Engineering Physics: PHY110

LASER AND APPLICATIONS: UNIT-2

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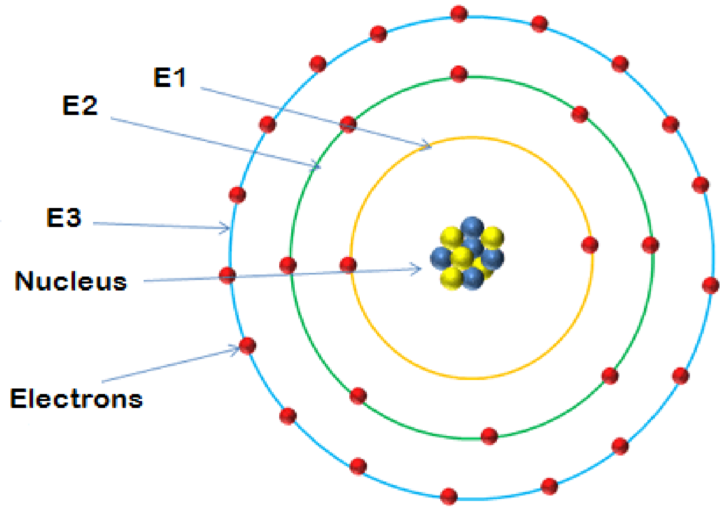
What is Light?

- Light is a kind of energy released by an atom. Light is made up of very small particles called photons having energy hv.
- Einstein believed that light is a particle or photon and the flow of photons is a wave. Light is obtained from various sources like candles, lamps and sun-rays.
- Candles and lamps are called as the man made light sources and sun-rays is called natural light source.
- The first reliable artificial light source (incandescent light bulb) was invented in 1879 by Thomas Edison.



What is LASER ?

- LASER stands for Light Amplification by Stimulated Emission of Radiation. Laser is a device that amplifies or increases the intensity of light and produces highly directional light.

- Laser light is different from the conventional light. Laser light has extra-ordinary properties which are not present in the ordinary light sources like sun and incandescent lamp.

- In 1917, Einstein gave the theoretical basis for the development of laser, when he predicted the possibility of stimulated emission.

- In 1954, using Einstein's idea, C.H. Townes and his co-workers invented a device called MASER (Microwave Amplification by Stimulated Emission of Radiation).

- In 1960, Theodore Harold Maiman built the first laser device.

Characteristics of Laser:

Laser light has four unique characteristics that differentiate it from ordinary light: These are

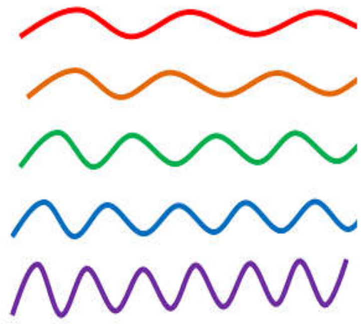
- Coherence
- Directionality
- Monochromatic
- High intensity

Coherence:

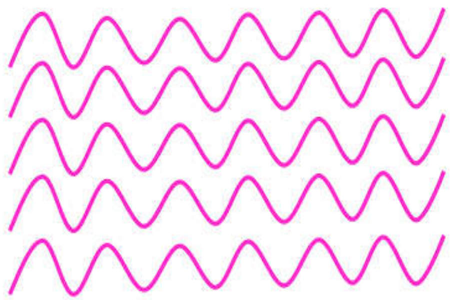
- In Laser, the wave of the laser light are in phase in space & time.
- Light generated by laser is highly coherent.
- Because of this coherence, a large amount of power can be concentrated in a narrow space.
- TWO types:

  ✓Spatial/ Transverse Coherence

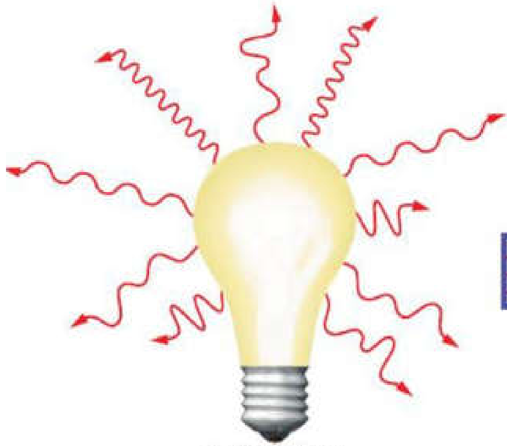
  ✓Temporal/ Longitudinal Coherence



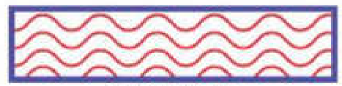
Incoherent light



Coherent light waves



Incoherent light

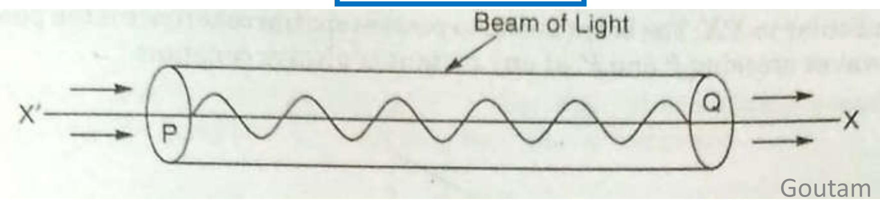


Coherent light

Types of Coherence:

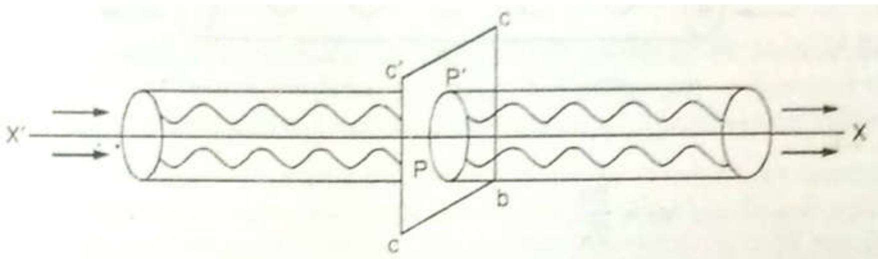
Temporal or Time coherence:

- A laser beam is said to possess temporal coherence, if the phase difference of waves crossing the two points lying along the direction of propagation of the beam is always constant at any instant of time.
- This coherence is also known as longitudinal coherence. It measures monochromaticity of waves.
- The time for which the phase difference remains constant is called Coherence Time (T_0) and the distance travelled by the light during this time is called Coherence Length (L_c). Then $\boxed{L_c = c.T_0}$
- Natural line width, $\boxed{\Delta\lambda = \lambda^2 / L_c}$



Spatial Coherence:

- A laser beam is said to possess spatial coherence, if the phase difference of the waves crossing the two points lying on a plane perpendicular to the direction of propagation of the beam is always constant at any instant of time.
- This coherence is also termed as transverse or lateral coherence.
- Spatial coherence measures directionality of waves.



Natural Line width

- Band width, $\Delta\omega = \frac{2\pi}{T_0}$

- If velocity of light is 'C' then coherence length is given by

$L_c = C.T_0$

Since $\Delta\omega = 2\pi\Delta\nu$

where $\Delta\nu$ is the frequency in Hz.

$$\therefore \quad 2\pi\Delta\nu = \frac{2\pi}{T_0}$$

$$\text{or} \quad \Delta\nu = \frac{1}{T_0}$$

$$\Delta\nu = \frac{c}{L_c}$$

Again, $\nu = \frac{c}{\lambda}$

$$\therefore \quad |\Delta\nu| = + \frac{c}{\lambda^2}\,\Delta\lambda$$

$$\frac{c}{L_c} = \frac{c}{\lambda^2}\,\Delta\lambda$$

$$\Delta\lambda = \frac{\lambda^2}{L_c}$$

Natural Line Width

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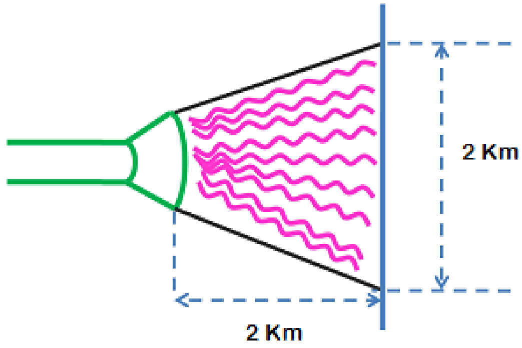
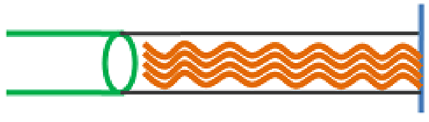
Directionality

- In conventional light sources (lamp, sodium lamp and torchlight), photons will travel in random direction. Therefore, these light sources emit light in all directions.
- On the other hand, in laser, all photons will travel in same direction. Therefore, laser emits light only in one direction. This is called directionality of laser light. The width of a laser beam is extremely narrow. Hence, a laser beam can travel to long distances without spreading.
- If an ordinary light travels a distance of 2 km, it spreads to about 2 km in diameter. On the other hand, if a laser light travels a distance of 2 km, it spreads to a diameter less than 2 cm.

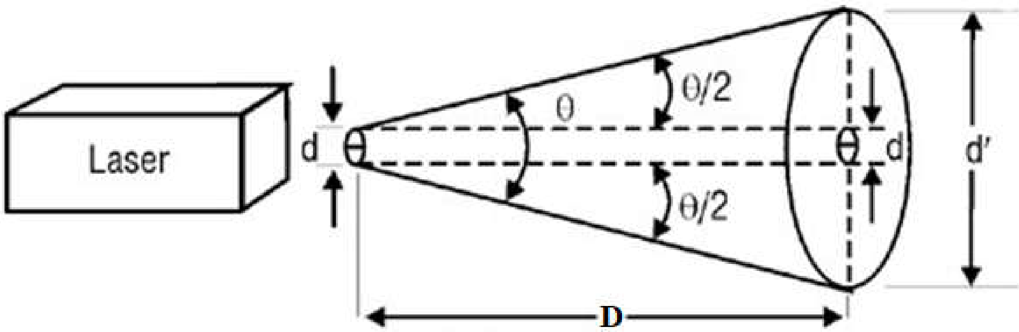


Ordinary light


Laser light

Angular Spread

- $Angular\ Spread = \frac{diameter\ of\ the\ spread\ laser\ beam}{distance\ of\ laser\ from\ screen} = \frac{d'}{D}$



Divergence of a laser beam

$$\boxed{\theta = \frac{1.22\,\lambda}{d}}$$

Angular Spread

Where d = Aperture or diameter of the laser beam
λ = Wavelength of the laser beam

$$\boxed{\text{Thus, Areal Spread} = (D.\,\theta)^2}$$

Monochromatic

- Monochromatic light means a light containing a single colour or wavelength.

- In laser, all the emitted photons have the same energy, frequency, or wavelength. Hence, the light waves of laser have single wavelength or colour.

- Therefore, laser light covers a very narrow range of frequencies or wavelengths.

High Intensity

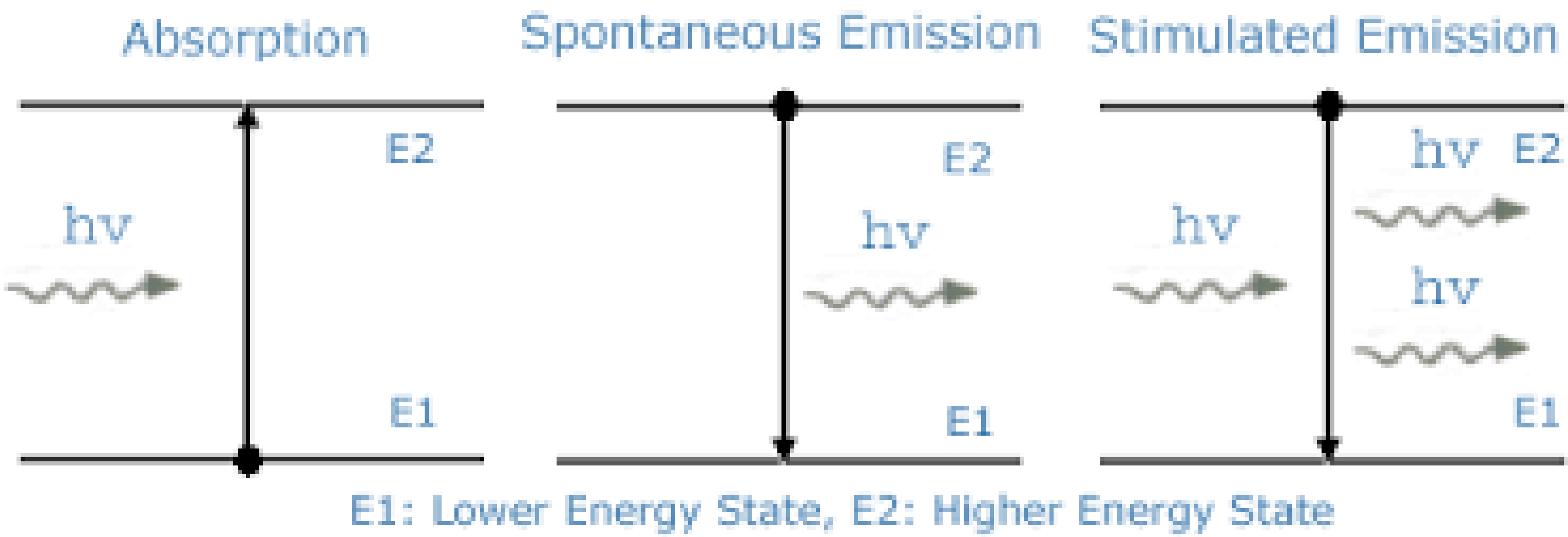
- The intensity of light is the energy per unit time flowing through a unit normal area.

- In laser, the light spreads in small region of space and in a small wavelength range. Hence, laser light has greater intensity when compared to the ordinary light.

- Example, If you look at a 100 Watt lamp filament from a distance of 30 cm, the power entering your eye is less than 1/1000 of a watt. However, in Laser, a 1 Watt laser would appear many thousand times more intense than 100 Watt ordinary lamp.

Interaction of external energy with atomic energy states:

- Different types of radiations:



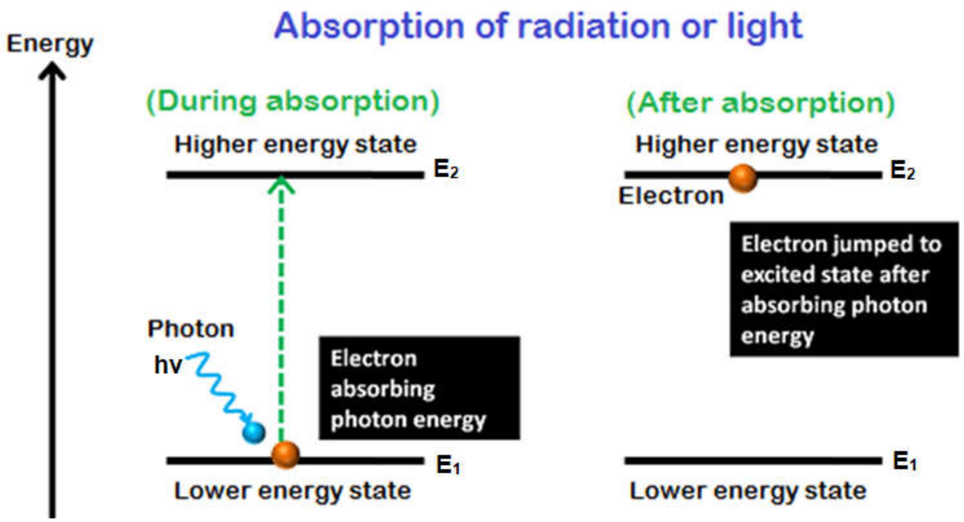
Absorption:

- The process in which an electron in the ground state gets raised to the excited state with the absorption of a photon called as absorption of radiation.
- If an atom is initially in a lower state 1, it can rise to a higher state 2 by absorbing a quantum of radiation (Photon) of frequency v given by

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

Where E1 and E2 are the energies Of the atom in the states 1 and 2 respectively.

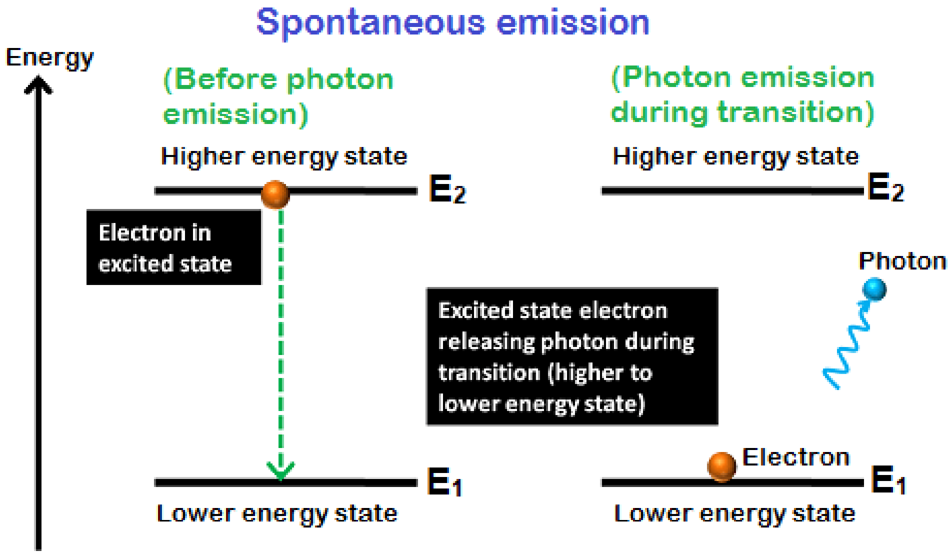
- This process is known as absorption of radiation.



- The probable rate of occurrence of the absorption transition 1→2 depends on the properties of states 1 and 2 and is proportional to the energy density u(v) of the radiation of frequency v incident on the atom.
- Thus, $\boxed{P_{12}=B_{12}u(v)}$ where B_{12} is proportionality constant and is known as Einstein's coefficient of radiation.

Spontaneous Emission:

- The process in which an excited electron transit to the ground or lower state on its own by emitting a photon is called spontaneous emission.
- Consider an atom initially in the higher (excited) state 2. Excited state with higher energy is inherently unstable, 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.



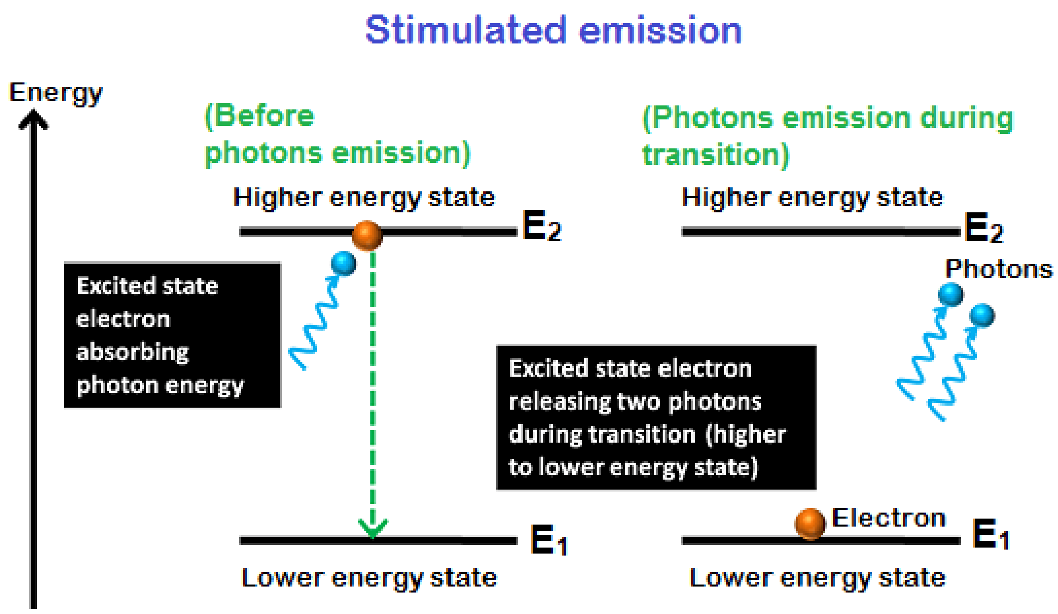
- The probability of spontaneous emission 2→ 1 is determined only by the properties of states 2 and 1. This is denoted by

$$\boxed{P_{21}=A_{21}}$$

Where A_{21} is known as 'Einstein's coefficient of spontaneous emission of radiation'. In this case the probability of spontaneous emissions is independent of it.

Stimulated (Induced)emission:

- The process in which an excited electron transit to the ground or lower state by absorbing a photon with emitting two photons is called stimulated emission.
- According to Einstein, an atom in an excited energy state may, under the influence of the electromagnetic field of a photon of frequency v incident upon it, jumps to a lower energy state, emitting an additional photon of same frequency (v). Hence two photons, one original and the other emitted, move together. This is stimulated (or induced) emission of radiation.
- The direction of propagation, phase, energy and state of polarisation of the emitted photon is exactly same as that of the incident stimulating photon, so the result is an enhanced beam of coherent light.



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

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

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

Relation bet^n Einstein's co-efficient:

- 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 states 1 and 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

$$N_1P_{12} = N_1B_{12}\, u(v)$$

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

$$N_2P_{21} = N_2[A_{21} + B_{21}\, u(v)]$$

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

i.e. $N_1P_{12} = N_2P_{21}$

- Relation bet. Einstein's co-efficient

$$N_1B_{12}\, u(v) = N_2[A_{21} + B_{21}\, u(v)] \Rightarrow\Rightarrow$$

$$u(\nu) = \frac{N_2A_{21}}{N_1B_{12} - N_2B_{21}}$$

$$u(\nu) = \frac{A_{21}}{B_{21}} \frac{1}{\frac{N_1}{N_2}\left(\frac{B_{12}}{B_{21}}\right) - 1}$$

- 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 $$u(\nu) = \frac{A_{21}}{B_{21}} \frac{1}{\left(\frac{N_1}{N_2} - 1\right)}$$

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

$$\frac{N_2}{N_1} = \frac{e^{-\frac{E_2}{KT}}}{e^{-\frac{E_1}{KT}}} \qquad \frac{N_2}{N_1} = e^{-\frac{E_2 - E_1}{KT}} = e^{-\frac{h\upsilon}{KT}}$$

- Consequently, $$u(\nu) = \frac{A_{21}}{B_{21}} \frac{1}{e^{\frac{h\nu}{KT}} - 1}$$

- 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:

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

- We get $$\boxed{\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}}$$

- This shows that the ratio of Einstein's coefficient of spontaneous emission to the Einstein's coefficient of absorption of radiation is proportional to cube of the frequency (v3). This means that the probability of spontaneous emission increases rapidly with the energy difference between two states.