Introduction to LASER
Prof. M.R. Shenoy
Department of Physics
Indian Institute of Technology, Delhi

Lecture – 02
Interaction of Radiation with Matter

Welcome to the MOOC Introduction to Lasers. So, in the last lecture I introduced the subject matter and the course contents that we will be covering in this course. So, today we will start with part 1 that is Interaction of Radiation with Matter.

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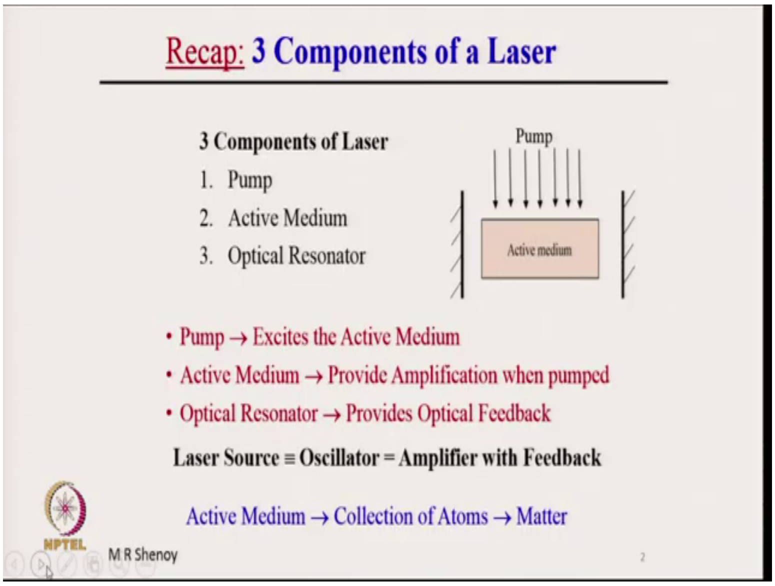

A very quick recap of what we had seen in the last class. So, we saw that laser is a source of optical radiation in that sense it is like an oscillator; an oscillator comprises of an amplifier and a feedback unit. And we have seen that the three components of a laser are the active medium which acts as an amplifier when pumped appropriately. A mirror which acts as a resonator and which provides the necessary feedback.

So, today we will discuss about the interaction of radiation with matter because, the active medium is a matter it is an atomic system or a collection of atoms and therefore, we will discuss interaction of radiation with matter alright. Some notes about the discussion that we will have.

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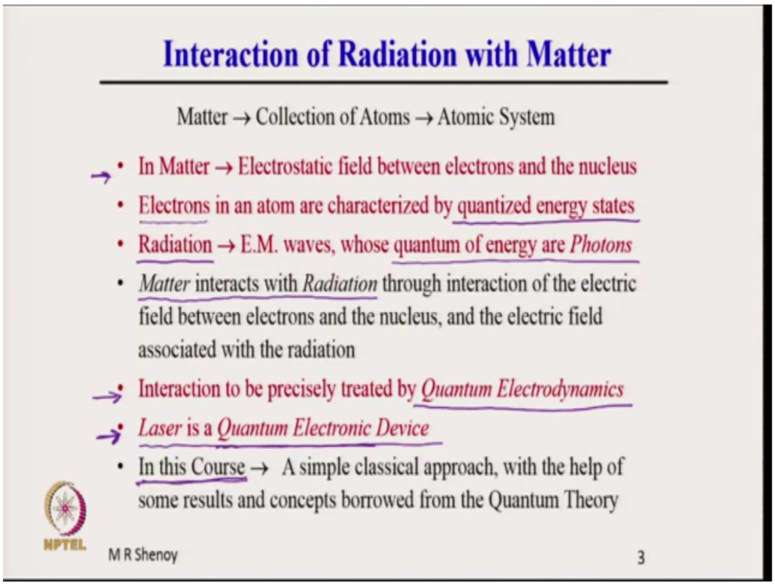

Matter is a collection of atoms. So, it is an atomic system and we know that in matter there is electrostatic field between the electrons and the nucleus and electrons in an atom. So, the electrons in an atom are characterized by quantized energy states there are discrete energy levels which are occupied by electrons. So, there are quantized energy states.

Radiation on the other hand radiation are electromagnetic waves whose quantum of energy is the photon. So, photons are the quanta of energy of electromagnetic waves. So, matter interacts with radiation therefore, matter interacts with radiation through interaction of the electric field between electrons and the nucleus and the electric field associated with the radiation.

To treat this interaction precisely we need to follow quantum electrodynamics this can be rigorously treated by quantum electrodynamics. A subject which rigorously discusses the laser physics and laser is indeed a quantum electronic device. So, quantum electronics is the branch of physics, which discusses interaction of radiation with matter and the various applications of this interaction.

Now, in this course so, now we come to in this course. So, in this course we will treat laser with a simple classical approach with the help of some results and concepts borrowed from the quantum theory. Laser is actually a very interesting device which can be described by a simple classical approach, it can also be described by what is called semi classical approach and it can also be described by the quantum approach or by the quantum theory.

In this first course this is a first course in which we will treat this in the simplest picture, but to complete the picture we would need to borrow some results from the quantum theory which we will assume and then we discuss the subject.

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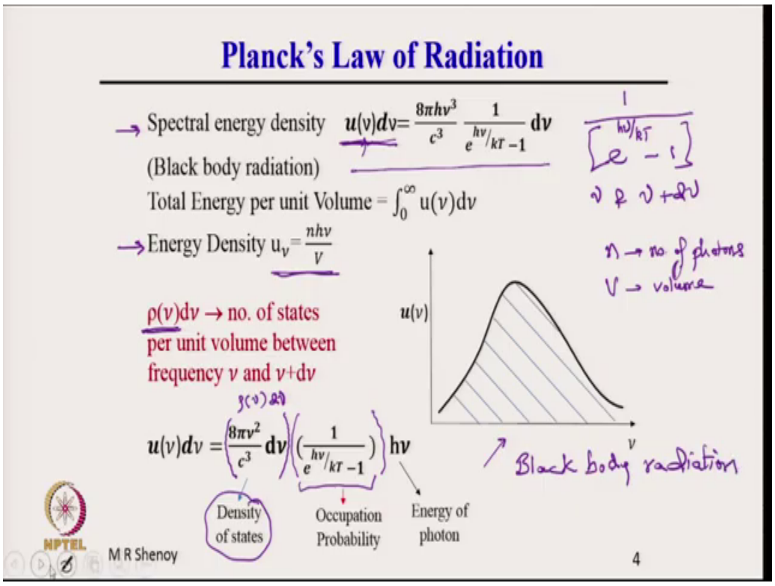

To begin with we start with the Planck's law of radiation. The Planck's law blackbody radiation we are all familiar with this where which gives the spectral density of energy or spectral energy density u nu d nu, u nu is called the spectral energy density. So, u nu d nu is given by an expression of this form 8 pi h nu cube by c cube into 1 by e to the power h nu by kT, this whole h nu by kT is the exponent. So, it is e to the power h nu by kT minus 1 in the denominator.

So, denominator is this e to the power h it is not kT minus 1 it is e to the power h nu minus kT by 1 into d nu. Now, the total energy it is the spectral density energy, spectral means with frequency energy density with frequency that is u nu d nu is defined as the energy per unit volume between frequencies nu and nu plus d nu.

So, this is defined as the energy per unit volume between frequencies nu and nu plus d nu a range of frequencies. So, that is defined by this term. So, this is Planck's blackbody radiation.

Therefore, the total energy per unit volume is integral 0 to infinity u nu d nu. If we are looking at energy density at a particular wavelength or a particular frequency nu then u nu is defined as n h nu by V. So, this is volume V is volume n is the number of photons. So, n here is the number of photons; number of photons and V is the volume capital V is the volume that is volume of the medium and h nu is the energy of the photon.

So, energy density at any particular frequency can be written as u nu is equal to n number of photons into energy of 1 photon per unit volume. Rho nu d nu is the number of states per unit volume between frequencies nu and d nu. So, rho nu if rho nu d nu is the number rho nu is called the density of states this rho nu is called the density of states the u nu is the spectral energy density.

So, rho nu d nu is the number of states it is defined as the number of states per unit volume between frequency nu and nu plus d nu. And therefore, when we write u nu d nu by the expression here it is now shown separately that this first part here is the density of states rho nu d nu. So, this is rho nu d nu. So, rho nu d nu and this is the occupational probability the second term here is the occupation probability and the last term is the energy of photon.

So, this expression has come because you have a certain density of states in the material. So, a certain density of states in the material and what is the multiplied by the occupation probability? Multiplied by the occupation probability will tell us the number of photon states there multiplied by energy density of photon the energy of one photon will give us u nu d nu.

So, basically the Planck's law radiation here I have shown it that it comprises of three components; one is the density of states occupation probability multiplied by energy of photons. A typical variation of u nu versus nu if you plot would look something like this. So, this is this shows the variation of blackbody radiation. So, this is blackbody radiation, blackbody the spectrum of blackbody radiation this is given by the Planck's law.

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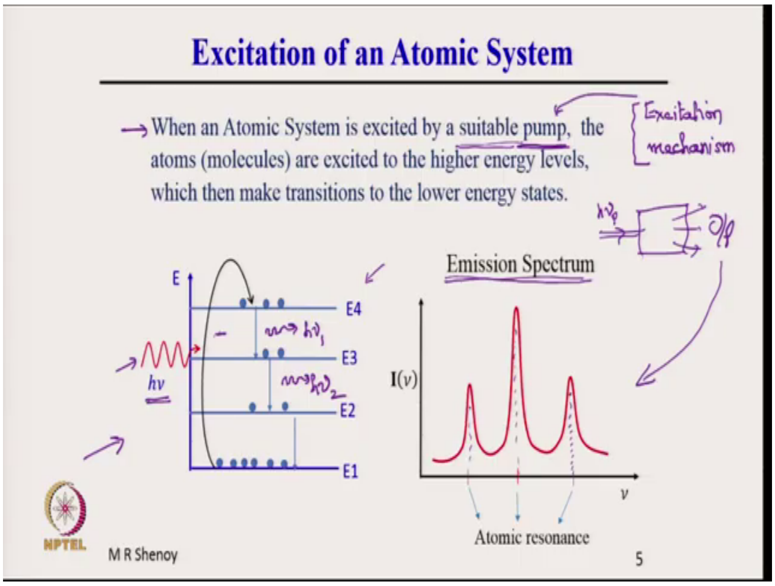

Now, let us look at the atomic system excitation of an atomic system. When an atomic system is excited here; when an atomic system is excited by a suitable pump. What is this pump? This is not some electrical pump or water pump or something this pump here refers to an excitation mechanism. So, the pump here refers to an excitation mechanism.

It could be excitation by another light source a flash lamp for example, it could be excitation by an electric discharge or it could be chemically excited, an excitation by chemical means chemical energy. So, everything is called as pump; pump is basically an excitation mechanism.

When an atomic system is excited by a suitable pump what is this suitable we will come to know, the atoms are excited to the higher energy levels which then make transitions to the lower energy levels That is what is depicted in this diagram here.

So, E1 is the ground state energy, due to an excitation mechanism here it is being pumped by a photon. So, this is a indicating a photon of energy h nu pumping means exciting to a higher level, it means an atom makes an upward transition by absorbing a photon of energy h nu and it makes an upward transition. So, the suitable pump what we meant by a suitable pump here?

So, suitable pump refers to if the energy of the photon is equal to the difference between E4 and E1 then the atom can absorb that photon and make an upward transition. If the energy was only up to this let us say only up to a level here, then it could not have made a transition up to E4. And that is what we mean by a suitable pump.

Suitable pump which whose energy corresponds to a higher level which can raise the atom in energy of course, raise this is not physical levels these are levels in energy then we call it as excitation. Now, the excited atom can make downward transitions they can come down to lower energy levels I must this is the first time I am drawing the energy levels.

I usually we show this as almost equally separated, but it is not so in an actual energy level diagram this will vary as 1 by n square, that is the n is the number 1, 2, 3, 4 here. So, therefore, the energy levels will come closer and closer as you go to higher values, but here schematically it is illustrated as separate levels now almost equally separated it is not equally separated.

Now, the excited atom comes down to the lower energy state here and then gives out a photon corresponding to another energy let us say h nu 1. And the atom from here could come down this atom could also come down to the ground state, this atom could also come down from level 3 to level 1, but I have shown here a some of them. So, it is coming down the difference between them is given in the form of radiation let us say this is h nu 2.

Then if you observe the emission spectrum of this material, emission spectrum means. So, if you take the material and let us say you excite it with pump of some radiation of energy h nu p. I am putting a subscript p to say that this is pump, then outside here we will get different photons or different radiation wavelengths here at the output different frequencies corresponding to the different transitions here.

And therefore, if you see the emission spectrum; emission spectrum means what? Intensity versus nu if you plot the output here. So, this is the output; so output.

If you see the output and plot the output as a function of frequency then you see distinct peaks corresponding to the transitions, the distinct peaks here correspond to different transitions. The strength of transitions may be different for different transitions and therefore, you see that the peaks are not all of the same height some peaks may be higher some peaks may be lower, but what you see in an emission spectrum is distinct lines or distinct peaks which correspond to transitions.

This clearly indicates that the energy levels of an of atoms are discrete a simple practical observation will tell you that they are discrete.

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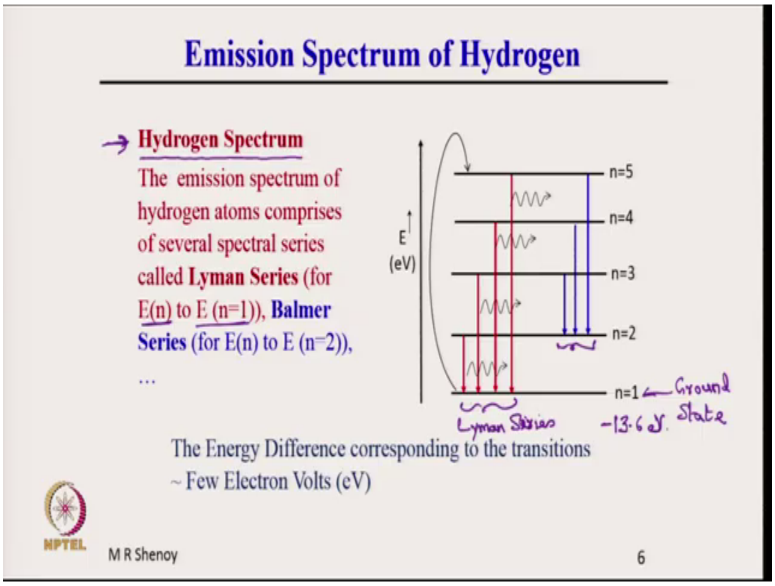

Now, the very well known emission spectrum of hydrogen so, we all have seen this hydrogen spectrum in the high school. That the emission spectrum of hydrogen atoms comprised of several spectral series called the Lyman series, Balmar series, Paschen series and so on.

So, Lyman series is this. So, this four lines which I have shown correspond to the Lyman series that is from E any higher level E of n to E n equal to 1; n equal to 1 is the ground state. So, this is the ground state. In the case of hydrogen the energy corresponding to this is minus 13.6 electron volt.

I repeat again that the energy levels are not equally spaced the spacing varies as you go higher in energy the spacing becomes smaller and smaller, it changes as 1 by n square the energy difference. And this is the Lyman series, the first one is the Lyman series, the second this one corresponds to the Balmer series that is from any higher energy level to level 2.

But, what is the point? The point is corresponding to these if we observed the spectrum of hydrogen if we see the hydrogen spectrum this will comprise of discrete output resonances or discrete line spectrum corresponding to the different transitions discrete transitions discrete energy differences we will have the output comprising of different wavelengths. So, if we see the output, then we will see atomic resonances in the output.

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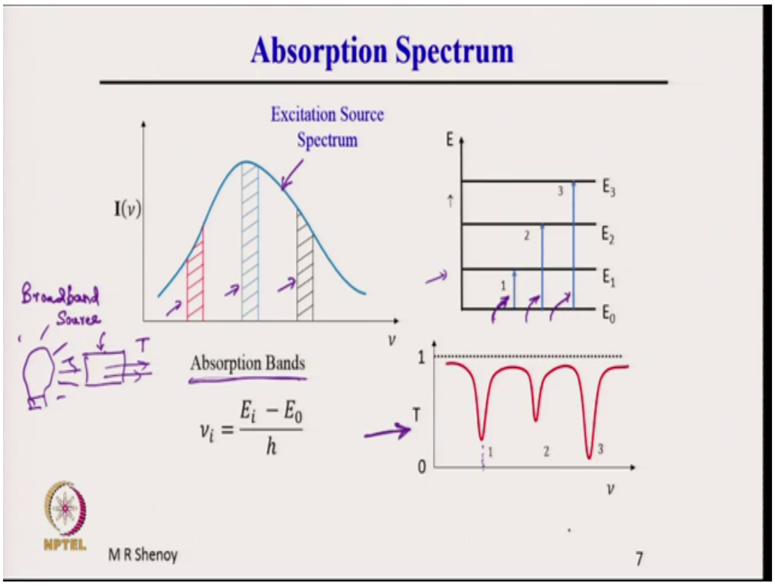

Similarly, so this is about emission. So, the atomic resonances are what I had shown here. So, you will see distinct lines corresponding to different transitions. The energy difference corresponding to these transitions are of the order of few electron volts normally energy in physics we talk in terms of Joules, but electron volt is a very convenient unit to talk about these energy differences. I will discuss about this electron volt for those of you are not familiar I will take an example and show in a subsequent slide.

Now, similarly the absorption spectrum. Absorption spectrum means what? If you see so, this if you excite a medium by. So, this spectrum which is shown here is the excitation source spectrum a broadband source. So, you use a broadband source. So, in this diagram here I had showed you that input if the input is not of a particular frequency, but if the input is a broadband source. Broadband source means it comprises of a range of wavelengths similar to white light.

For example, if you take white light a bulb a tungsten halogen bulb and then you pass this light through the medium, through the material and observe the spectrum on the other side the transmitted light here. So, t standing for transmitted light. So, this is the input. So, the white light illuminates this or a broadband source. So, this is a broadband source.

The transmitted light if we observe this as a function of frequency or wavelength using a spectrometer for example, then we see here. So, what is shown here in this graph is that there are dips corresponding to different transitions.

Now, what is happening is the wavelength here correspond the frequency or the wavelength corresponding to this one is absorbed in this transition here from ground state to the upper state. So, here it is shown as E 0 some most of the times we will write ground state as E 1.

So, similarly two here it is a higher frequency. So, higher energy is absorbed in undertaking this transition an atom getting excited by absorbing this wavelength and going to upper state. And similarly the 3 here corresponds to the 3rd transition. Accordingly if you see the input spectrum is like this then there are absorptions taking place certain bands of absorption. So, these are called absorption bands, a range of frequencies which are absorbed by this material here.

So, this is the material here the range of frequencies absorbed is called the absorption band centered around a particular frequency and that is why if you see the transmitted light so, this is transmission. So, transmitted light if you plot the transmission, transmission is the transmissivity or transmission is the ratio of the output by input at that wavelength; ratio of the output by input at a particular wavelength.

So, at every wavelength if you determine the T transmission, then you see that there are dips in the transmitted spectrum this indicate these dips correspond to the absorptions here which I have indicated in this diagram absorptions and that is called the absorption spectrum.

So, both the emission spectrum and the absorption spectrum has distinct peaks or distinct dips corresponding to the energy difference between different levels this clearly indicates that an atom or an atomic system is characterized by discrete energy levels, the quantized the energy levels are quantized alright.

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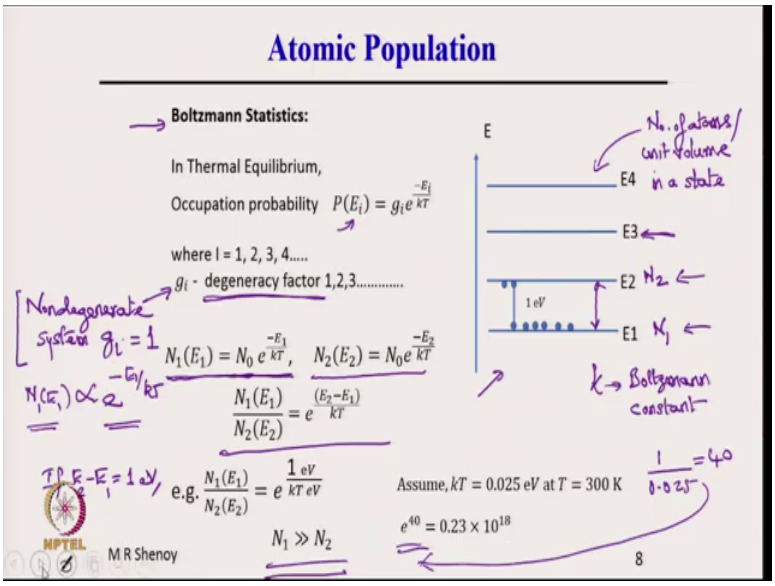

So, let us see the atomic population; atomic population here refers to the number of atoms. So, atomic population refers to number of atoms per unit volume; per unit volume in a given energy state; unit volume in a state, state is energy level characterized by one energy value.

So, what is shown here is an atomic system characterized by different energy levels and we want to see the atomic population of these different levels. The Boltzmann statistics here shows that in thermal equilibrium the occupation probability that is the probability that an atom occupies a level with energy E i is given by g i into e to the power minus E i by kT; E i is the energy level here for example, E4, E1, E2, E4. So, I is 1, 2, 3, 4 kT here is k is the Boltzmann constant.

So, k is the Boltzmann constant and T is the absolute temperature gi. So, g i is shown here, g i is called the degeneracy factor, that is what it means is at a given energy value let us say E3 corresponding to one energy E3 if there are two different levels; two different levels which are contributed by different mechanisms the energy levels are contributed by certain mechanisms in an atom.

If there are two energy levels occur at the same value of energy, then we say that there is a degeneracy of 2. So, degeneracy of 2 means at a given energy value we have two different energy levels, the energy levels may be characterized by different labels. So, what about this label? We will discuss a bit later.

The energy levels may be characterized by different labels corresponding to different mechanisms, but they have the same value and then we say that degeneracy is 2 or 3 or so on. In a non degenerate system when we say that we have a non degenerate system. So, non degenerate system all g i is equal to 1. So, in a non degenerate system g i is equal to 1 otherwise you have to have the degeneracy factor g i.

So, in this course I will consider only non degenerate systems simply because otherwise everywhere we will have a g i factor extra in the analysis. And therefore, I will drop the gi and say that we will consider a non degenerate system for which g i is equal to 1. Now, for a non degenerate system therefore, this means P of E i is equal to this implies the number of atoms N of E i that is N 1 for example, N 1of E 1 is proportional to e to the power minus E 1 by kT.

It is proportional because it is proportional the number of atoms at a given level is proportional to the occupation probability g i is 1. So, it is proportional to the occupation probability and this proportionality constant is written as N 0 this depends on the atomic system. Therefore, we have number of atoms in level 1 per unit volume N 1 of E 1 is equal to N 0 into e to the power minus E 1 by kT.

Similarly, the number of atoms in level E 2 is equal to N 0 into e to the power minus E 2 by kT and therefore, N 1 by N 2 is equal to e to the power E 2 minus E 1 by KT. What does this mean, what is E 2 minus E 1? E 2 minus E 1 is the energy difference here. So, we have N 1 number of atoms here N 2 number of atoms here and it is shown that N 1 of E 1 by N 2 of E 2 is equal to this.

If we take for example, N 1 in a particular example if E 2 minus E 1. So, for example, if E 2 minus E 1 is equal to 1 eV, then we have N 1 by N 2 is equal to e to the power 1 eV divided by kT; kT is also a unit of energy which is in terms of electron volts. And then if we take kT for room temperature at room temperature kT is approximately 0.025 eV.

I will show this in a slide later next slide, kT is equal to this then we get N 1 by N 2 is equal to e to the power of 40, that is 1 divided by 0.025. So, 1 divided by 0.025. So, this is 40. And that is why we have e power 40 here. So, e power 40 which is approximately 0.23 into 10 to the power of 18. What is this? This is the ratio of N 1 to N 2. N 1 by N 2 is of this order.

It means N 1 is much much greater than N 2 this numbers I have used to give an idea that if you have two energy levels E1 and E2 with occupation numbers of N 1 and N 2 what is the kind of numbers that we are talking of? N 1 here in the lower level is much much greater than N 2 and the difference is exponential that is what is indicated by this number alright let us see further.

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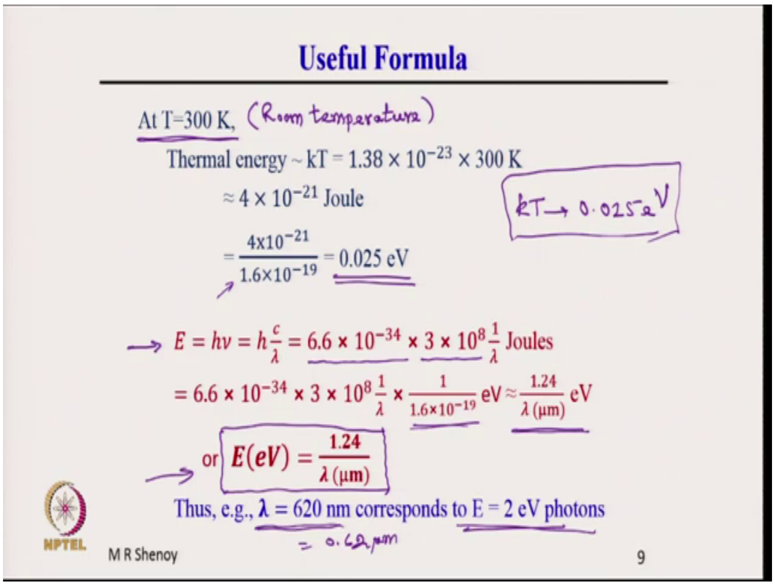

So, here it is what I mentioned at 300 K that is usually room temperature means we take the absolute temperature as 300 K. So, this is room temperature. So, whenever in any question if you have room temperature assume that T is equal to 300 K temperature room temperature. The thermal energy is given by kT. So, k is the Boltzmann constant this is 1.38 into 10 to the power of minus 23 Joules per Kelvin and T is 300K.

So, we have 4 into 10 to the power of minus 21 Joule this is. So, we this is a very very small number in terms of Joule and that is why we convert it to a convenient number which is electron volt. So, you divide by the charge of one electron which is 1.6 into 10 to the power of minus 19 coulombs and you get 0.25. Therefore, for all practical purposes actually the correct calculation if you make it will come out to be 256 or 259 something like that.

But we in this course we will take room temperature kT means please assume 0.025 eV you do not need to calculate this if in numericals or quiz questions etcetera. If kT is to be used please use the value of kT as 0.025 electron volts alright. The other thing which I wanted to show here is E, E is equal to h nu which is equal to h c by lambda h is the Planck's constant.

So, Planck's constant value is 6.6 into 10 to the power of minus 34 Joule second and c is the velocity of light 3 into 10 to the power of 8 meters per second into 1 by lambda so many Joules because this is Joules per second. So, we have so many Joules. Now, if you simplify this we want to convert this again to electron volts. So, we divide by this just as in this case. So, divide by this to convert into electron volt you will get that E is equal to 1.24 by lambda micrometers.

Or this is another formula which you freely use in this course that E in electron volt is equal to 1.24 divided by lambda in micrometers. Thus for example, if you take lambda is equal to 620 nanometer; lambda is equal to 620 nanometer means this is 0.62. So, 0.62 micrometers and therefore, 1.24 by 0.62 micrometer gives you E is equal to 2 eV.

So, photons of energy E is equal to h nu is equal to 2 eV correspond to a wavelength of lambda is equal to 620 nanometer. So, these two formulae are very useful kT is equal to this assume this in all calculations and similarly use this E in eV is equal to 1.24 by lambda that lambda should be is substituted in micrometer alright.

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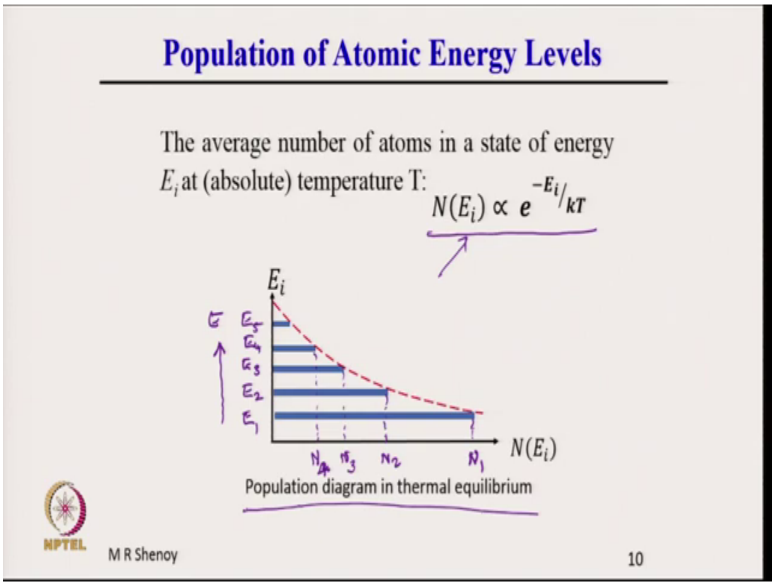

Now, finally, we come again come back to the population. So, population of atomic energy levels we have already shown that N is proportional to the occupation probability that is P of E i which is equal to e to the power of minus E i by kT.

So, that is exactly what I had written two slides back here N of E 1 is proportional to e to the power minus E 1 by kT. So, here N of E i is equal to this therefore, if we wish to plot a variation qualitative variation of the population. So, population what does this mean? So, if I mark this as E 1, E 2, E 3, E 4 and E 5 levels, then the number here N this is N of E i this number is N 1 number of atoms, this number is N 2 here, this number is N 3.

So, this such a diagram is called the population diagram N 4 and N 5. So, this is called the population diagram. In thermal equilibrium the population diagram shows that the number of atoms exponentially decrease, it is decreasing if you go in this direction as energy increases as this is energy increasing and therefore, we see that the number of atoms exponentially decrease the variation is exponential that is because of this formula here N of E i is proportional to e to the power of minus E i by kT. Now, this is such a diagram is called population diagram.

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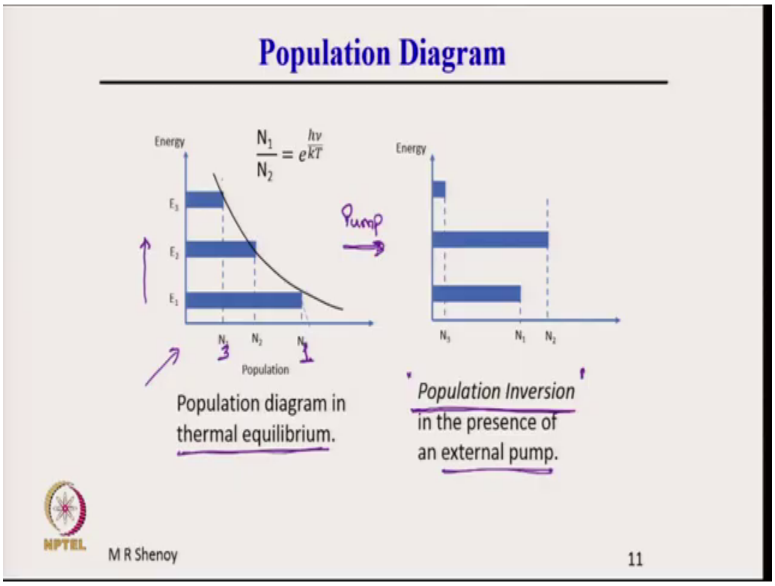

So, let us see the population diagram. If we take an atomic system then in thermal equilibrium. So, in thermal equilibrium we will always have a population diagram which drops down exponentially like this or as you increase oh these numbers are not correct here. So, this is N 3 this is N 2 and this is N 1. E 1 has energy N 1.

So, this is N 1, N 2, N 3. So, as the energy increases in this direction the numbers drop, the dependence is exponential this is the population diagram. Why do I draw this? I draw this because there is an important term which is called population inversion in laser physics. So, population inversion as we will see later is the necessary condition for amplification by stimulated emission.

We will see in subsequent lectures that population inversion is the necessary condition for amplification. What is illustrated in this diagram here is population inversion that is normally it is like this what is shown in the left, but if you pump appropriately in a suitable medium not in every medium. If you choose certain atomic systems or certain media and pump it with a suitable pump it is possible to create a situation where N 2 is greater than N 1.

And such a situation when created is called population inversion which is possible in the presence of an external pump; external pumping mechanism. And we will see that this would be required to achieve amplification by stimulated emission and that is why I have shown these population diagrams. So, we will stop here for the day and then we will take up the amplification conditions in the next class.

Thank you.