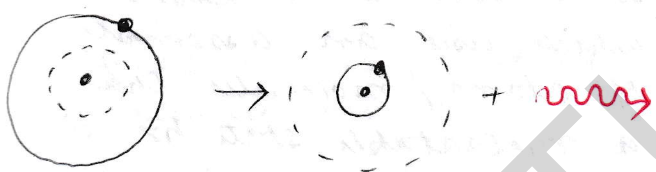
# LASERS

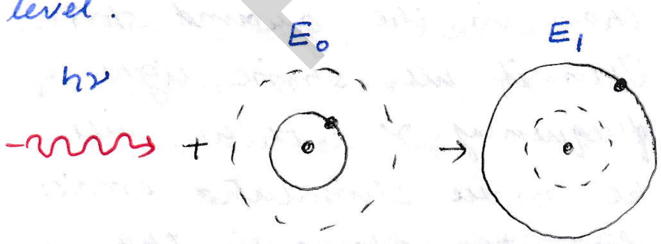
Since atoms have discrete energy levels, the excitation or deexcitation of an atom is associated with the absorption or emission of an equivalent energy, respectively.

One way in which an atom can be excited to an energy above its ground state is via collission. When an atom collides with another atom, the kinetic energy is absorbed by the atom. Such an excited atom returns to its ground state in $10^{-8}$ sec, by emitting one or more photons.



(spontaneous emission)

Another excitation mechanism is when an atom absorbs a photon with just the right amount of energy to raise the atom to a higher energy level.




(Stimulated absorption)

So, above two transitions involving electromagnetic radiation are possible b/w two energy levels $E_0$ and $E_1$.

① If atom is initially in the lower state $E_0$, it can be raised to a higher state $E_1$ by absorbing a photon of energy $E_1 - E_0 = h\nu$. This process is called stimulated absorption.

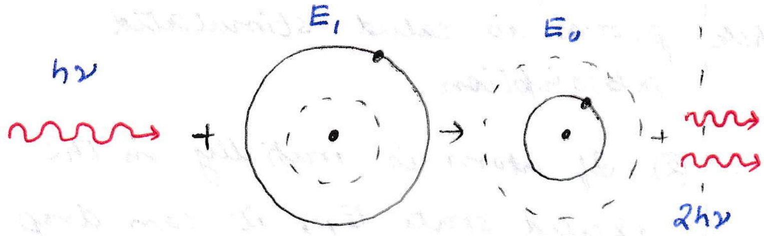
② If atom is initially in the excited state $E_1$, it can drop to the lower state $E_0$ by spontaneously emitting a photon of energy $h\nu = E_1 - E_0$. This is called spontaneous emission.

Einstein, in 1917 was the first to point out a third possibility

③ Stimulated emission.

In stimulated emission, an incident photon of energy $h\nu$ stimulates / causes a transition from $E_1$ to $E_0$. In this emission, the radiated light waves are exactly in phase with the incident ones, so the result is an enhanced beam of coherent light.

An analogy of stimulated emission is the harmonic oscillator, for instance a simple pendulum. If a sinusoidal force is applied to the pendulum, whose period is the same as the period of oscillation, the applied force is exactly in phase with the swinging pendulum, then the amplitude of the swing increase. This corresponds to stimulated absorption. However if the applied force is 180° out of phase, the amplitude of the swing decreases. It corresponds to stimulated emission.




(Stimulated emission)

The working mechanism of laser is based on the above concept of stimulated emission.

What is a laser?

A laser is a device that produces light with some remarkable properties :-

① The light is very nearly monochromatic.

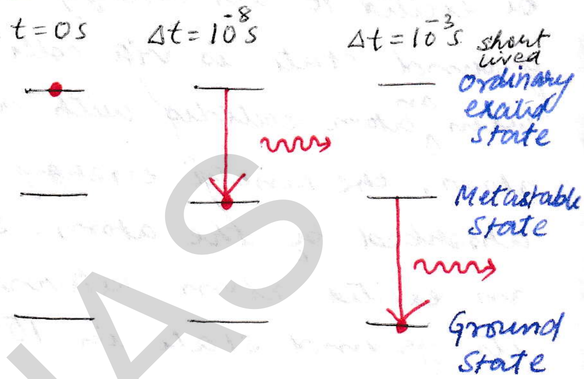
② The light is coherent, with all the waves exactly in phase with each other.

③ A laser beam hardly diverges.

④ The beam is extremely intense.

The laser therefore stands for LIGHT AMPLIFICATION BY STIMULATED EMISSION OF RADIATION.

The key to the laser is the presence of many atoms of one or more excited energy levels whose lifetimes may be $10^{-3}$s or more instead of the $10^{-8}$s that is usual. Such relatively long lived states are called meta-stable states.




The simplest kind of laser is a three level laser which uses an assembly of atoms / molecules that have a metastable state hν in energy above the ground state and a still higher ordinary excited state that decays to the metastable state.

What is needed is more atoms in the metastable state than in the ground state. Then if we shine light of frequency ν, there will be more stimulated emissions from the atoms in the metastable state than stimulated absorptions in the ground state. The result is an amplification of the original light. This is the concept behind laser.

This process is called population inversion, which describes an assembly of atoms in which majority of atoms are in energy levels above the ground state, compared to atoms in ground state. Normally, the ground state is occupied to the greatest extent.

A number of ways exist to produce population inversion. One of them is called optical pumping. Here, an external light source is used to raise ground state atoms to excited state that decays spontaneously to the desired metastable state.

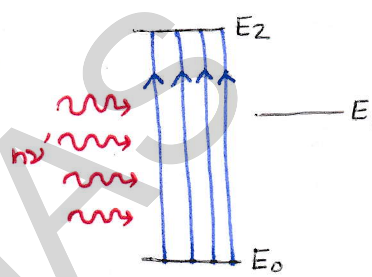
Why do we need a third metastable state?

Suppose there were only two states - the more photons of frequency $\nu$ we pump into the assembly, the more upward transitions there will be from the ground state to the excited state. When half the atoms are in each state, the rate of stimulated emissions will equal the rate of stimulated absorption. In this situation laser amplification cannot occur.

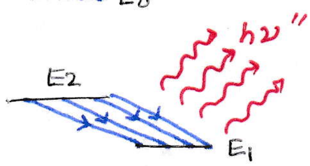
A population inversion is only possible when the stimulated absorptions are to a higher energy level than a metastable one from which stimulated emission occurs, which prevents the pumping from depopulating the metastable state.

In three level laser, more than half the atoms must be in metastable state for stimulated emission to predominate.

① Optical Pumping

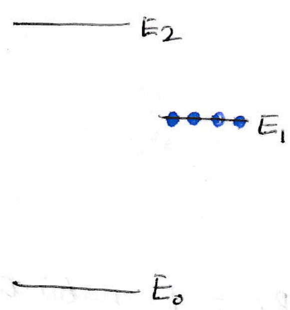



② Spontaneous emission to metastable state

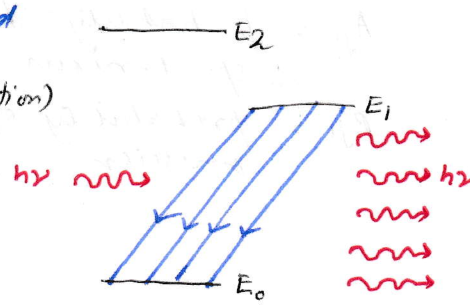



(Non-radiative Transitions)
- Vibrational Relaxation
- Internal conversion
- Creation of phonons

③ Population Inversion




④ Stimulated Emission (Lasing transition)



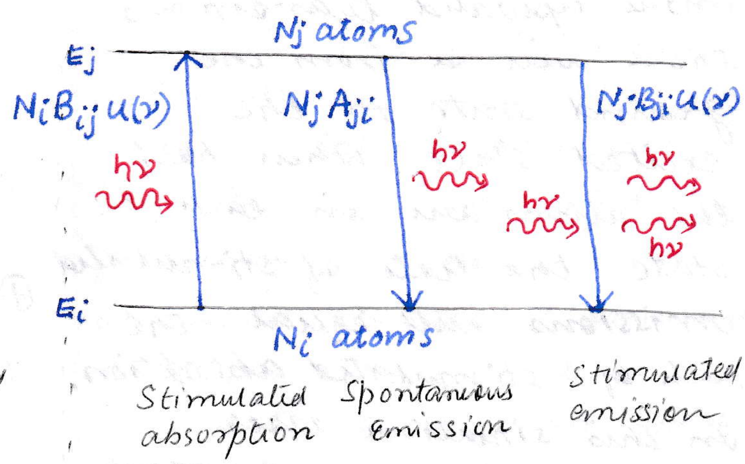
# Einstein Coefficients

In 1917, Einstein introduced stimulated emission & used it to arrive at the form of Planck's radiation law in an elegantly simple manner.

Let us consider two energy states, a lower state $E_i$ and higher state $E_j$, such that if the atom is in state $i$, it can be raised to state $j$ by absorption of a photon of frequency

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

Now lets imagine an assembly of atoms, where no. of atoms in $i$-state is $N_i$ and no. of atoms in $j$-state is $N_j$. The system is in thermal equillibrium with radiation energy density $u(\nu)$.




$B_{ij}$ = probability of stimulated absorption

$A_{ji}$ = probability of spontanious emission

$B_{ji}$ = probability of stimulated emission

① Absorption of photons:-

The probability that an atom in state $i$ absorbs a photon is proportional to the radiation energy density $u(\nu)$ and also some properties of state $i$ & $j$ which we can include in some constant $B_{ij}$, in addition to $N_i$

Hence the rate of absorption of photons

$$N_{i\to j} = N_i B_{ij} u(\nu)$$

② Emission of photons.

Spontaneous emission doesnot depend on radiation density as it is spontaneous. So rate of spontaneous emission is $N_j A_{ji}$.

Stimulated emission is also possible in which light of frequency $\nu$ can induce an atom in state $j$ to transition to lower state $i$. Hence its probability not only depends on energy density $u(\nu)$ but also on properties of state $i$ and $j$, $B_{ji}$ and number of atoms, $N_j$, so rate is

$$N_j B_{ji} u(\nu).$$

Thus rate of net emission is

$$N_{j\to i} = N_j A_{ji} + N_j B_{ji} u(\nu)$$
$$= N_j [A_{ji} + B_{ji} u(\nu)]$$

If the system is in thermal equilibrium, the no. of atoms per second that go from state $i$ to $j$ must equal the number that go from $j$ to $i$.

$$N_{i\to j} = N_{j\to i}$$

So,

$$N_i B_{ij} u(\nu) = N_j [A_{ji} + B_{ji} u(\nu)]$$

$$\Rightarrow \left(\frac{N_i}{N_j}\right)\left(\frac{B_{ij}}{B_{ji}}\right) u(\nu) = \frac{A_{ji}}{B_{ji}} + u(\nu)$$

$$\Rightarrow \left[\left(\frac{N_i}{N_j}\right)\left(\frac{B_{ij}}{B_{ji}}\right) - 1\right] u(\nu) = \frac{A_{ji}}{B_{ji}}$$

$$\Rightarrow u(\nu) = \frac{A_{ji}/B_{ji}}{\left(\frac{N_i}{N_j}\right)\left(\frac{B_{ij}}{B_{ji}}\right) - 1}$$

Now, we can use the Maxwell Boltzman Distribution function $f(\varepsilon) = Ae^{-\varepsilon/KT}$ to get an estimate of the no. of atoms in state $i$ as opposed to state $j$.

So,

$$N_i = A e^{-E_i/KT}$$
$$N_j = A e^{-E_j/KT}$$

So,

$$\frac{N_i}{N_j} = e^{-(E_i - E_j)/KT}$$

where, $E_j - E_i = h\nu$

Thus,

$$\frac{N_i}{N_j} = e^{h\nu/KT}$$

Then we have

$$u(\nu) = \frac{A_{ji}/B_{ji}}{\left(\frac{B_{ij}}{B_{ji}}\right)e^{h\nu/kT} - 1}$$

This formula gives the energy density of photons of frequency $\nu$ in equilibrium at temperature $T$ with atoms of energies $E_i$ and $E_j$.

as long as

$$B_{ij} = B_{ji}$$

and $\frac{A_{ji}}{B_{ji}} = \frac{8\pi h\nu^3}{c^3}$

we get the Planck's Energy density for Blackbody spectrum,

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

Conclusions :-

① Stimulated emission does occur and its probability is equal to probability of absorption.

② The ratio b/w probabilities for spontaneous & stimulated emission varies with $\nu^3$, so the relative likelihood of spontaneous emission increases rapidly with energy difference b/w states.

③ All we need to know is one of the probabilities $A_{ji}$, $B_{ij}$, $B_{ji}$ to find the others. Hence the process of spontaneous emission is intimately related to the process of absorption & stimulated emission.