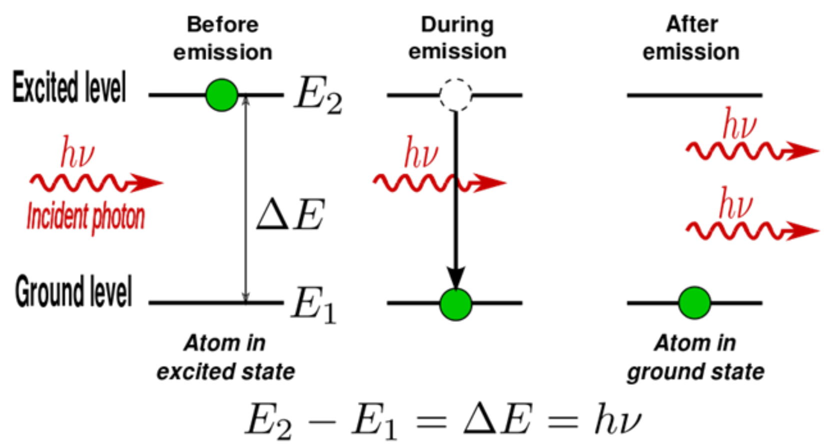
# PHY 110 Engineering Physics

Lecture 2

UNIT 2 – laser

# Lasers and applications:

- Fundamentals of laser- energy levels in atoms
- Radiation matter interaction
- Absorption of light
- Spontaneous emission of light
- Stimulated emission of light
- **Population of energy levels**
- **Einstein A and B coefficients**
- **Metastable state**
- **Population inversion,**
- **Resonant cavity**
- Excitation mechanisms
- Nd – YAG
- He-Ne Laser
- Semiconductor Laser
- lasing action
- Properties of laser
- Applications of laser: holography



# Revision Lecture 1



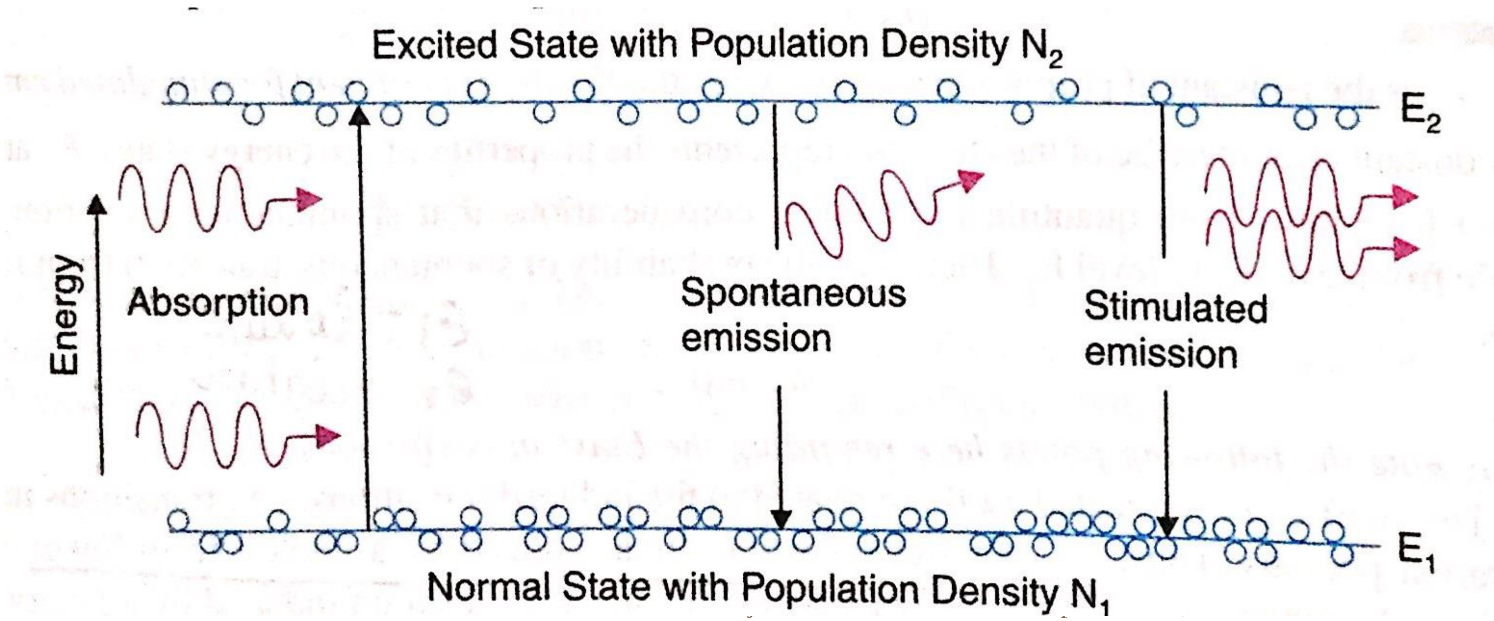
When photons of energy (hν) travel through a material three different processes occur

1. **Absorption,**
2. **Spontaneous emission**
3. ***Stimulated emission***

$$R_{abs} = P_{12}N_1 = B_{12}\,\rho(\nu)N_1$$

$$R_{sp} = P_{21}N_2 = A_{21}N_2$$

$$R_{st} = (P_{21})_{st}N_2 = B_{21}\,\rho(\nu)N_2$$



**LASER** is the acronym of

a) Light amplification and stimulated emission of radiation
b) Light amplification by stimulated emission of radiation
c) Light absorption by stimulated emission of radiation
d) Light absorption by spontaneous emission of radiation

**Ans: B**

Spontaneous emission of radiation is

a) Unpredictable
b) Independent
c) Uncontrollable
d) Incoherent
e) All of the above

**Ans: E**

Which scientist first came up with the idea of stimulated emission ?

a) Alexander Graham Bell
b) Isaac Newton
c) Arthur Schalow
d) Albert Einstein

**Ans: D**

Principle of laser is

(a) Induced absorption
(b) Stimulated emission
(c) Spontaneous emission
(d) All of the above

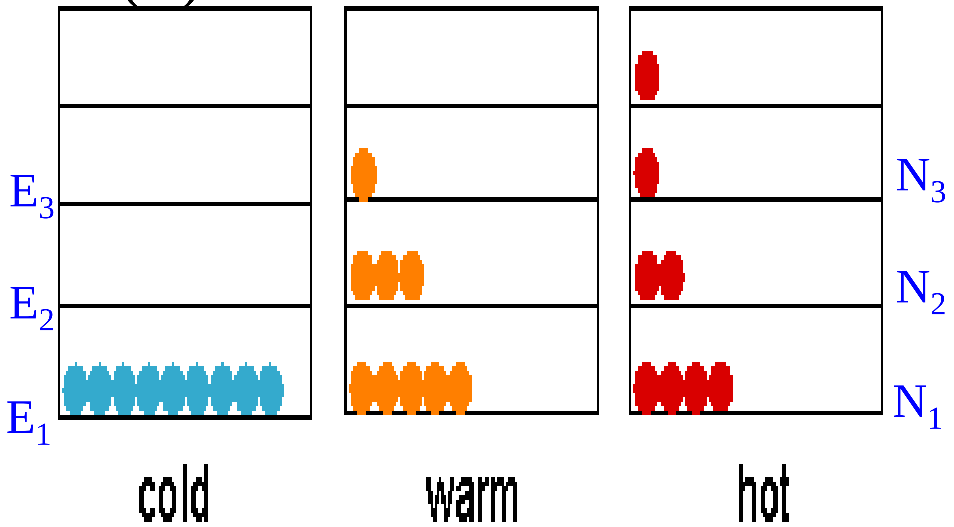
**Ans: D**

# POPULATION OF ENERGY LEVELS



**Populations of energy levels** is nothing but the total number of atoms occupying the particular Energy level (E).

$$\frac{N_1}{N_2} = \frac{e^{-E_1/kT}}{e^{-E_2/kT}} = e^{(E_2-E_1)/kT}$$




the *Boltzmann distribution* tells us that how the ratio of populations varies exponentially with the energy difference, and the greater the level difference the smaller the population in the $E_2$ level.

# EINSTEIN RELATIONS



Under steady state condition, Rate of absorption transitions and rate of emissions (induced as well as spontaneous) will balance each other

$$R_{abs} = R_{sp} + R_{st}$$

$$B_{12}\,\rho(\nu)N_1 = A_{21}\,N_2 + B_{21}\,\rho(\nu)N_2$$

Where, $B_{12}$, $A_{21}$, $B_{21}$ are Einstein's coefficients for induced absorption, spontaneous emission and stimulated /induced emission respectively. $N_1$ and $N_2$ populations of atoms in the ground ( $E_1$) are excited ($E_2$) states, respectively.

# EINSTEIN RELATIONS

Just now we saw $B_{12}\,\rho(\nu)N_1 = A_{21}\,N_2 + B_{21}\,\rho(\nu)N_2$ under thermal equilibrium

Eq.1

Number of atoms absorbing photons per second per volume = Number of atoms emitting photons per second per volume

Re-arranging equation 1 we get,

$$\rho(\nu)[B_{12}\,N_1 - B_{21}N_2] = A_{21}\,N_2$$

So the photon density can be expressed as

$$\rho(\nu) = \frac{A_{21}\,N_2}{[B_{12}\,N_1 - B_{21}N_2]}$$

Eq. 2

# EINSTEIN RELATIONS

Now divide numerator and denominator with $B_{12}N_{2,}$ we get

$$\rho(\nu) = \frac{A_{21}/B_{12}}{\left[\frac{N_1}{N_2} - \frac{B_{21}}{B_{12}}\right]} \quad \text{-------------------------->} \quad \text{Eq. 3}$$

But Boltzmann's law, the distribution of atoms among the energy levels $E_1$ and $E_2$ at thermal equilibrium at Temperature T is

$$\frac{N_1}{N_2} = \frac{e^{-E_1/kT}}{e^{-E_2/kT}} = e^{(E_2-E_1)/kT} \qquad \text{And} \qquad E_2 - E_1 = h\nu$$

k Boltzmann's constant, h Planck's const and ν frequency of photon

Eqn.3 becomes

$$\rho(\nu) = \frac{A_{21}}{B_{12}} \frac{1}{[e^{h\nu/kT} - B_{21}/B_{12}]} \quad \text{-------------------------->} \quad \text{Eq. 4}$$

$$\rho(\nu) = \frac{A_{21}}{B_{12}} \frac{1}{[e^{h\nu/kT} - B_{21}/B_{12}]} \text{ --------------------------> Eq. 4}$$

But according to Planck's law, the energy density of radiation $\rho(\nu)$, is given by the formula

$$\rho(\nu) = \left[\frac{8\pi h\nu^3}{c^3}\right]\left[\frac{1}{[e^{h\nu/kT} - 1]}\right] \text{ --------------------------> Eq. 5}$$

Wher μ is the refractive index of the medium and c is the velocity of light in free space. Photon energy density given by Eq.4 must be consistent with and Eq.5, then we get two relations for 3 Einstein's coefficients

$$\frac{A_{21}}{B_{12}} = \frac{8\pi h\nu^3}{c^3} \text{ --------------------------> Eq. 6}$$

$$\frac{B_{21}}{B_{12}} = 1 \qquad B_{21} = B_{12} \text{ --------------------------> Eq7}$$

**In normal conditions, absorption is more probable, and hence spontaneous emission dominate the stimulated emission.. Why?**

a) More atoms are in the ground state compared to excited state.
b) Less atoms are in the excited state compared to ground state.
c) All of the above.
d) None of the above.

# LASER



So to realize LASER we need light amplification and for that stimulated emission is essential

*But Under normal conditions*

1. Induced absorption dominate stimulated emission for a given photon density. $N_1 >> N_2$
2. Spontaneous emission dominate stimulated emission for lower life time at the excited level. $\tau < 10^{-7}$s

**How to get rid of these two issues to succeed in stimulated emission and hence light amplification? To understand we use two parameters $R_1$ and $R_2$, $R_{st}/R_{sp}$ and $R_{st}/R_{abs}$, respectively.**

# Stimulated emission/spontaneous emission ($R_1=R_{st}/R_{sp}$)?



To get an idea about it let us find the typical value of **$R_{st}/R_{sp}$**

From our last lecture we know, rate of stimulated transition ($R_{st}$) and rate of spontaneous transitions ($R_{sp}$)are

$$R_{st} = B_{21}\,\rho(\nu)N_2 \qquad\qquad R_{sp} = A_{21}N_2$$

Now take the ratio of $R_{st}$ to $R_{sp}$

$$R_1 = \frac{R_{st}}{R_{sp}} = \frac{B_{21}\,\rho(\nu)N_2}{A_{21}N_2} = \frac{B_{21}}{A_{21}}\rho(\nu) \quad \text{-------------------------------->} \quad \textbf{Eq. 9}$$

$$\rho(\nu) = \left[\frac{8\pi h\nu^3}{c^3}\right]\left[\frac{1}{[e^{h\nu/kT} - 1]}\right]$$

# Stimulated emission/ spontaneous emission ($R_1=R_{st}/R_{sp}$)?



Now Eq.9 changes to

$$R_1 = \frac{B_{21}}{A_{21}}\left[\frac{8\pi h\nu^3}{c^3}\right]\left[\frac{1}{[e^{h\nu/kT}-1]}\right] \text{ -----------------------------> } \textbf{Eq. 10}$$

But $\dfrac{B_{21}}{A_{21}} = \dfrac{c^3}{8\pi h\nu^3}$ then Eq.10 *becomes*

$$R_1 = \left[\frac{1}{[e^{h\nu/kT}-1]}\right] \text{ -----------------------------> } \textbf{Eq. 11}$$

In the optical region, say $5\text{x}10^{14}$ Hz (600 nm) and at room temperature T=300 K, the value of $R_1$ can be found to be $10^{-58}$. Stimulated emission is negligible compared to spontaneous emission.

# How to increase $R_1=R_{st}/R_{sp}$ to realize LASER?



We have $R_1 = \frac{B_{21}}{A_{21}}\rho(\nu)$; so when the photon density ($\rho$) and ratio of Einstein coefficient ($B_{21}/A_{21}$) are large, stimulated emission will dominate

1. But as the radiation density ($\rho$) increase absorption also increases, due to $B_{21}=B_{12}$. Hence large photon density of course help for more stimulated emissions…. ***Optical cavity?***
2. If the excited state has more life time ($1/A_{21}$ represents the lifetime of the excited state), $R_1$ increases many fold and stimulated emission increases substantially…. ***Metastable state***?

So an increase in the photon density ($\rho$) and the life time of atoms in the excited state, along with the dominance over **absorption transition** may work out for increasing the stimulated transition.

# How to increase $R_2=R_{st}/R_{abs}$ to realize LASER?



$$R_2 = \frac{R_{st}}{R_{abs}} = \frac{B_{21}\,\rho(\nu)N_2}{B_{12}\,\rho(\nu)N_1}$$

$R_{21}=R_{12}$

$$R_2 = \frac{N_2}{N_1} \quad \text{-----------------------------}\rightarrow \quad \textbf{Eq. 12}$$

i.e. stimulated transition overcome absorption transition if $N_2 >> N_1$.

**3**. Unfortunately, under normal condition population in the excited level ($N_2$) is very much lower than that in the ground state($N_1$). We have to invert this situation…. ***Population inversion?***

So we need three different requirements for getting dominant stimulated transition and LASER action

- **(i) Large photon density (ρ) –Optical resonant cavity**
- **(ii) Large life time of atoms in the excited state- Metastable state**
- **(iii) Large number of excited atoms - population inversion**

How to attain these three requirements? we will see next….

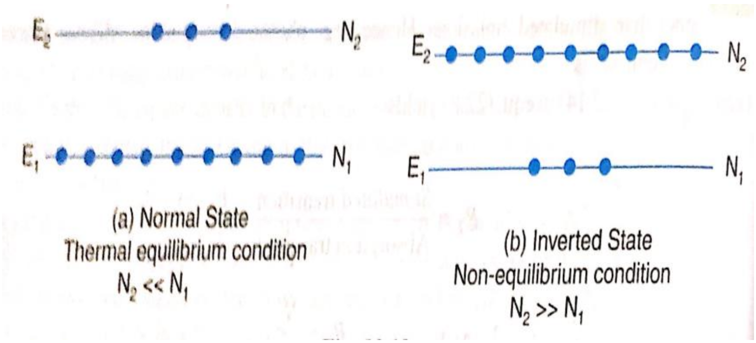
Meeting the requirements?



## 1. POPULATION INVERSION by Pumping

When the material is at thermal equilibrium, population ratio between $E_1$ and $E_2$ is given by the Boltzmann's law

$$\frac{N_2}{N_1} = e^{-(E_2-E_1)/kT}$$

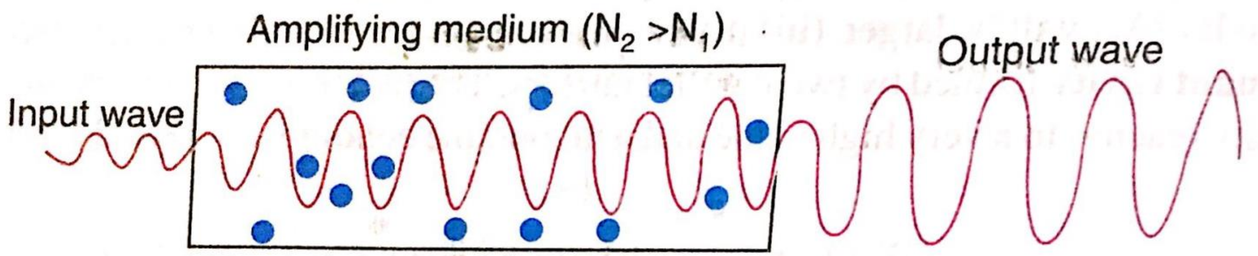



So one has to supply energy from outside to attain $N_2 >> N_1$ and hence population inversion occurs…. *There are different* ***excitation mechanisms*** *which we will see later*

## 1. POPULATION INVERSION by Pumping



In the inverted case, stimulated transition is triggered and photon multiplication occurs and hence light amplification happens




Amplification of a light wave in a medium with population inversion.

However, due to continued stimulated emission, population of $E_2$ reduces and this action comes to an end. To sustain one has to continuously excite atoms from $E_1$ to $E_2$ and this process is called **pumping**– like you pump water to your tank for continuous usage of water☺

Meeting the requirements?

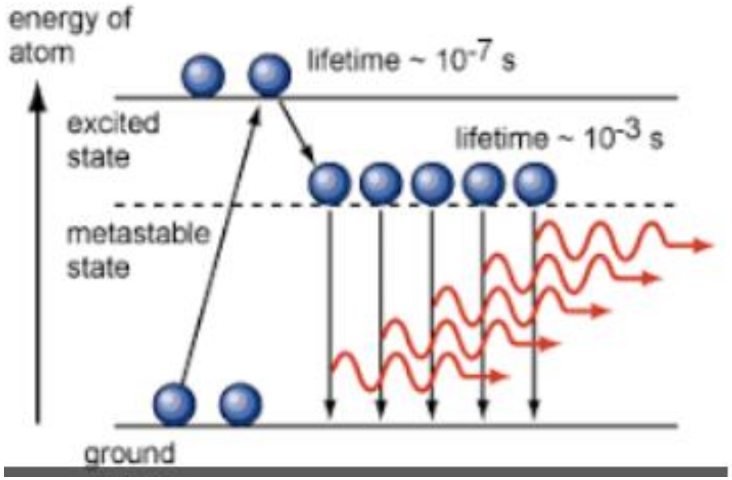


## 2. METASTABLE STATE to increase life time

After achieving population inversion, one has to suppress spontaneous emission that generally happens in nano seconds time

To increase the population at the excited state, life time at that state should be increased $10^{-6}$ to $10^{-3}$ s..

This is achieved by allowing the excited atoms at the pumping level to loose fraction of the energy and jump to another level where they stay longer time.. This third state is called **Metastable state**



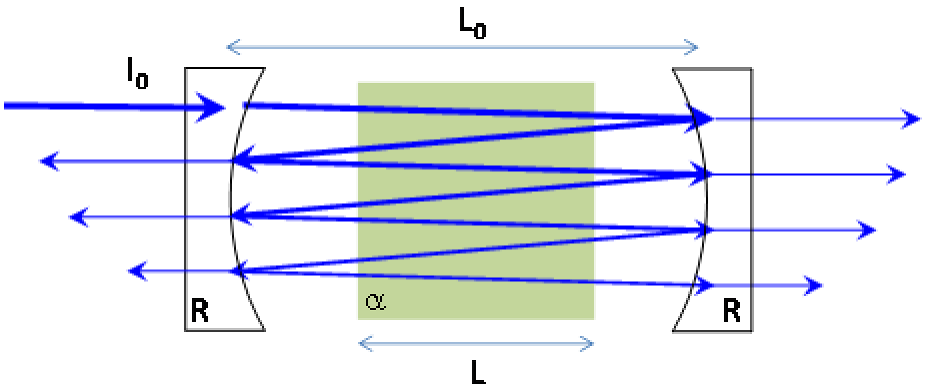

This is possible in material by doping

Meeting the requirements?



**3. Large photon density (ρ) –Optical resonant cavity**

To make stimulated emission to overtake spontaneous emission

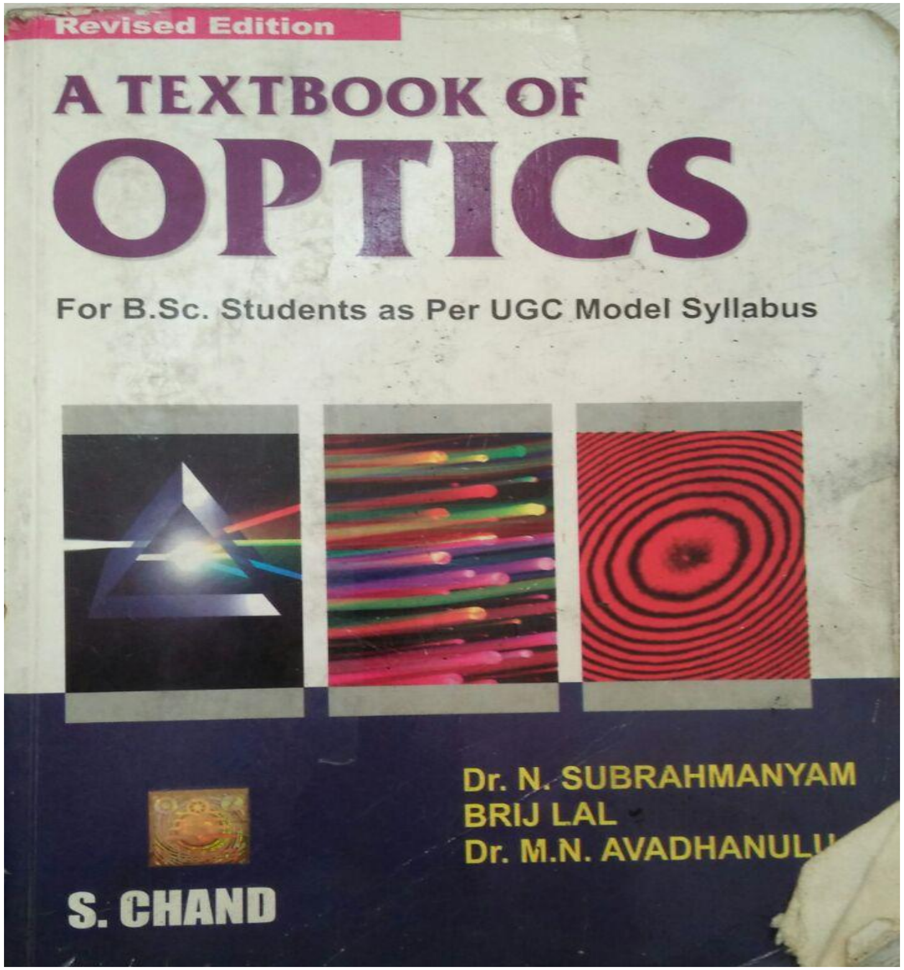



That can be achieved

- By placing laser medium (material) between two mirrors
- Photon density build up due to repeated reflections
- Contained in the cavity to increase interaction- confinement

Life time of atoms in the metastable state is

a) $< 10^{-8}$ s
b) between $10^{-6}$ - $10^{-3}$ s
c) $\sim 10^{6}$ s
d) $\sim 10$ s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