Module 5 : MODERN PHYSICS

Lecture 28 : Principle of Laser

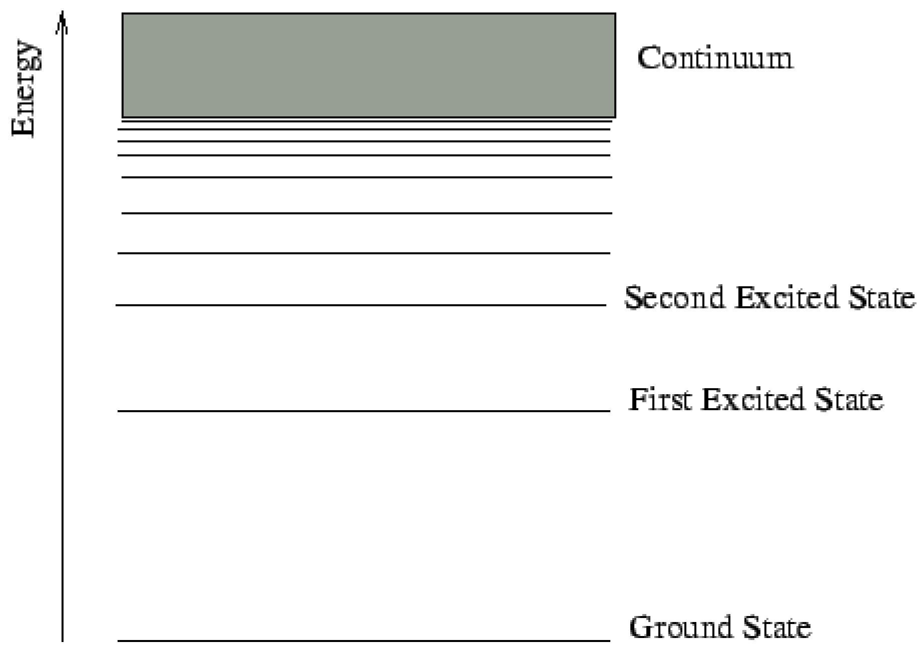
Objectives

In this course you will learn the following

- Principle of Laser - population inversion.
- Einstein relation for spontaneous and stimulated emission.
- Microwave amplification by stuimulated emission.
- Different types of lasers and their applications.

Principle of Laser

We have learnt that the energy levels in an atom are discrete. The lowest possible energy level is known as the **ground state** and higher energy levels are called the excited states. As the energy of the excited states increase, the separation between the adjacent energy levels become smaller and smaller until the separation becomes so small that the energy levels appear continuous. Such continuous spread of energy is called the **continuum**.



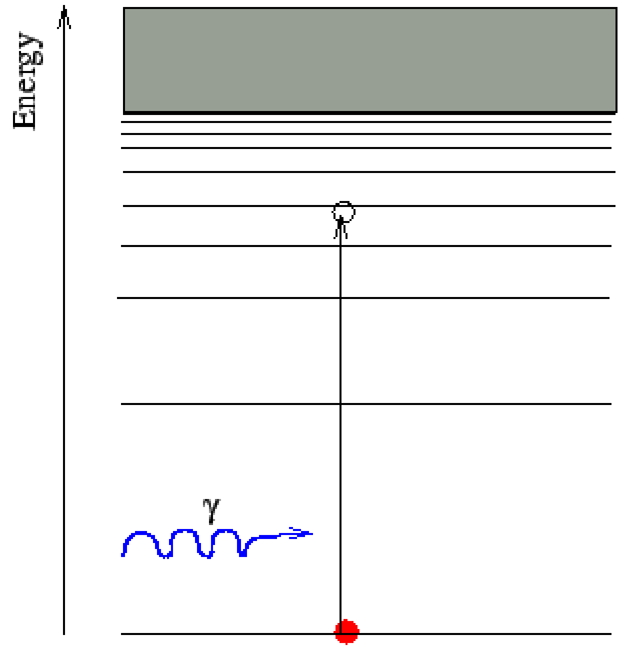
There are three ways in which an incident radiation can interact with the energy levels of atoms.

Absorption :

An electron in one of the lower level (ground state or a lower lying excited state) with an energy E_i can make a transition to a higher level having an energy E_f by absorbing an incident photon. Absorption can occur only when the frequency of the incident radiation ν is given by

$$\nu = \frac{E_f - E_i}{h}$$

If this condition is not satisfied, the matter become transparent to incident radiation.

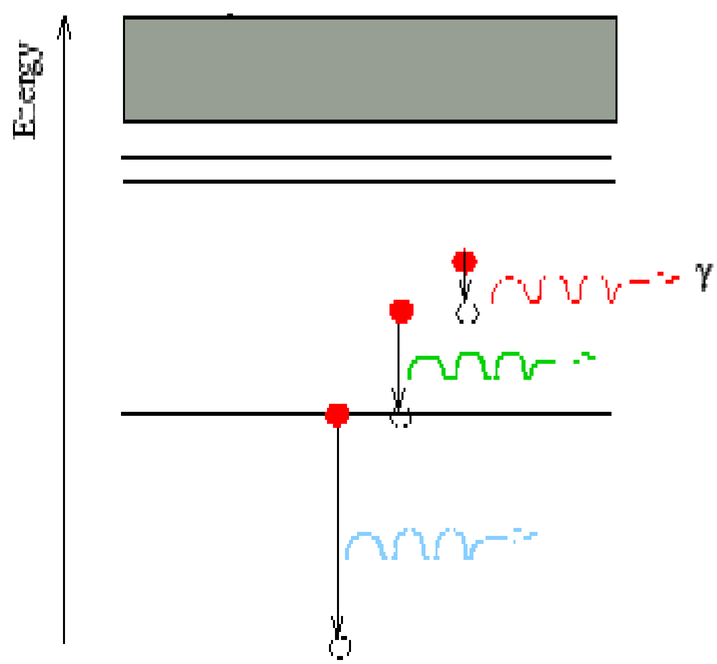


Absorption

Spontaneous Emission :

Atoms which are in excited states are not in thermal equilibrium with their surroundings. Such atoms will eventually return to their ground state by emission of a photon. If E^* is the energy in the excited state and E the energy of a lower lying state (which could be the ground state), the frequency of the emitted photon is given by

$$\nu = \frac{E^* - E}{h}$$



Spontaneous Emission

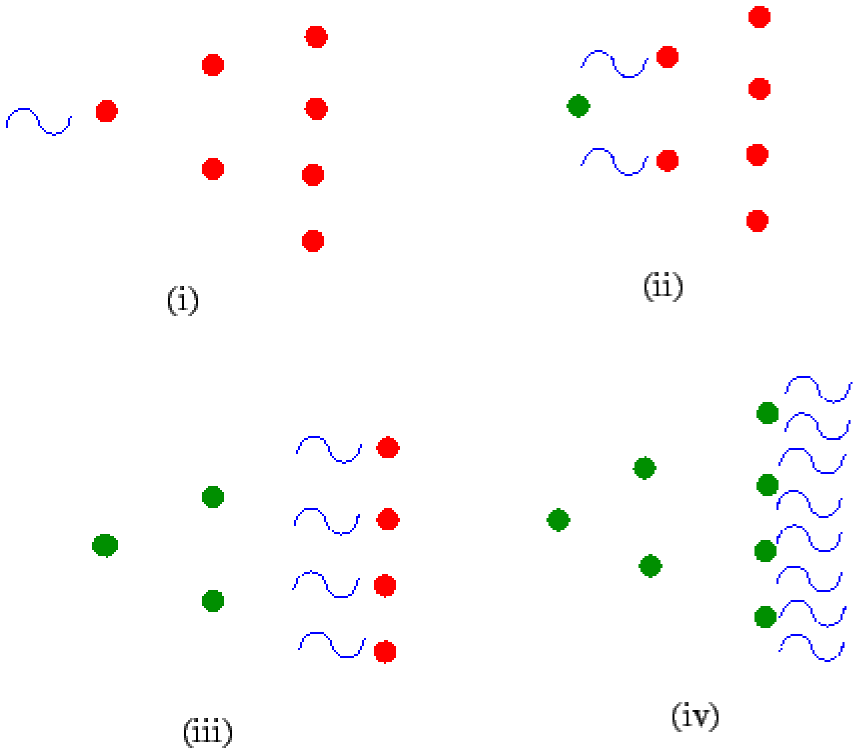
Stimulated Emission :

In 1917, Einstein showed that under certain conditions, emission of light may be stimulated by radiation incident on an excited atom. This happens when an electron is in an excited state E^* and a photon whose energy is equal to the difference between E^* and the energy E of a lower lying level (could be the ground state) is incident on the atom. The incident photon induces the electron in the excited state to make a transition to the lower level by emission of a photon. The emitted photon travels in the same direction as the incident photon. Significantly, the new photon has the same energy as that of the incident photon and is **perfectly in phase** with it. When two waves travel in the same direction with a constant phase relationship, they are said to be **coherent** .

LASER - Light Amplification by Stimulated Emission of Radiation :

In 1958, Charles H. Townes and Arthur L. Schawlow showed that the effect of stimulated emission can be amplified to produce a practical source of light, which is coherent and can travel long distances without appreciable spread of the beam width. Such a light source is called LASER, an acronym for *Light Amplification by Stimulated Emission of Radiation.*

The principle behind such amplification is simple. Suppose we start with one photon which strikes an atom in an excited state and releases a photon, we would have two photons and an atom in the ground state. These two photons, in turn, may be incident on two more atoms and give rise to four photons, and so on.



In the figure above, the excited state atoms are shown in red while those in the ground states are in green. However, the simple picture above does not work in practice because of the following :

- The time for which an electron remains in an excited state is approximately 10^{-8} seconds. Thus it is difficult to keep atoms in excited states till they are stimulated to radiate a photon. The excited atom is more likely to de-excite **spontaneously** . Photons released through spontaneous processes are emitted in random directions and are not coherent with the incident photon.
- The photons that are incident and those which are generated may be absorbed by atoms in ground states, leading to depletion in the number of photons.

Einstein Relations : A and B Coefficients

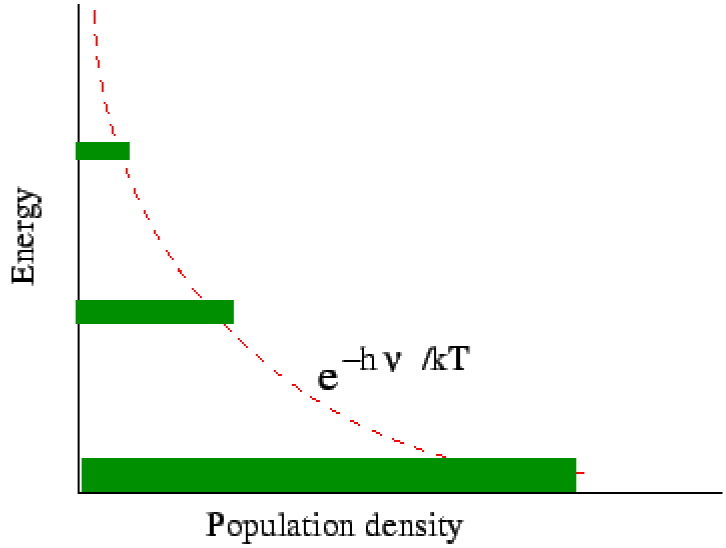
Consider a two level system. Let there be N_1 number of atoms per unit volume in the energy level E_1 and N_2 per unit volume in a higher energy level E_2. Let $E_2 - E_1 = h\nu$. Total population density in the system is

$$N = N_1 + N_2$$

If the atoms are in thermal equilibrium with the surrounding at a temperature T, the relative population in the two levels are given by **Boltzmann distribution**

$$\frac{N_2}{N_1} = e^{-h\nu/kT}$$

This equation shows that as the temperature increases, the population of excited states increase. However, the population of an excited state always lies lower than the population of the ground state, under equilibrium condition.



See the animation

The distribution of atoms in the two energy levels will change by absorption or emission of radiation. Einstein introduced three empirical coefficients to quantify the change of population of the two levels.

- **Absorption -** If B_{12} is the probability (per unit time) of absorption of radiation, the population of the upper level increases. The rate is clearly proportional to the population of atoms in the lower level and to the energy density $u(\nu)$ of radiation in the system. Thus the rate of increase of population of the excited state is given by $B_{12}u(\nu)N_1$.
- **Spontaneous Emission -** If A_{12} is the spontaneous emission probability, the rate of depletion of atoms in the excited state is $A_{12}N_2$. A_{21}^{-1} gives the average $lifetime$ of an atom in the excited level before the atom returns to the ground state.
- **Stimulated Emission -** Stimulated or induced emission depends on the number of atoms in the excited level as well as on the energy density of the incident radiation. If B_{21} be the transition be the transition probability per unit time per unit energy density of radiation, the rate of decrease of the population of the excited state is $B_{21}u(\nu)N_2$.

The rate equation for the population of the upper level is

$$\frac{dN_2}{dt} = B_{12}u(\nu)N_1 - [A_{21} + B_{21}u(\nu)]N_2$$

When equilibrium is reached, the population of the levels remain constant, so that $dN_2/dt = 0$ and the rate of emission equals rate of absorption, so that

$$B_{12}u(\nu)N_1 = [A_{21} + B_{21}u(\nu)]N_2$$

Using the Boltzmann facor $N_2/N_1 = \exp(-h\nu/kT)$, and simplifying, we get

$$u(\nu) = \frac{A_{21}}{B_{12}e^{h\nu/kT} - B_{21}} = \frac{A_{21}/B_{12}}{e^{h\nu/kT} - B_{21}/B_{12}}$$

If we regard the matter to be a blackbody and compare the above expression for the energy density with the corresponding energy density expression derived for the blackbody radiation, viz.,

$$u(\nu) = \frac{8\pi h\nu^3}{c^3}\frac{1}{e^{h\nu/kT} - 1}$$

we get

$$\frac{A_{21}}{B_{12}} = \frac{8\pi h\nu^3}{c^3}$$

and

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

The last equation shows that the probability of stimulated emission is equal to that of absorption. In view of this we replace the two coefficients by a single coefficient B and term them as B- coefficient. The spontaneous emission coefficient will be called the A- coefficient. The ratio of spontaneous emission probability to the stimulated emission probability is

$$\frac{A}{Bu(\nu)} = e^{h\nu/kT} - 1$$

so that for low temperatures, when $h\nu/kT \gg 1$, spontaneous emission is much more probable than induced emission and the latter may be neglected. For high enough temperatures, stimulated emission probability can be significant though for optical frequencies, this requires very high temperature. For microwave frequencies the stimulated emission processes may be significant even at room temperatures.

Exercise 1

Find the ratio of the probability of spontaneous emission to stimulated emission at 300 K for (a) microwave photons ($h\nu/kT \gg 1$ Hz.) and (b) optical photons ($\nu = 10^{13}$ Hz).

(Ans. (a) $\nu = 10^{15}$ (b) 0.17.)

Recap

In this course you have learnt the following

- Atoms and ions have sharp energy levels. Electrons occupy these energy levels from bottom upwards.
- The pouplation of energy levels is determined by Boltzmann distribution according to which the population in the lower energy levels is more than that in the upper levels. If for some reason the population in the upper levels become more than that in the lower level (population inversion), the atoms would make transition to the lower levels by emission of radiation.
- Einstein equations (called A and B coefficients) establish connection between spontaneous and induced emission. Laser is based on the principle that under certain conditions, induced emission may dominate over other processes.
- It is not possible to establish a lase with only two energy levels. Different lasers based on three or four levels are realised in practice.

- The utility of laser lies in the fact that it provides a highly monochromatic and coherent beam with a very high degree of directionality.