Laser

Syllabus: *Absorption of radiation, Spontaneous and stimulated emission of radiation, Einstein's coefficients, Population inversion, various levels of laser, Ruby laser, He-Ne Laser, Laser applications.*

Laser stands for 'Light Amplification by Stimulated Emission of Radiation'. It is a process by means of which we get a strong, intense, monochromatic, collimated, unidirectional and highly coherent beam of light.

Absorption and Emission of Radiation:

An atom has different discrete energy levels. It may undergo a transition between two energy states E_1 and E_2 if it emits or absorbs a photon of the appropriate energy given by the relation $E_1 - E_2 = \pm h\nu$, where the plus sign indicates absorption of quanta of energy and the minus sign that of emission. Consider an assembly of large number of free atoms some of which are in the ground state with energy E_1 and some in the excited state with energy state E_2. If photons of energy $h\nu = E_2 - E_1$ are incident on the sample, basically three transition process can take place: Absorption of radiation, spontaneous emission and stimulated emission of radiation.

Stimulated or Induced Absorption:

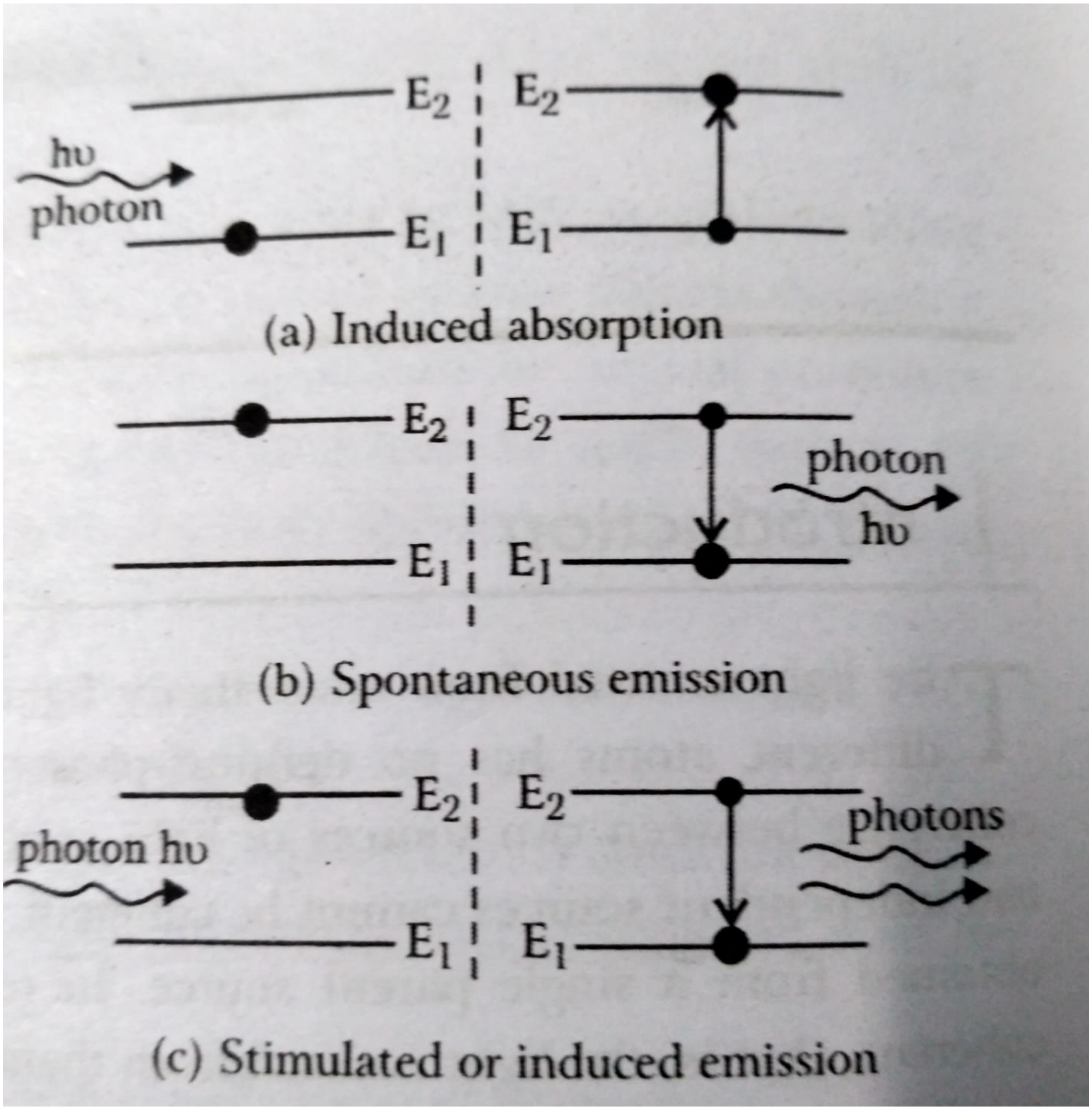
If an atom is initially in a lower energy state E_1, it can rise to a higher energy state E_2 by absorbing a quantum of radiation (Photon). The frequency of corresponding photon is given by

$$\nu = \frac{E_2 - E_1}{h}$$

This process is known as stimulated absorption or induced absorption. The probable rate of occurrence of the absorption transition from stage 1 to stage 2 depends on the properties of states 1 and 2 and is proportional to the energy density $u(\nu)$ of the radiation of frequency v. Thus

$$P_{12} = B_{12} u(\nu)$$

Where B_{12} is proportionality constant and is known as Einstein's coefficient of stimulated or induced absorption.



Spontaneous Emission:

Consider an atom initially in the higher (excited) energy state 2. Excited state with higher energy is inherently unstable (average life time 10^{-8} sec), hence atom in excited state does not stay for longer time and it jumps to the lower energy state 1 emitting a photon of frequency *v*. This is spontaneous emission of radiation. If there is an assembly of atoms, the radiation emitted spontaneously by each atom has a random direction and a random phase and is therefore incoherent from one atom to another.

The probability of spontaneous emission from energy state 2 to energy state 1 is determined only by the properties of states 2 and 1. This is denoted by

$$A_{21}$$

This is known as Einstein's coefficient of spontaneous emission of radiation. In this case the probability of spontaneous emission is independent of energy density $u(v)$.

Stimulated or Induced Emission:

According to Einstein, an atom in an excited energy state E_2 may, under the influence of the electromagnetic field of a photon of frequency v [= $(E_2-E_1) / h$] incident upon it, jump to a lower energy state E_1, emitting an additional photon of same frequency v. Hence two photons, one original and the other emitted, move together. This is stimulate (or Induced) emission of radiation. The direction of propagation, phase, energy and state of polarization of the emitted photon is exactly same as that of the incident stimulated photon, so the result is an enhanced beam of coherent light.

The probability of stimulated emission transition from energy state 2 to energy state 1 is proportional to the energy density $u(v)$ of the stimulating radiation and is given by

$$B_{21}\, u(v)$$

where B_{21} is the Einstein's coefficient of stimulated emission of radiation. The total probability for an atom in state 2 to drop to the lower state 1 is therefore given by

$$P_{21} = A_{21} + B_{21}\, u(v)$$

Difference between the Spontaneous and Stimulated Emission Processes

In the case of spontaneous emission, the atom emits an electromagnetic wave which has no definite phase or directional relation with that emitted by another atom.

In the case of stimulated emission, since the process is forced by the incident electromagnetic wave, the emitted light by the atom is in phase with that of the incident electromagnetic wave. The emitted wave is also in the same direction as that of the incident wave.

<u>Relation between different Einstein's Coefficients:</u>

Let us consider an assembly of atoms in thermal equilibrium at temperature T with radiation of frequency v and energy density $u(v)$. Let N_1 and N_2 be the number of atoms in energy states E_1 and E_2 respectively at any instant. The number of atoms in state 1 that absorb a photon and rise to state 2 per unit time is

$$N_1 P_{12} = N_1 B_{12} u(v)$$

The number of atoms in state 2 that drop to state 1, either spontaneously or under stimulated emission, emitting a photon per unit time is

$$N_2 P_{21} = N_2 [A_{21} + B_{21} u(v)]$$

For equilibrium, the absorption and emission must occur equally. Thus

$$N_1 P_{12} = N_2 P_{21}$$

or, $$N_1 B_{12} u(v) = N_2 [A_{21} + B_{21} u(v)]$$

$$(N_1 B_{12} - N_2 B_{21}) u(v) = N_2 A_{21}$$

$$u(v) = \frac{N_2 A_{21}}{N_1 B_{12} - N_2 B_{21}}$$

or, $$u(v) = \frac{A_{21}}{B_{21}} \cdot \frac{1}{\frac{N_1}{N_2}\left(\frac{B_{12}}{B_{21}}\right) - 1}$$

Einstein proved thermodynamically that the probability of stimulated absorption is equal to the probability of stimulated emission

i.e. $$B_{12} = B_{21}$$

Then, we have $$u(v) = \frac{A_{21}}{B_{21}} \frac{1}{\frac{N_1}{N_2} - 1}$$

The equilibrium distribution of atoms among different energy states is given by using Boltzmann's Distribution law according to which

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

or,

$$\frac{N_2}{N_1} = e^{-\frac{(E_2 - E_1)}{k\,T}}$$

or, $$\frac{N_2}{N_1} = e^{-\frac{(hv)}{k\,T}}$$ here, h is Planck's constant and h*v* = (E_2 - E_1)

Consequently, $$u(v) = \frac{A_{21}}{B_{21}} \frac{1}{e^{\frac{hv}{k\,T}} - 1}$$

This is the energy density of photon of frequency *v* in equilibrium with atoms in energy states 1 and 2, at temperature T. Comparing it with the Planck's radiation formula (according to which the energy density of the black body radiation of frequency *v* at temperature T is given as)

$$u(v) = \frac{8\,\pi\,h\,v^3}{c^3} \frac{1}{e^{\frac{h\,v}{k\,T}} - 1}$$

we get $$\frac{A_{21}}{B_{21}} = \frac{8\,\pi\,h\,v^3}{c^3}$$

This shows that the ratio of Einstein's coefficient of spontaneous emission to the Einstein's coefficient of stimulated absorption or emission (as B_{12} = B_{21}) of radiation is proportional to cube of the frequency (v^3). This means that the probability of spontaneous emission increases rapidly with the energy difference between two states.