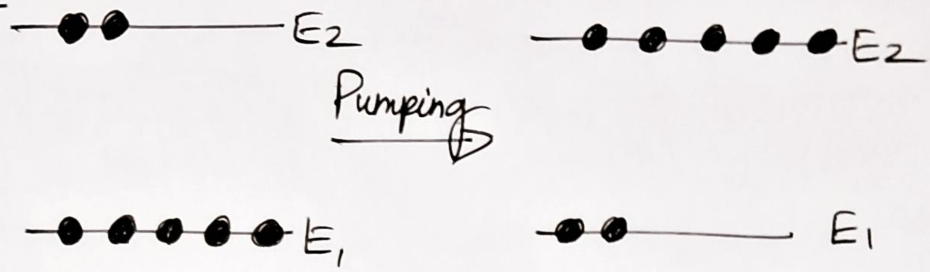


Inverted state does not follow MB distribution as it is a non-equilibrium state.

Problem:
A 10mW He-Ne laser has efficiency of 1%. Assume that all input energy is utilized in pumping the atoms from ground state to the excited state,

which is 20 eV above the ground state. Find how many atoms are promoted to the excited state in one second.

Solution:



normal state or equilibrium state

inverted state or non-equilibrium state

$$\eta = \frac{P_{out}}{P_{in}} \times 100$$

$$P_{out} = 10 mW$$

$$\Rightarrow P_{in} = \frac{P_{out}}{\eta} \times 100$$

$$= \frac{10 mW}{1} \times 100$$

$$= 1 W$$

So 1 Joule per second is ~~given~~ pumped to the He-Ne system.

To pump one electron from ground state to excited state, it requires 20 eV

$$= 20 \cdot 1.6 \cdot 10^{-19} J$$

So in 1sec, number of electrons that are pumped to the excited state is

$$\frac{1 J}{20 \cdot 1.6 \cdot 10^{-19} J} = \frac{10^{19}}{32} \approx 3 \cdot 10^{17}$$

So Rate of ~~stimulated~~ absorption / pumping $= 3 \cdot 10^{17} s^{-1}$

Confinement of radiation within medium (to achieve condition ①)

To achieve lasing action, ~~spo~~ stimulated emission must dominate spontaneous emission.

If the photon density is high, there is a scope for ~~both~~ high rates of both spontaneous and stimulated transitions.

By enclosing laser medium between optically flat parallel mirror, photons can be contained/confined within the medium.

This arrangement is called <u>optical resonant cavity</u> or <u>optical resonator</u>.