# Engineering Physics

(PHY1701)

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- Laser Characteristics,
- Spatial and Temporal Coherence,
- Einstein Coefficient & its significance,
- Population inversion,
- Two, three & four level systems,
- Pumping schemes,
- Threshold gain coefficient,
- Components of laser,
- Nd-YAG, He-Ne, CO2 and their engineering applications

❖ William Silfvast, Laser Fundamentals, 2008, Cambridge University Press.

# The interpretation of Einstein Relations

- All the 3 Einstein Coefficients are interrelated

$$\boxed{B_{12} = B_{21}} \qquad \boxed{\frac{A_{21}}{B_{21}} = \frac{8\pi h\upsilon^3}{C^3}}$$

- The rates differ depending upon the population densities $N_2$ and $N_1$.

$$R_{st} = B_{21}\rho(\vartheta)N_2 \text{ and } R_{abs} = B_{12}\rho(\vartheta)N_1$$

$N_2 > N_1$ leads to increase in $\rho(\vartheta)$ and hence, amplification.

$N_1 > N_2$ leads to decrease in $\rho(\vartheta)$ and hence, attenuation.

- For laser to operate, it is necessary that $N_2 > N_1$. This is the condition of population inversion.

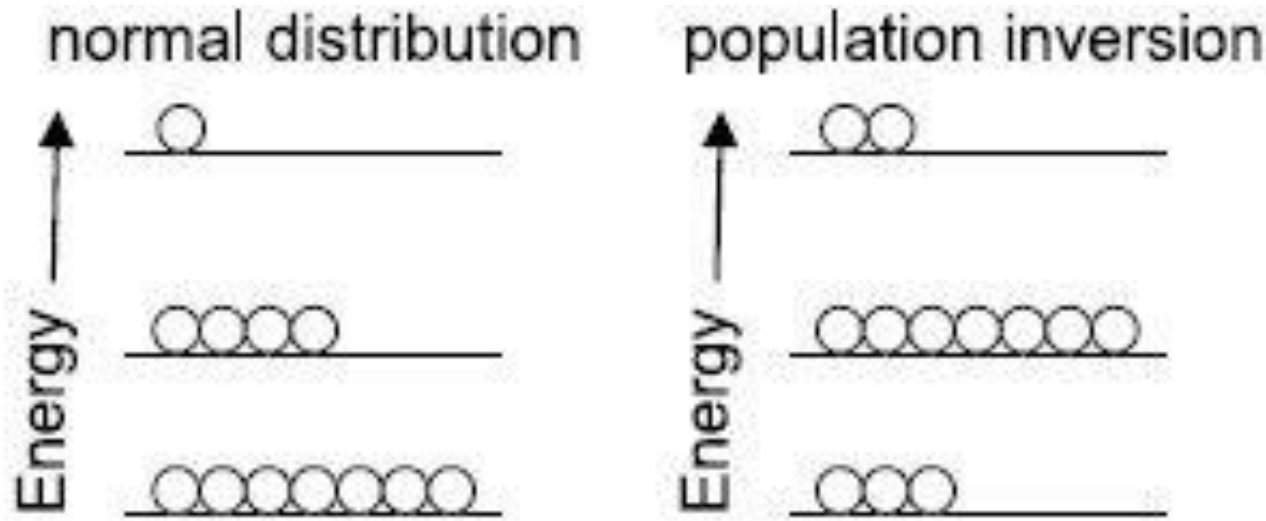
- $$\frac{A_{21}}{B_{21}} = \frac{8\pi h\upsilon^3}{C^3} \Longrightarrow \frac{B_{21}}{A_{21}} \alpha \frac{1}{\upsilon^3}$$
  -High frequency (Short wavelength)
  -Lasers are difficult to operate

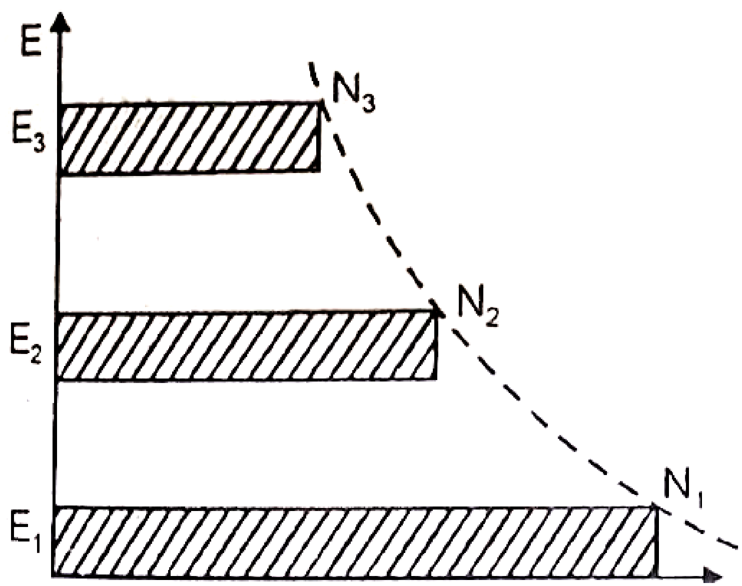
- Although Einstein relations are derived from equilibrium condition, they are valid for any general condition as they are related to characteristics of the atom.

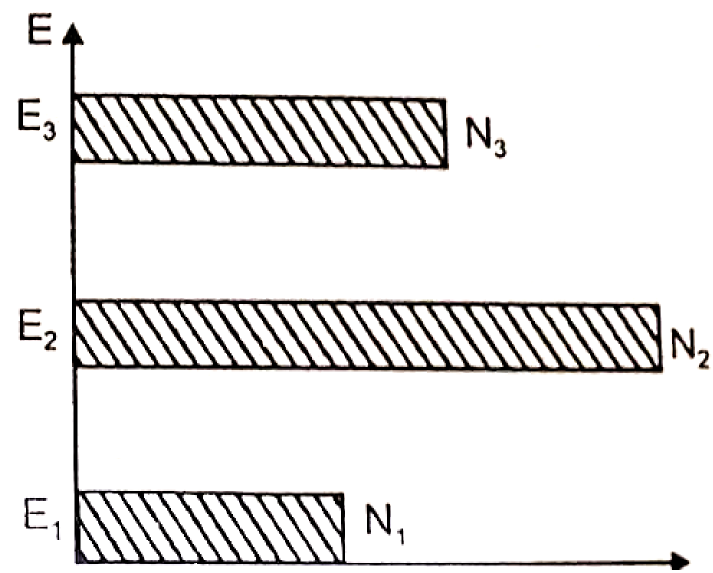
# Population inversion

- When an atom or molecule in the lasing medium absorbs light it is excited.
- The excited molecule then decays to a lower level either through emission of a photon (stimulated or spontaneous) or via a non-radiative loss of the energy.
- For lasing action, stimulated emission must dominate.
- As determined by the Boltzmann factor, the population of the ground state > population of excited state.
- Hence, typically absorption dominates.
- For stimulated emission to be the dominant process, the excited state population must be larger than the lower state population.
- In other words, for a medium to produce laser light, there must be a "**population inversion**"
- Here, $\mathbf{N_{upper} > N_{lower}}$

# Population inversion



# Population inversion



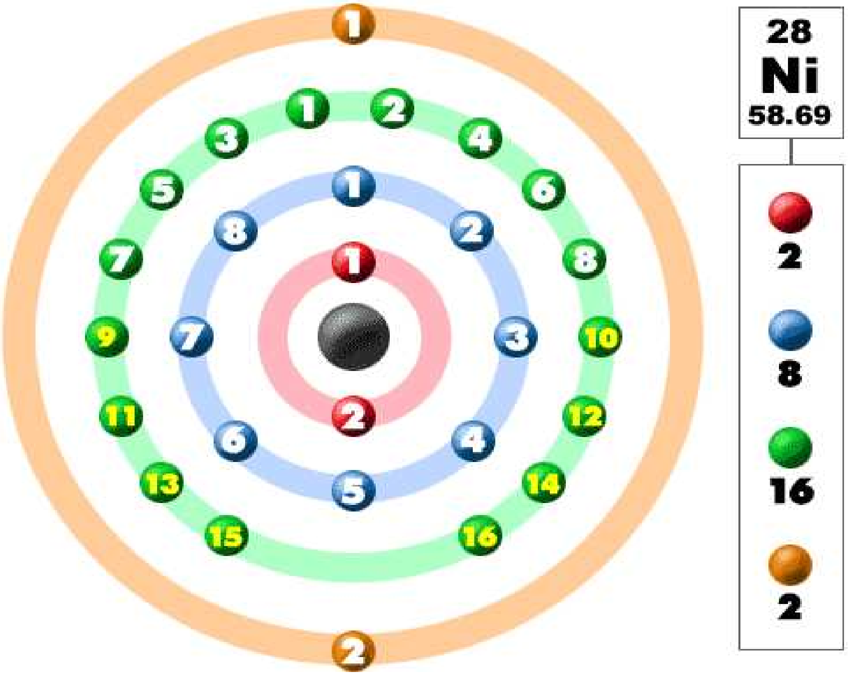
- No. of atoms present in the energy levels is called population. To get laser action more atoms will be present at higher energy level than ground level.
- At thermal equilibrium more atoms are in ground level than excited level. If $E_1$ is ground level, $E_2$ is excited level having populations $N_1$ and $N_2$ respectively. Then,

$$\frac{N_2}{N_1} = \exp\left(\frac{E_2 - E_1}{K_B T}\right)$$

- If $N_1$ be the no. of atoms in the ground level, the population is maximum in the ground level and decreases exponentially to higher level.
- During the thermal excitation the no. of atoms in the higher energy levels are more populated than the lower energy levels when such a condition is fulfilled we say that population inversion is achieved.
- ***"If the number of atoms is more in the higher energy level than the number of atoms in the lower level is called as population inversion or inverted population".***

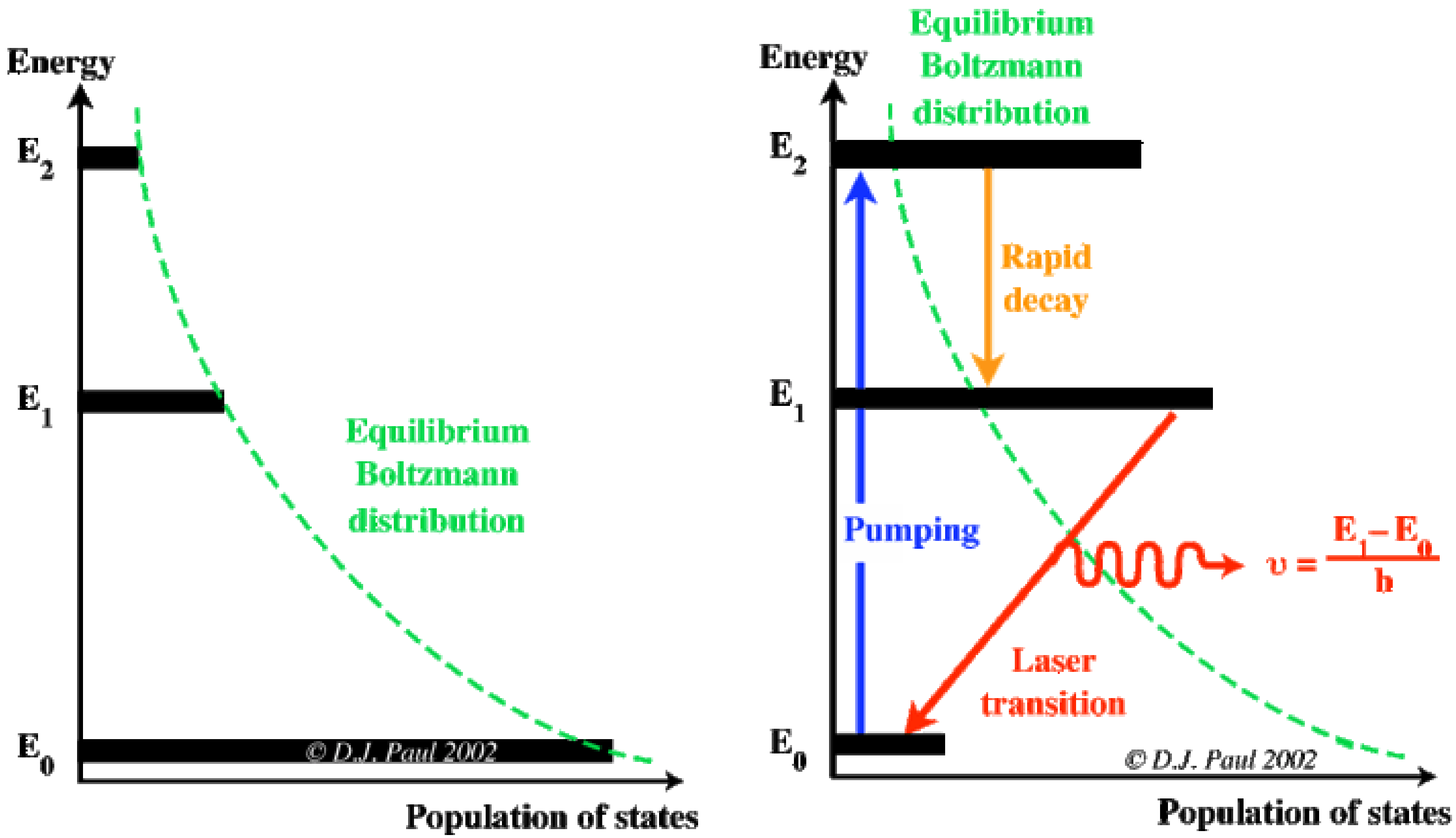
# Population inversion

- Consider a system that has three energy states $\mathrm{E}_1$, $\mathrm{E}_2$ and $\mathrm{E}_3$.
- With the system in equilibrium, the uppermost level $\mathrm{E}_3$ is populated least and lowest level $\mathrm{E}_1$ is populated most.
- The dotted curve shown in figure represents a normal Boltzmann distribution.
- Since the population in three states is such that $\mathrm{N}_3 < N_2 < \mathrm{N}_1$, the systems absorbs photons rather than emitting photons.
- However, if the system is supplied with external energy such that $\mathrm{N}_2$ exceeds $\mathrm{N}_1$, we say that the system has reached population inversion. Under the population inversion condition, the stimulated emission can produce a cascade of light.



# Population inversion



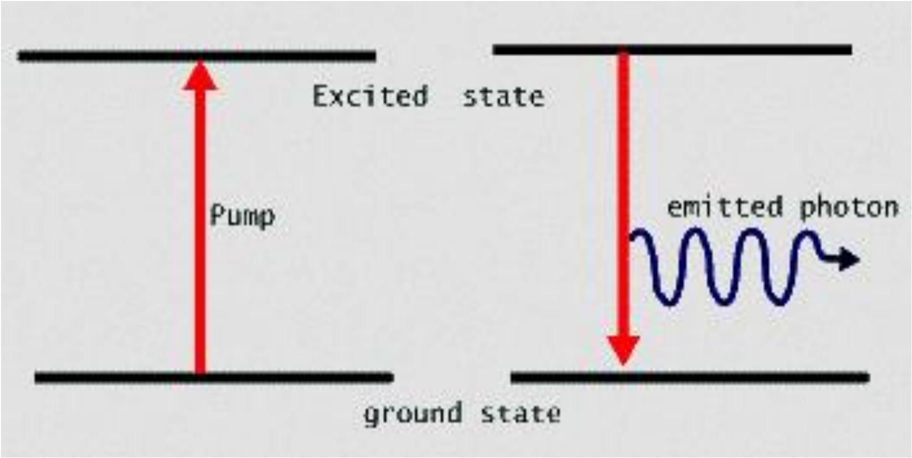



- The figure shows population inversion required for light amplification with the dashed curve being the Boltzmann distribution. As atoms get de-excited, the laser action would stop unless atoms are continuously pumped into the upper level by some means.

# Two level system



- Consider a two level laser system having energy levels $E_1$ and $E_2$ with $N_1$ and $N_2$ number of atoms per unit volume, respectively.




- A radiation with frequency '$\vartheta$' and energy density '$\rho(\vartheta)$' is incident on the system.
- Atoms absorb the radiation and are excited to the upper level. But basically a two level pumping scheme is not suitable for attaining population inversion.
- This is due to two basic reasons.

1. It is difficult to keep a large number of atoms in higher state until they undergo stimulated emission – Hard Pumping
2. The atoms in ground state will absorb the photons emitted thus removing the photons from the beam

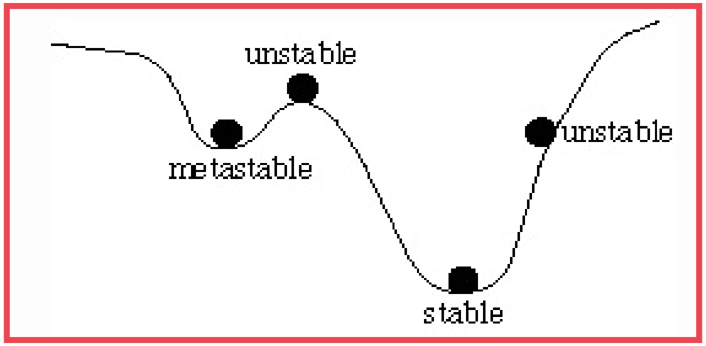
# New terms to learn

- **Three-Level and Four-Level Lasers utilize Metastable states**

- **Life-time of an energy level is** the average amount of the time an atom stays in that energy level before it comes down to ground-level through spontaneous emission.

- **Metastable states** are excited states from which quantum transitions to states with lower energy, accompanied by radiation are prohibited by exact or approximate selection rules.

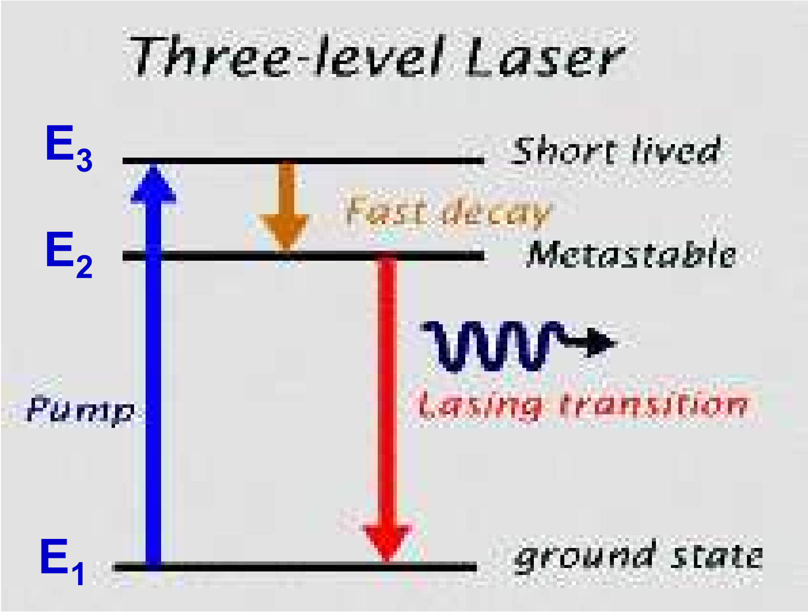
**Life time:**
- **Normal state ~ $10^{-9}$ sec.**
- **Metastable state ~ $10^{-3}$ sec.**



# THREE level system

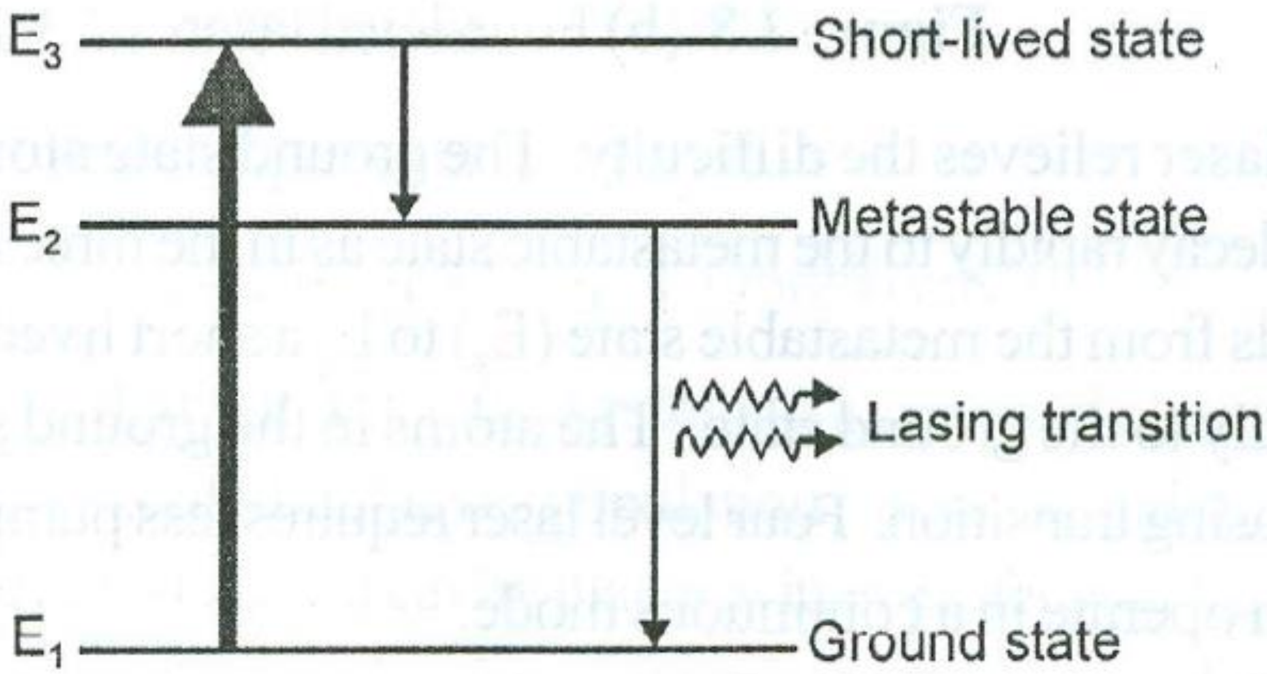


- Consider three level laser system with energy levels $E_1$, $E_2$ and $E_3$. All these energy levels are degenerate. $N_1$, $N_2$ and $N_3$ are population densities of the three energy levels, respectively.
- In the three level pumping scheme the atoms originally in the ground state are pumped into the excited state by some external source of energy (an electric pulse or a flash of light).
- The excited atoms decay by spontaneous emission very rapidly into a lower excited which is a metastable state.
- Atoms stay in metastable state for about $10^{-6}$ to $10^{-3}$ sec. Therefore it is possible for a large number of atoms to accumulate at a metastable sate. In the metastable state, population can exceed the population of a lower level and lead to the state of population inversion.



# THREE level system



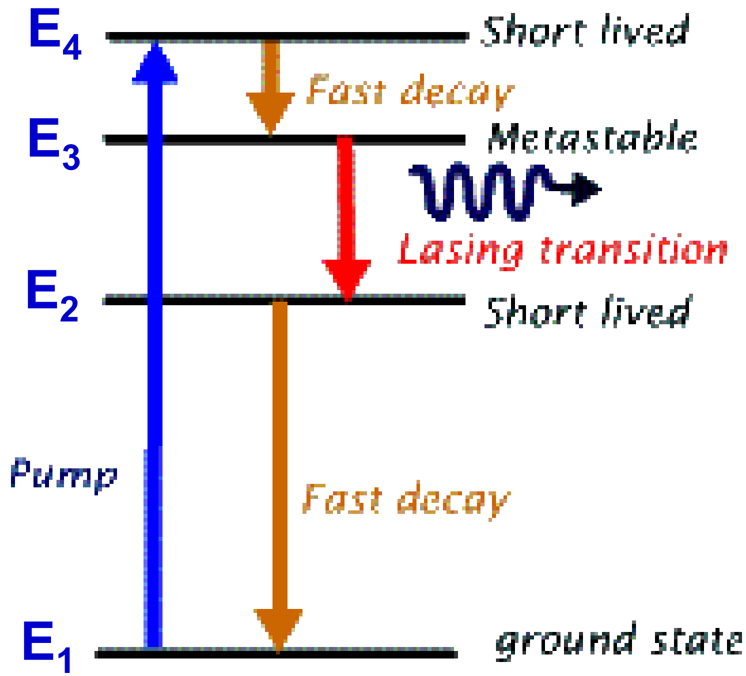



A three-level laser

- If the metastable state does not exist, there could be no population inversion, no stimulated emission and hence no laser operation.
- By using metastable states, 3-level lasers overcome the problem of **pumping difficulty**
- But it does not solve the problem of **photon-reabsorption**

# FOUR level system

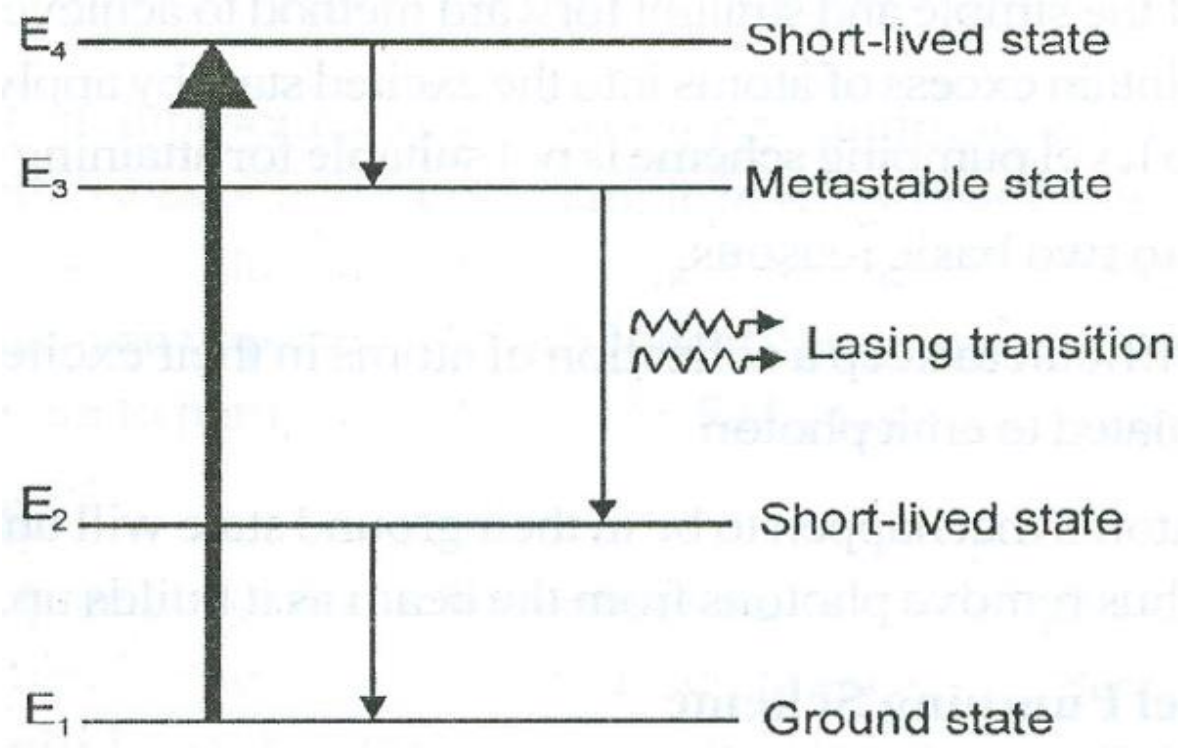





- ✓ Level 1 is the ground level and levels 2, 3, and 4 are excited levels of the system.
- ✓ Atoms from level 1 are pumped to level 4 from where they make a fast non-radiative relaxation to level 3.
- ✓ Level 3 which corresponds to the upper laser level is usually a meta-stable level having a long lifetime. The transition from level 3 to level 2 forms the laser transition.

# FOUR level system






Four-level laser

- By using metastable states, 4-level lasers overcome the problem of **pumping difficulty**
- It also solves the problem of **photon-reabsorption** by avoiding the use of ground state as the lower lasing level

# Pumping Techniques



- Bringing of the atoms from ground level to excited level by giving sufficient energy is called pumping. Different types of pumping techniques are shown below.
  1) Optical pumping: In optical pumping a light source is used to supply luminous energy. Most often this energy comes in the form of short pulses of light. This mechanism is used in ruby lasers and Nd-YAG laser.
  2) Electric Discharge: In this process electric discharge is used for the excitation of atoms. This is used in gaseous lasers especially He-Ne laser. Electrons collide with the atoms and produce the required population inversion.
  3) Atomic Collisions: In lasers like He-Ne , electric discharge still provides the initial excitation which raises the one type of atoms(say He atoms) to their excited levels. These atoms collide with other type atoms (Ne atoms) and produce population inversion.

# Pumping Techniques

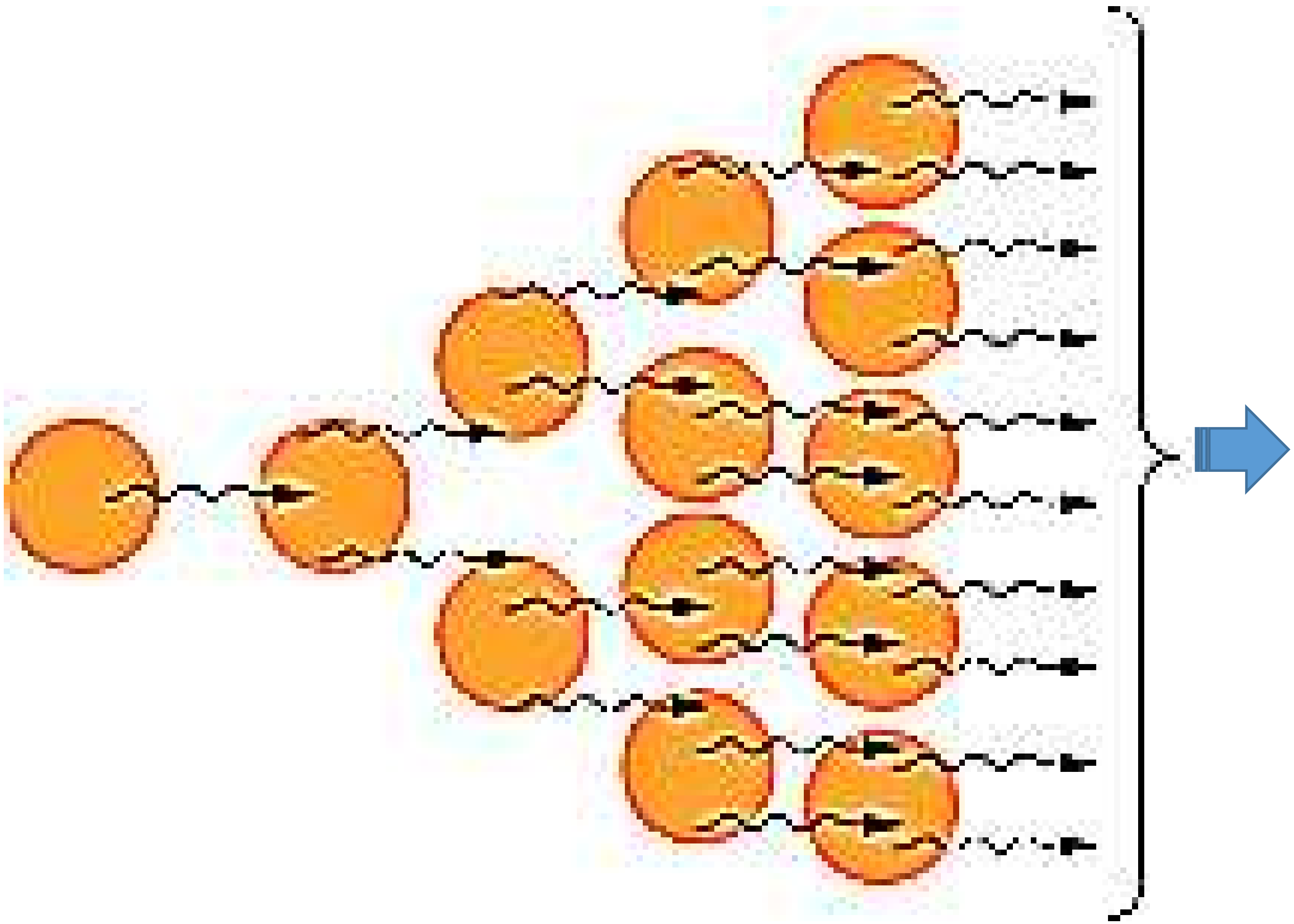
4) Direct Conversion: Electrical energy is directly converted into radiation in devices like LEDs and semiconductor diode lasers.
5) Chemical Reactions: In a chemical laser energy comes from chemical reactions without any need for other energy source.

   For ex: $H_2 + F_2 \longrightarrow 2HF$ + heat.

   Medium is excited by absorbing this heat energy.

# Principle of LASER





***Intense Laser Beam***