UNIT II LASER (Complete notes)

[Topics mentioned in Syllabus:

Polarization: Basic theory of double refraction, Malus Law, Ordinary and Extra-ordinary ray, Production and Detection of plane, circularly and elliptically polarized light, specific rotation and polarimeters

Laser: Spontaneous and stimulated emission of radiation, Einstein Coefficient's, Principle of laser action, Construction and working of ruby and He-Ne laser, Photovoltaic effect.

Fibre Optics: Introductiom to Fibre Optics, Types of Fibre, Acceptance angle and cone, Numerical Aperture]

Dear students

- *We start this UNIT II with **Laser** for your perusal.*
- *The basics essential to understand and required for derivation have been elaborated so that an understanding of the topic can be developed. In this unit you learn how the laser has been produced.*

Characteristics and applications of a LASER.

*[**LASER** = light amplification by **stimulated emission** of radiation].*

Characteristics:

✓ **Coherent: C**oherent means highly ordered. LASER maintains both the ***temporal*** and ***spatial coherence.*** Both type of coherence is required for ***high quality interference.***

✓ **Monochromatic:** *L*ASER typically comes from one atomic transition with a single precise wavelength. So the laser has a single spectral color and is almost the purest light available.

✓ **Collimated:** Collimated means it does not spread much. It is due to cavity of the laser that it attains a parallel path after reflections.

Applications:

✓ Because of its narrow band width laser can be focused on a very small area of the order of $\mathbf{10^{-6}cm^2}$.

- ✓ A typical laser beam spreads less than 0.01 mm for every meter.
- ✓ An image of intensity 10^5Watt/cm^2 can be obtained by a laser of 10mW power.
- ✓ Used to ***measure long distances***. A fast laser pulse is sent to a corner reflector at the point to be measured and the time of reflection is measured to get the distance.
- ✓ Used in ***scientific study*** of law of interaction of atoms and molecules.
- ✓ Due to its collimated highly intense property, it is used ***in communication*** to send data at higher rates without overlap of pulses.
- ✓ Due to its collimated highly intense property it is used in ***general cutting and welding purposes***. (CO_2 laser carries high power).
- ✓ Due to highly collimated property, in ***medical*** it is used in ***eye or skin surgery, treatment of dental decay***.
- ✓ Used in recording and reproduction of 3D images, as in **HOLOGRAPHY.**
- ✓ Common consumer devices ***Bar code scanners, LASER Printer, scanners, optical disk drives.***

Used for ***fibre optic*** and ***free space communication.***

Spontaneousand Stimulated emission:

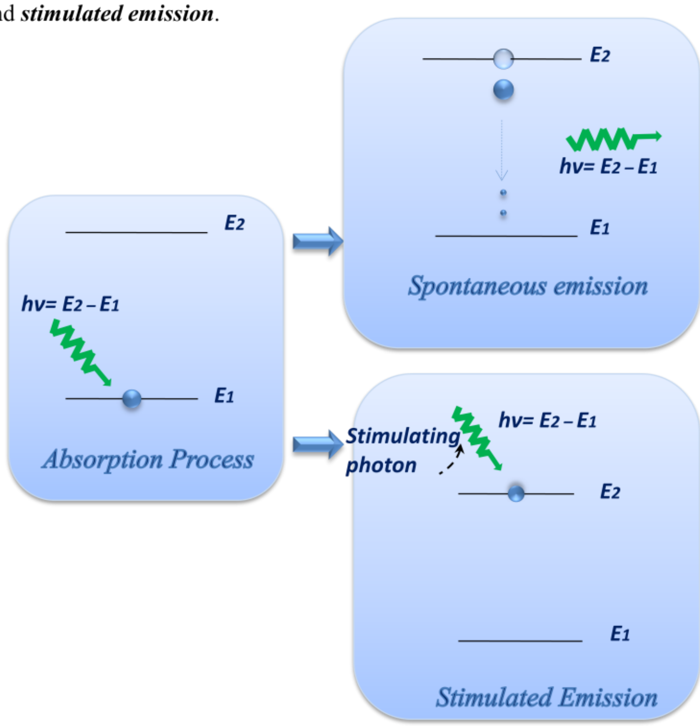
Spontaneous emission: *In the process of absorption, an atom absorbs a photon (hv) whose energy is equivalent to the difference of excited state and lower state ($h\nu = E_2 - E_1$).*

After absorption, an atom gets to its excited state. It can reside in excited state for minimum time of 10^{-8} ***sec*** *or can stay for longer period. If it* ***stays*** *there* ***for minimum time 10^{-8} sec*** *and comes to its lower state by again emitting a photon (radiation) equivalent to the difference of excited state and lower state. Then such type of emission is called* ***Spontaneous emission.***

Stimulated emission: *When a Photon passes by an atom that is in its* ***metastable state*** *(an excited state where an atom can reside for 10^{-3} to longer period) then magnetic field of photon may disturb the magnetic field of excited atom (Figure2). Consequently, excited atom gets to lower state by emitting a photon having energy (radiation) equivalent to the difference of excited state and lower state. This process is called* ***induction or stimulation*** *and photon is called* ***inducing photon****.*

LASER Physics:

Radiation: Radiation (Visible/Non-visible) originates due to the ***transition between two energy levels of a atom or molecule***. It includes **Absorption** of radiation and **then emission process**. Emission process is of two types : ***spontaneous*** and ***stimulated emission***.



There are certain states in atoms or molecules which very short i.e. 10^{-8} second.

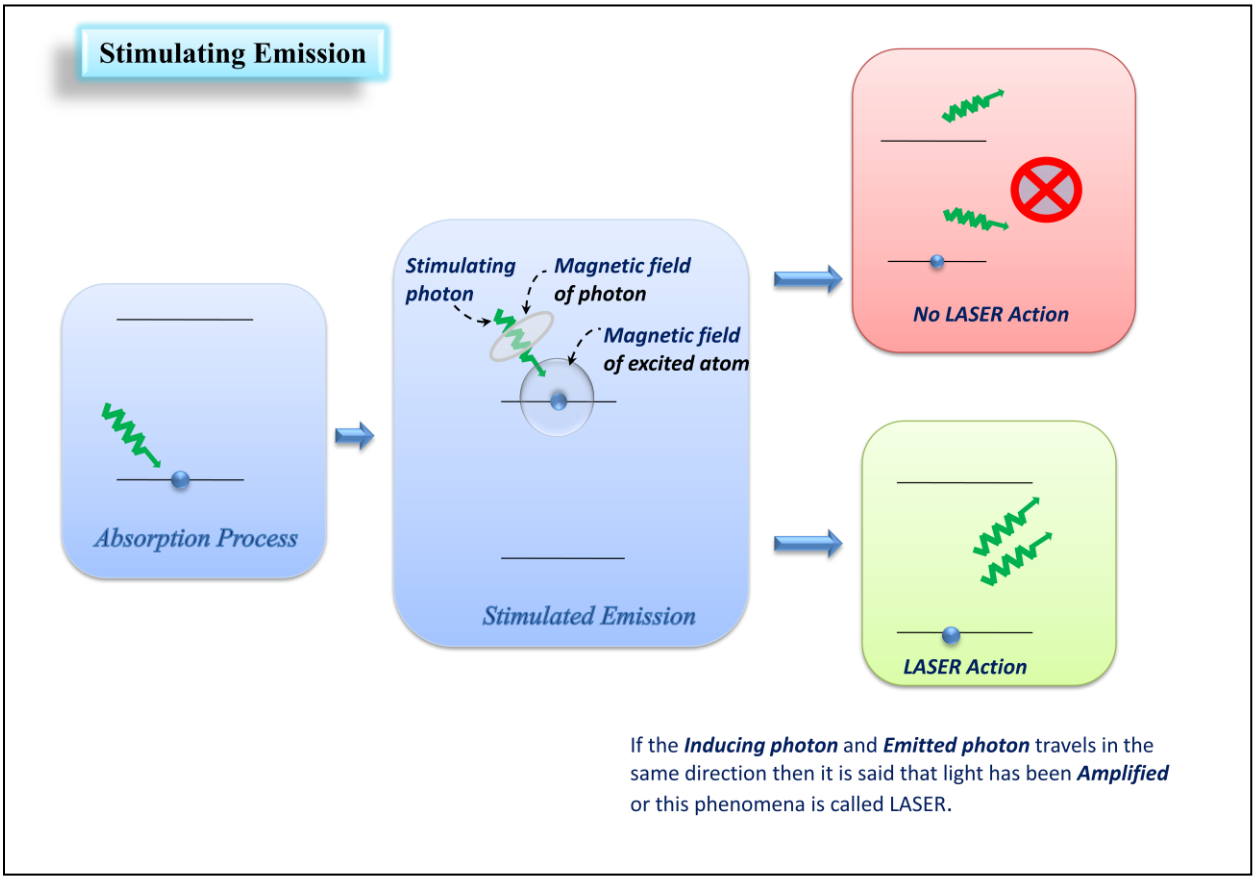
When atom comes to lower state after 10^{-8} second, it emits energy equivalent to the difference of two energy levels($h\nu = E_2 - E_1$). Such emission is called **spontaneous emission.**

There are certain states in atoms or molecules which are of $\sim 10^{-3}$ second. Such states are called **Metastable states**.

Stimulated emission is possible only if

Energy of stimulating photon (***hv***) = Energy of difference of two energy-levels of atom (***E2 – E1***)

*Now, there is certain probability that **inducing photon and emitted photon** may travel in same direction. If they **travel in same direction** then **we say that light has been amplified by stimulation of photon** or called LASER (light amplification by stimulation of radiation).*



Einstein's coefficients:

All the technological innovation of LASER lies **in fundamental physics research, specifically, a 1917 paper by Albert Einstein on the quantum theory of radiation**.

The process of absorbing suitable energy (Photon-EM energy) by an atom is called **Process of Absorption**. Once the atom gets to excited states, it comes to lower stated by emission of same amount of energy, this **process is called Process of Emission**.

Einstein stated that the atom can came to its lower state ***either by spontaneous emission*** (A self-process in which atom completes its **time in Meta stable state (every state has its own characteristic time for an atom; the time more than 10^{-3} sec is called meta stable state)**), **or** by **Stimulated emission** (process in which *atom requires another photon of same energy to induce* it so that it could come to its lower state). Assuming this Einstein laid mathematical derivation which laid the foundation of Practical LASER (1917).

[***In 1917, Albert Einstein established*** the ***theoretical foundations*** for the ***laser and maser*** in the paper 'Zur Quantentheorie der Strahlung' (on quantum theory of radiation) via a derivation of Max planck's law of radiation, conceptually based upon probability coefficients for absorption, spontaneous and stimulated emission. ***1958, Charles Hard Townes and Arthur Leonard Schawlow*** filed ***first patent of 'optical maser***'.

On May 16, 1960, Theodore H. Maiman operated the first functioning Laser at Hughes research laboratories, Malibu, ***California***.]

Derivation:

The ***process of absorption*** is directly proportions to atoms in lower state (N_1) and energy density (u (ν)) of an incident radiation of a particular frequency (ν).

$P_{12}\, \alpha\, u(\nu)$ **(Absorption process** depends upon energy density $(u(\nu)$)of falling radiation**)**

$P_{12} = B_{12}u(\nu)$ B_{12} = Einstein's coefficient of Absorption of radiation

Or $N_1P_{12} = B_{12}N_1u(\nu)$

And the process of **emission** i.e., **spontaneous emission** is auto process therefore it depends upon no. of atoms in excited state (N_2) only, but **stimulated emission** depends upon atoms in excited state (N_2) and energy density (u (ν)) (because for stimulation of excited atoms a inducing agent (a photon having energy equivalent to difference of lower and excited state is required)).

Hence the total probability of atoms coming down in lower state (21; means excited to lower state)

$$P_{21} = P_{21\,(Spontaneous\ emission)} + P_{21\,(Stimulkated\ emission)} \qquad \text{……[1]}$$

The probability of spontaneous emission:

$$P_{21\,(Spontaneous\ emission)} = A_{21}N_2$$

Here A_{21} = Einstein's coefficient of spontaneous emission of radiation

The probability of spontaneous emission:

$$P_{21\,(Stimulkated\ emission)} = B_{21}N_2u(\nu)$$

Here B_{21} = Einstein's coefficient of stimulated emission of radiation

At equilibrium of Absorption and Emission process, the probabilities P_{12} and $P_{21(spon.\ +stiml.)}$ become equal. Hence eq. [1] becomes.

$P_{12} = P_{21}$ **(spontaneous +stimulated)**

substituting values from above we get,

$$B_{12}N_1u(\nu) = A_{21}N_2 + B_{21}N_2u(\nu)$$

$$B_{12}N_1u(\nu) - B_{21}N_2u(\nu) = A_{21}N_2$$

$$(B_{12}N_1 - B_{21}N_2)\boldsymbol{u(\nu)} = A_{21}N_2$$

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

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

According to Boltzmann Distribution Law of atoms in an excited energy state (N_2) is

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

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

$$or\ \frac{N_1}{N_2} = e^{\frac{(h\nu)}{kT}} \dots\dots\dots.(2)$$

Substituting eq. (2) into (1)

$$u(\nu) = \frac{A_{21}}{B_{21}\left(\frac{B_{12}}{B_{21}}e^{\frac{(h\nu)}{kT}} - 1\right)} \dots\dots\dots.(3)$$

According to **Planck's radiation formula** energy density u(ν) is

$$u(\nu) = \frac{8\pi h\nu^3}{c^3}.\frac{1}{\left(e^{\frac{(h\nu)}{kT}} - 1\right)} \dots\dots\dots..(4)$$

Therefore, comparing eq. (3) and (4) we get

$\boldsymbol{B_{12} = B_{21}}$ and

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

$$\boldsymbol{\frac{A_{21}}{B_{21}}\ \alpha\ \nu^3}$$

It means at thermal equilibrium; the probability of spontaneous emission increases rapidly with the energy difference between two states (i.e. ν^3).

Therefore, it is difficult to achieve stimulated process for high energy radiation (like x-rays).

Types of LASER: Solid-State Laser (Ruby laser, Nd-YAG Laser), Gas Lasers (He-Ne Laser, CO_2 laser), Semiconductor Laser (GaAs-GaAsAl), Liquid laser.

Q.4 What are the components of a LASER.

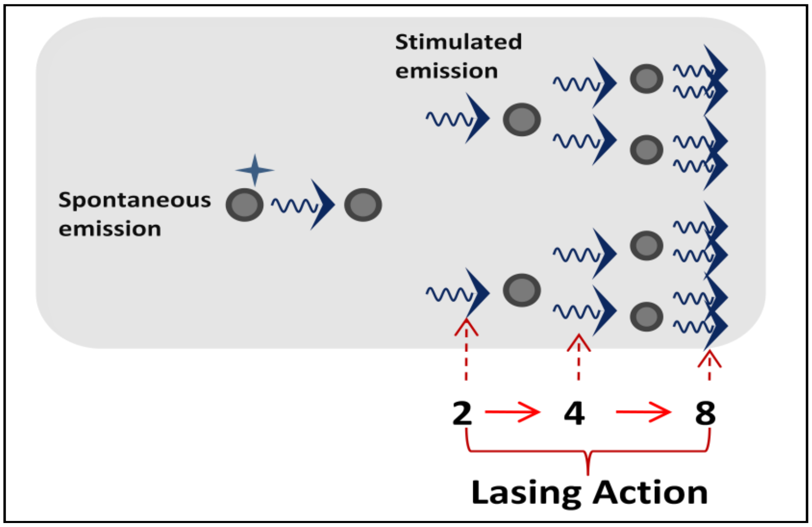
A LASER action cannot occur with three basic arrangements these are called

Components of a LASER:

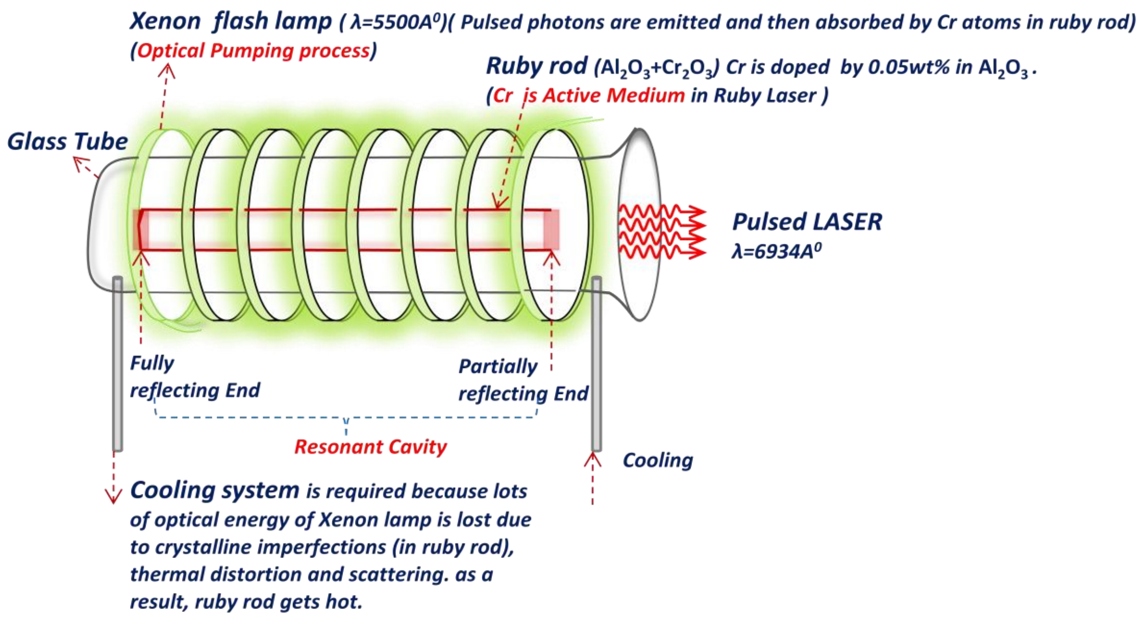
1. **Active Medium:** The medium which is responsible for a LASER action is called **Active medium**.
2. **Pumping:** The method of raising the molecules or atoms from their lower energy state to higher energy state is known as **pumping.**
3. **Resonant Cavity:** In a Laser, the active medium is enclosed in an optical cavity (resonant cavity) usually made up of two parallel surfaces, one of which is perfectly reflecting and the other surface is partially reflecting. In this resonant cavity, the intensity of photons travelling in direction of axis is raised tremendously through stimulated process.

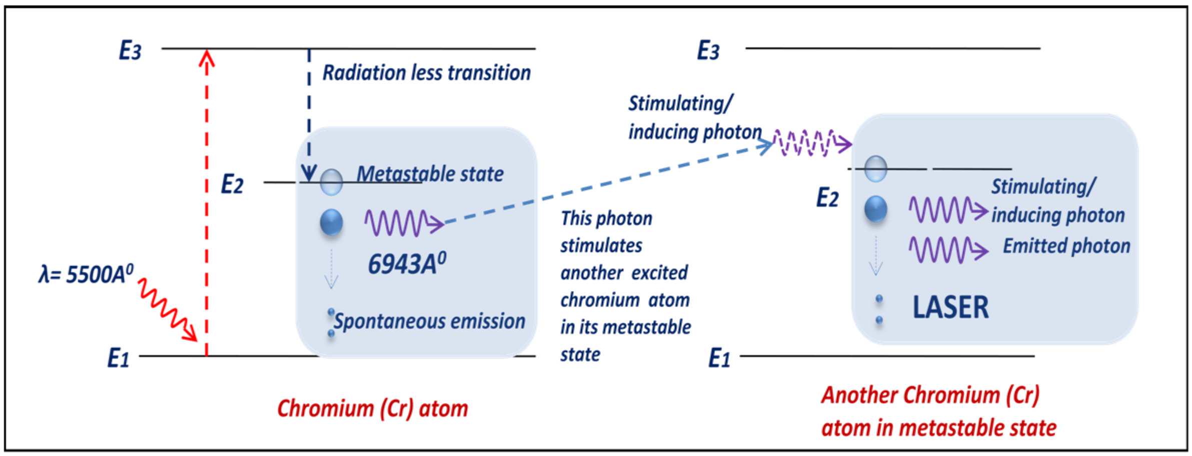
Lasing action

The basic requirement of a laser is to have predominantly induced or stimulated transition so that the radiation emitted should be in the same direction as the incident radiation and also they must possess a definite phase relationship. This provides very intense, highly directional, high monochromatic and highly coherent amplified radiation. The Multiplication of photons in a direction is called LASING action. As shown in figure below.



LASER:



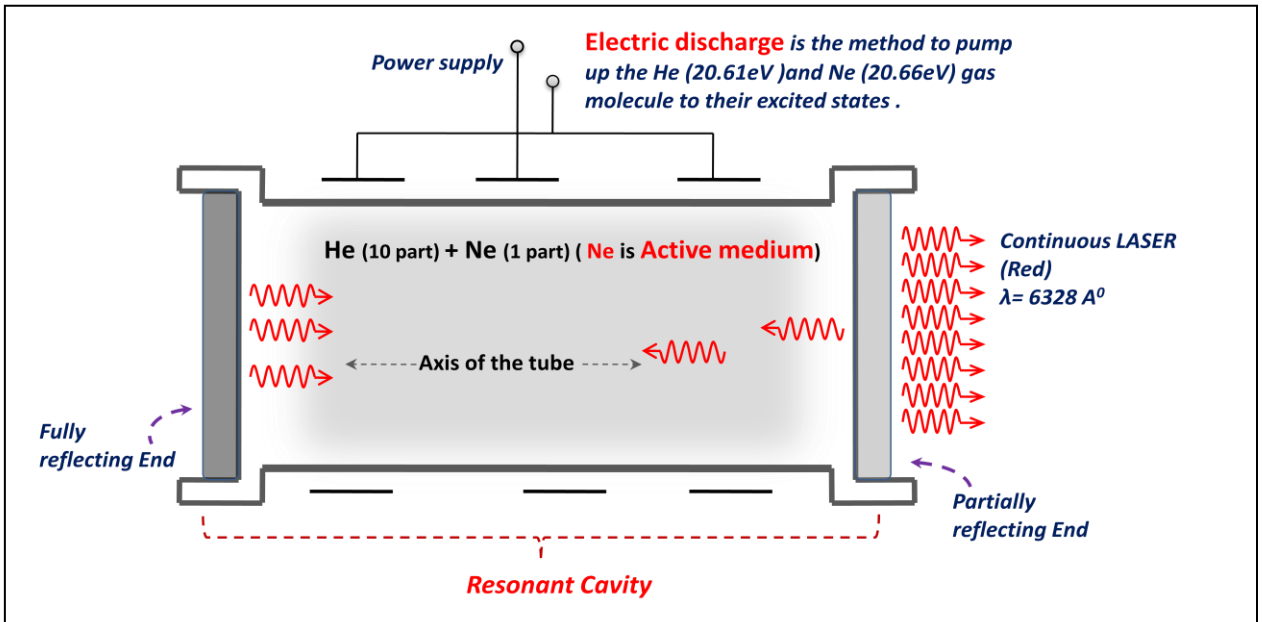


Lasing Action along the direction of rod

When the ruby rod is irradiated by a flash of radiation of λ = 5500A^0, the **Ch**romium (Cr) ions absorbs it and gets to excited state E_3.The excited ions give up part of its energy to the crystal lattice and decay radiationlessly to the **Metastable state E_2**.

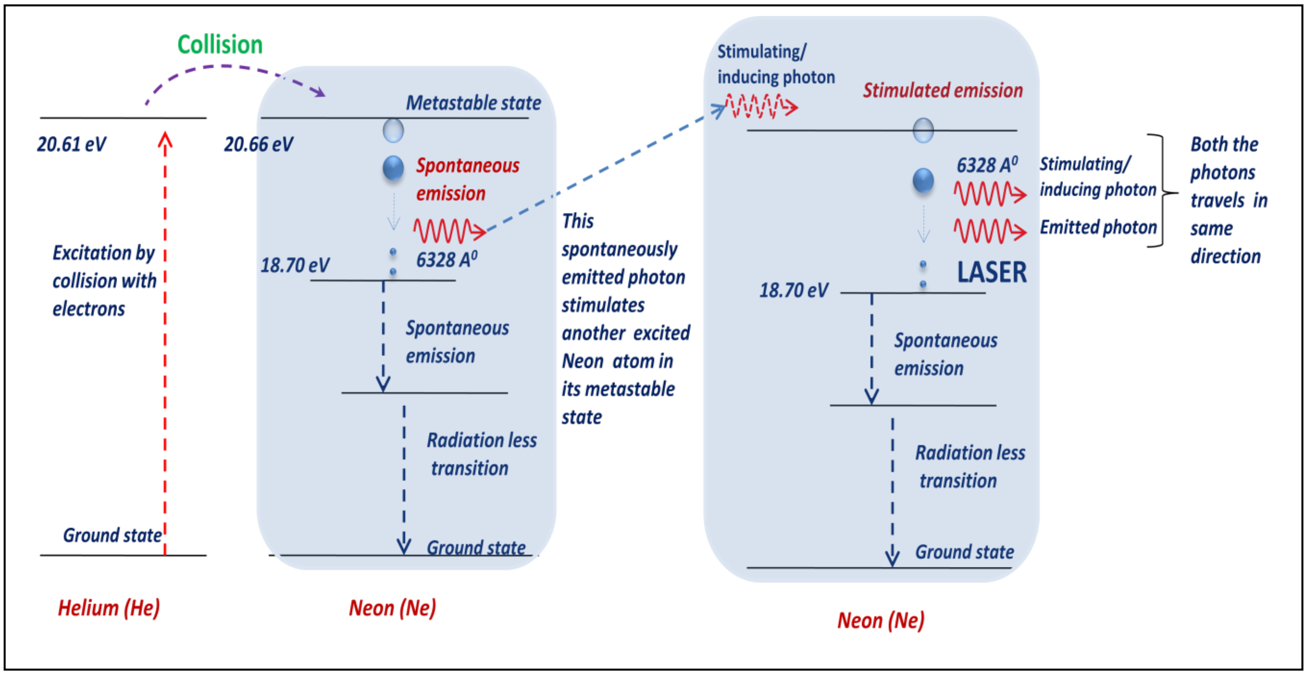
When an excited ion from the metastable state **E_2** drops down spontaneously to the ground state E_1 (transition **3**), it emits a photon of wavelength 6943A^0. As sown in fig it travels through the ruby rod and, if it is moving in a direction parallel to the axis of the crystal, is reflected back and forth by the silvered ends until it stimulates other excited ion and causes it to emit a fresh photon in phase with the stimulating photon. Thus, the reflections will amount to additional stimulated emission. They are called amplification of stimulated emission. This stimulated transition **4** is the laser transition.

He-Ne LASER:



He–Ne LASER

Lasing Action along the direction of tube



A **Helium–Neon laser** or **HeNe laser**, is a type of gas laser whose gain medium consists of a mixture of helium and neon (10:1) inside of a small bore capillary tube, usually excited by a DC electrical discharge. The pressure inside the tube is 1 mm of Hg. The best-known and most widely used He-Ne laser operates at a wavelength of 6328 A^0 in the red part of the visible spectrum.

Working of He-Ne Laser:

When an electric discharge passes through the gas, the electron in the discharge tube collide with the **He** and **Ne** atoms and excite or pumped to the metastable state 20.61eV and 20.66eV respectively above the ground state. Some of the excited **He** atoms transfer their energy to unexcited **Ne** atoms by collision. Thus, lighter **He** ***atoms help in achieving a population inversion in the heavier Ne atoms***. When an excited **Ne** atom drop down spontaneously from the metastable state at 20.61eV and 20.66eV to lower energy state at 18.70eV, it emits a 6328 A^0 photon in the visible region (this is shown by an arrow in above figure). This photon travels through the mixture of gas, and if it is moving parallel to the axis of the tube, is reflected back and forth by the reflector-ends until it stimulates an excited **Ne** atom and causes it to emit a fresh 6328 A^0 photon in phase with the stimulating photon. The photons emitted spontaneously which don't move parallel to the axis of the tube escape through the side of the tube. The stimulated transition from 20.66eV to 18.70 eV level is the laser transition. The two photons will knock out two more photons and the process is repeated again and again, the photon that multiply. When this beam becomes sufficiently intense, a portion of it escapes through the partially silvered end.

Assignment:

1. What is **LASER**? Discuss **spontaneous** and **stimulated emission** of radiation.
2. Discuss the characteristics and applications of a LASER.
3. Derive the Einstein's coefficients.
4. What is a pumping process? Describe the various pumping processes.
5. What is Lasing action.
6. Discuss the construction and working of ruby laser.
7. Discuss the construction and working of He-Ne laser. Why He-Ne laser is superior than ruby laser.