Techniques of Materials Characterization
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Lecture - 42
Continuous and Characteristics X-ray Spectrum

Welcome everyone to this NPTEL online certification course on techniques of materials characterization. We are in module 9 and we are discussing about x-ray diffraction, in fact we just started in the last class and we were continuing about a little few lectures, few topics from scanning electron microscopy and then we just started about the x-ray diffraction and history of x-ray.

How x-ray was discovered and how what is the present status at this moment? And then we just started discussing about the discovery of Braggs law and how it is becoming so important. Today we will be discussing about continuous and characteristic x-ray spectrum.

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Basically, how the x-rays are generated? So, we will discuss about the electromagnetic radiations in general first and then we will move on to discuss about continuous x-ray spectrum and characteristic x-ray radiation.

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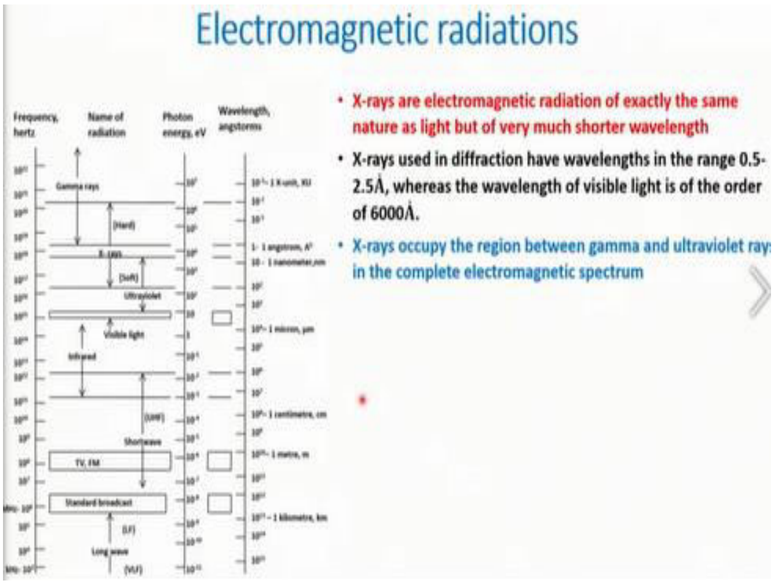

So, the electromagnetic radiation, as the name suggest obviously it has an electrical component and a magnetic component. And x-rays are electromagnetic radiation and they are exactly of the same nature as light but with a much shorter wavelength. So, x-rays that we use for diffraction experiments, particularly for diffraction experiment these have a wavelength in the range of 0.5 to 2.5 angstrom.

And whereas the light the wavelength of the visible light is of the order of around 6000 angstrom that is 600 nanometre we are talking. So, this is like on an average the lower side of the visible light spectrum and the highest side of course close to the ultraviolet we have the higher side there we have something like 200 nanometre or 2000 angstrom and so on. So, if we look at this x-ray this electromagnetic radiation this complete spectrum of electromagnetic radiation.

X-rays are lying somewhere between the ultraviolet and the gamma rays so it is actually having an overlap with the gamma rays. And there are two types of x-ray signals that is generally used. It is a quite a broad spectrum one is called the hard x-ray and that is generally used for the diffraction experiment or scientific instruments that is the hard x-ray that is used and the x-rays which are used for medical purposes.

For example, we discussed in the last one radiographs for capturing radiographs of our more sophisticated techniques these days is the computerized tomography so for that we use something called soft x-ray. The difference is basically the wavelength and of course the energy as well. The softer x-rays are not harmful to the human body up to an extent definitely with I should must put a statutory warning in here.

That it is up to a level up to a particular dose it is not really harmful to human body but that values person to person definitely but the hard x-rays definitely are harmful to human body and that is why in scientific instruments we should not be going close to it when the operation is running. Because that can harm that x-ray radiation can be harmful to human body. So, do not think that it is the same x-ray machines that you see possibly in a hospital.

The same extra machine you are when you see it in a lab, for a scientific research it is not the same thing. Basically, particularly the difference is this wavelength and correspondingly the energy but the point is x-rays are also electromagnetic radiation in the spectrum. And they are having a shorter wavelength than and higher energy correspondingly higher energy also than the visible lights.

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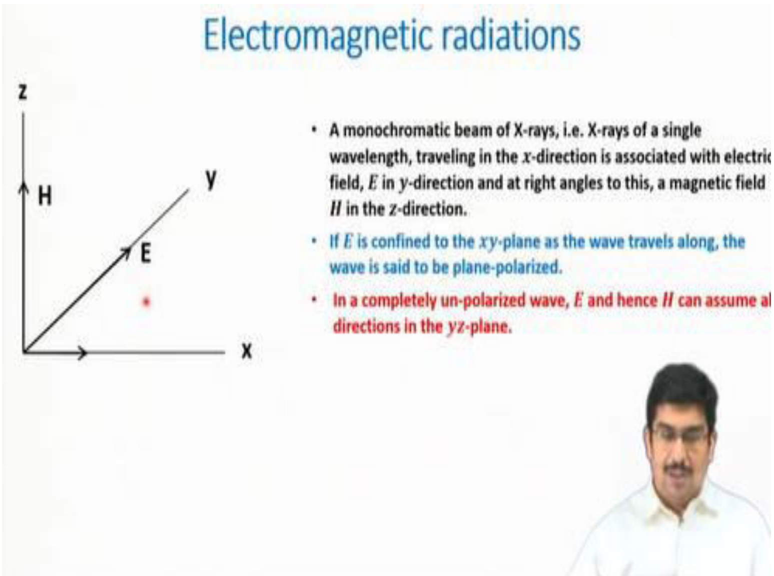

Now any electromagnetic radiation basically can be expressed in this form. That is if we have a monochromatic x-ray monochromatic means something that we already discussed something as electromagnetic radiation which has the same wavelength which has a one particular wavelength and that is called the monochromatic beam. So, any monochromatic x-ray beam that of single wavelength.

And if it is travelling in this x direction imagine that the direction of travel is in x direction then we can imagine that it is associated since it is an electromagnetic radiation it is associated with a electric field E in the y direction perpendicular to this here and there will be right angle to it there will be a magnetic field that that is working in the z direction. So, if E is in the y direction, then 90 degree to it the magnetic field will be working in the z direction.

The point is if E is confined to the x-y plane as the wave is travelling along the x direction if the magnetic field or if the electric field vector is always confined within the x-y plane, then this wave is called plane polarized wave. So, this is kind of polarized wave, the polarized wave if you remember we also discussed during in the optical microscopy part where we were discussing about the polarized light there, we discussed the same thing.

This exactly the same so this plane polarized here at least in for case of x-ray the plane polarization means this electric field vector will be confined to the x-y plane if the movement is in the x direction. And if it is an unpolarised wave then the E that is the electric field vector and correspondingly the magnetic field vector because magnetic field vector has to be in a right angle to this electric field vector.

So, the magnetic field vector and electric field vector can be on any direction in the y-z plane. That means in within this plane the E and H can be of any direction with respect to this x they were not confined E is not confined only within the x-y plane that means in that case H will not be at right angle or H will not be on the z direction any longer. So, that is called unpolarised and the previous case it is called plane polarized electromagnetic radiation.

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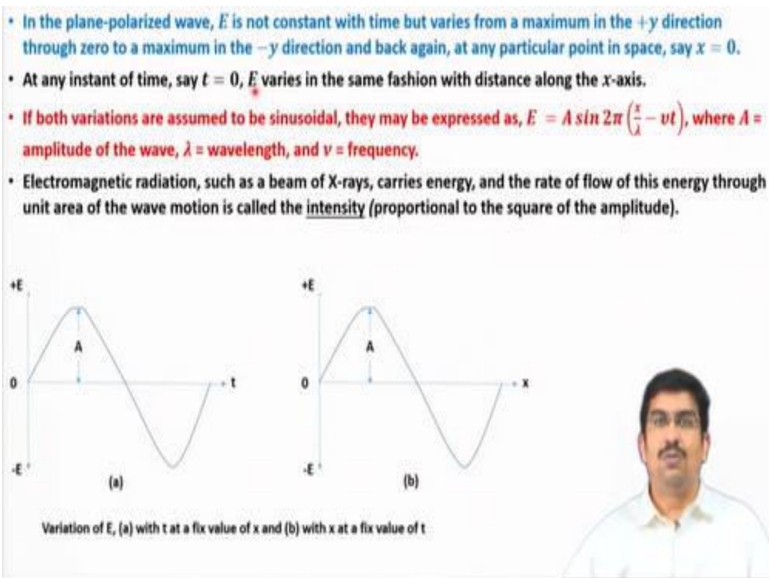

These two are quite important for us to consider. Now if we take one such plane polarized wave and consider the electric field this E is not constant with time, so E varies with time the electric field vector varies with time. And it goes through a maximum in the y direction and then comes back to zero and then goes to minimum again another maximum in the minus y (-y) direction.

So, one maximum it goes in the +y direction one in the -y direction at any given point of x. So, at any given point x the y the electric field vector has a variation almost like a sinusoidal variation with respect to the time. Similar thing happens that means the electric field vector has a sinusoidal variation with respect to the distance for any given time for any particular t = 0 or any given particular t it also varies with respect to the distance.

That it travels the sinusoidal distance again it goes through a maximum in the + x direction. And then it goes to a minimum in the -y direction. So, in both variation if we assume the both of these variations is sinusoidal then what we can write is for electric field vector E we can write it as a where A is the amplitude of this variation A sine 2 pi (x by lambda - nu t), where A is basically amplitude, lambda is the wavelength of this variation of the sinusoidal wave and nu is definitely the frequency.

So, this is basically their equation that is or this is the characteristic equation of this electromagnetic radiation in terms of electric field vector. And the electromagnetic radiation for this kind like for example x-ray that carries an energy and the intensity of this energy which is proportional to the square of the amplitude. Again, the intensity of the x-ray beam or rather the which is a measure of the energy of the x-ray beam as well.

And it is proportional to the square of amplitude this is expressed as the rate of flow of energy through unit area of wave motion. So, in the x direction if the wave is propagating through in the x direction, then an unit area placed perpendicular to this x direction that amount of energy that flows within a given time. Within a unit time through a unit area the amount of energy that flows.

That is the measure of intensity for the electromagnetic radiation and x-ray is being an electromagnetic radiation this is the same thing here. So, these are the important things we must remember about electromagnetic radiation electric field vector and intensity and so on.

So, any electromagnetic radiation will have and wavelength will have a frequency and will have a particular energy. And that is what you are able to see here.

There are 3 different things in the electromagnetic spectrum there are 3 different things. One is the frequency one is the energy photon energy or each quantum of energy and then the wavelength of this and wavelength as we know frequency and wavelength is inversely related basically. So, x-rays also will have these three characteristics, features that is it will have a frequency it will have a certain particular energy and a certain particular lambda which are all three are related.

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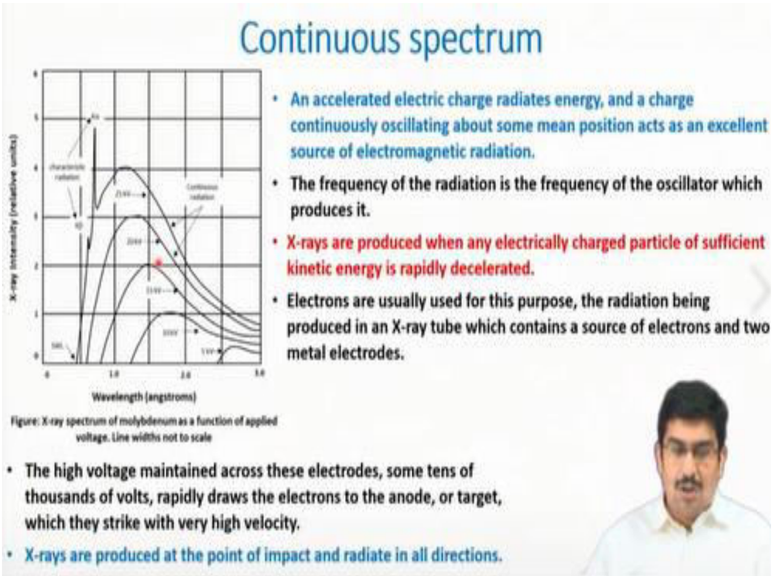

So, now let us discuss about something called continuous spectrum. And before doing that we have to understand how we can generate an electromagnetic wave. So, the most easiest way of generating an electromagnetic wave is basically to think of an accelerated electric charge. So, any accelerated electric charge it radiates energy and if the charge is continuously oscillating between about some mean position.

Then that will emit an electromagnetic radiation. So, accelerated electric charge continuously oscillating about some mean position that can emit an electromagnetic radiation and this is exactly how a radio waves are generated from an antenna basically they are also it is a accelerated charge which is continuously oscillating between mean position. So, that is what is electromagnetic and it is radio waves and similarly visible lights also the same thing happens.

That basically the electrons are or atoms are vibrating about their mean position and if they are charged particles if we consider them the charged particles then they are constantly vibrating about their mean position and in that way, they will emit a electromagnetic radiation. So, that is how the visible lights the light emitting materials are working in some sense. But this is one of the way; that electromagnetic radiations are generated.

And what happens is that the frequency of that electromagnetic radiation is basically equivalent or equal to the frequency of the oscillator which is producing. So, this charge particle that frequency at which it is oscillating within its mean position the electromagnetic radiation that emits from the charged particle will have exactly the same wavelength or exactly the same frequency and in turn exactly the same wavelength.

Now x-ray signals or x-rays are typically produced when an electrically charged particles of sufficient kinetic energy is rapidly deaccelerated. So, what happens is that you have some charged particles accelerated charged particles you have and that accelerated charged particle is rapidly deaccelerated, then that energy is emitted as x-ray. So, the same thing happens there also the accelerated charge particles.

And then it makes to oscillate about in mean position by through this deacceleration, it emits or it oscillates with its mean position. And then suddenly deacceleration happens and that amount that energy of that charged particle will now create and or will be transferred to an electromagnetic radiation. And the frequency of this electromagnetic radiation or this x-ray that is generated from this charged particle will be exactly the same at the frequency.

At which this charge particle is deaccelerated, that is how x-rays are generated. So, in a generation of x-ray the charged particles; as a charged particle electrons are usually used for this purpose and the radiation is produced in a x-ray tube which basically contains a source of electron that means a cathode and a metal electrode and anode. So, it is accelerated so pretty much similar to the configuration like an electron gun what we discussed previously.

This also has a filament which generates basically which works like a cathode and it generates the electrons and then those electrons are accelerated at a very high under a very high potential difference the electrons are all accelerated. And then unlike the electron gun what happens is that they are allowed to hit this anode and in the heating process when they heats this anode what happens is that those charge particles or electrons they got deaccelerated.

And in the deacceleration process they emit this x-ray as an electromagnetic radiation. So, that is how it happens that is how the x-rays by enlarge, the x-rays are produced in the extra tube. One cathode which acts as a source of electron these electrons and huge and very high accelerated very high potential difference is created between cathode and anode. So, electrons are accelerated towards the anode.

Then they strike the anode and there they lose their kinetic energy in the form of x-rays. The x-rays are produced at the point of impact and it radiates in all possible direction. So, these x-rays are in 360 degree these x-rays are produced.

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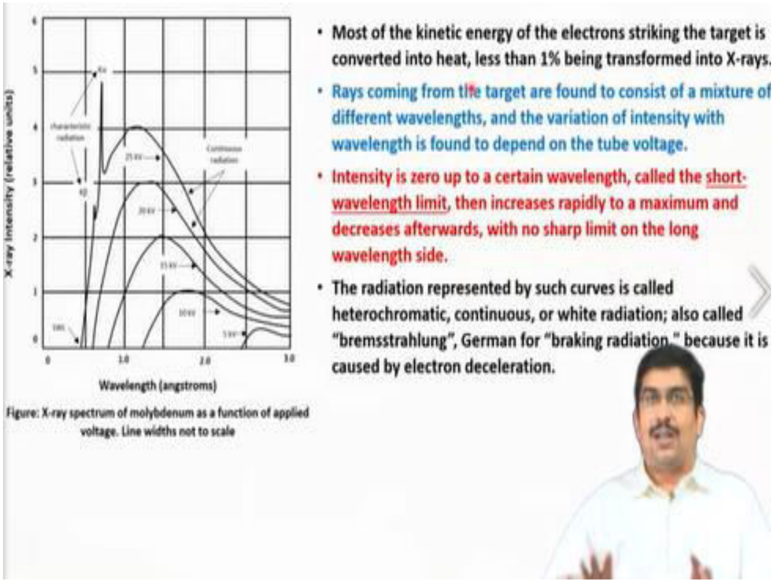

Now what is continuous spectrum? So, continuous spectrum is basically when the electrons are stopped and these x-rays are produced. So, this is the kind of diagram that we get if we consider the wavelength versus the intensity of the x-ray that is produced in this process, that means electrons accelerated by a huge potential difference and then electrons are strongly they are hitting the anode they stop there and then producing this x-ray signal.

So, in this in this method if we then the x-rays that is produced if we collect those x-rays then we will see that with wavelength they have a huge variation in their intensity. That means the energy of the x-rays varies with the wavelength. So, they all possible wavelengths are there in the spectrum and all possible and all this at a particular given wavelength it has difference in the intensity.

The different wavelength or x-rays that is produced with different wavelength they have very different intensity in this. So, this entire thing is called the continuous spectrum. So, before understanding this spectrum we have to understand one thing that most of this kinetic energy of these electrons basically striking the target is converted into heat and only a very few only a fraction small fraction of this kinetic energy is basically transformed into x-ray.

Typically, 1% less than or even less than 1% of this energy of the incoming electrons are transformed to x-ray. So, heating of the anode is a very big issue in the x-ray tube and that requires a huge amount of cooling of that anode. Because most of the; electrons which hits the anode finally give up their kinetic energy as a heat. So, that we must remember. So, now the rays the x-rays which are coming out from the target.

They are having all forms of wavelength they are having very a mixture of different wavelength and a variation of intensity with the wavelength which depends on again the tube voltage. Tube voltage means the acceleration voltage. So, this relationship between wavelength and the x-ray intensity that also depends on the tube voltage. So, what happens first is that if we go from zero in the wavelength then up to a certain intensity or up to a certain wavelength.

We will see there is no x-ray generation at all. So, there is no intensity for the x-rays, only after a certain finite wavelength that these x-rays are started producing. And then the extra intensity of the x-ray increases very steadily with increasing wavelength. That reaches to a final maximum and then again it decreases but in this decreasing side there is no end this curve literally never touches the zero line again.

So, wavelength even at if we go at a very high wavelength intensity is never zero. But in the shorter side here the intensity up to certain wavelength intensity is zero. So, the intensity up to which or wavelength up to which the intensity of this x-ray beam is zero that is called the short wavelength limit. And short wavelength limit is that wavelength up to which the intensity is zero and only after that we started getting a measurable intensity of the extra beams was generated.

So, this x-ray radiation generated in this process and represented by this curve is generally called heterochromatic or continuous or white radiation. And the German name for this is bremsstrahlung. That means the breaking radiation because it is caused by the electron deacceleration this continuous spectrum. So, if you find these terms like white radiation or continuous spectrum, they are all interchangeably used.

And all of them basically they are the characteristics of them is a mixture of wavelength so they are not one particular wavelength the x-ray that is present in this white radiation or continuous radiation they have all possible x-rays with a very different intensity. I mean the intensity will vary with the wavelength as well.

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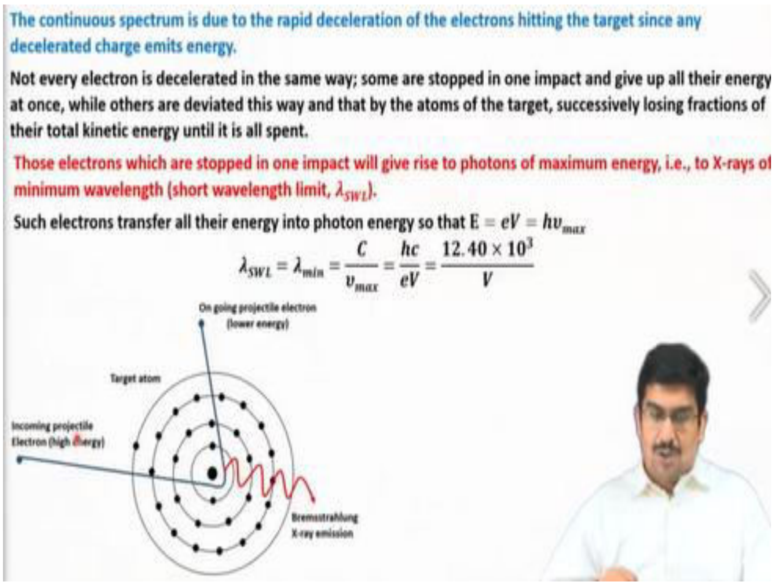

So, now the question is how this continuous spectrum is generated how what makes this continuous spectrum? So, this continuous spectrum as we already discussed is because of the rapid deacceleration of electrons which are hitting the target and this deacceleration. In the deacceleration process basically, the electrons are those charged particles continuously accelerated charged particles continue or suddenly gets deaccelerated they emits the electron.

So, this we understand. Now the point is not every electron is deaccelerated in the same way. So, it is a kind of there is a randomness in the process so there is a finite probability approach is there. So, some of these electrons will stop under one impact. So, the electrons accelerated electron hits the target and hits the target means basically it hits the atoms in the electrons will be hitting the target to metal atom.

So, it hits the atom in one impact it stops it gives all its energies at once. Some other kind of phenomena also we can imagine that the accelerated electrons will be scattered. It will not be transferring all its energy to the specimen or to the metal anode atom. So, it will be like scattering, the kind of scattering processes that we already have studied elastic scattering inelastic scattering and so on.

So, it will not be stopped in one impact it will be giving its energy slowly and in that slow process it will be can be an elastic scattering or it can be an inelastic scattering. But ultimately this will be stopped but before it stops it will release its energy continuously in small steps. So, the electrons which are stopped in one impact will give all its photons all the energies. So, the x-ray that is generated from this electron.

The electrons which are stopped in one instant or in the first blow itself the electron loses all its kinetic energy and it gives that kinetic energy to the x-rays. Those x-rays will have the highest energy and correspondingly those x-rays will have the minimum wavelength. That means those wavelengths those x-rays will be having or those wave x-rays will constitute the short wavelength limit.

So, that means the short wavelength limit continuous spectrum basically is coming up due to this deacceleration process. Deacceleration process is very much stochastic in nature it has a finite probability some electrons are stopping at one blow some electrons are continuously decreasing giving away their energy and producing the x-ray in the process. So, that is why we are having x-rays of all possible wavelengths in the continuous spectrum with different, different intensity.

Because of this stochastic nature of the process itself or this process is not in one. So, that is the reason we are getting this continuous spectrum generation. The short wavelength limit on the other hand is a special one and that is generated by the electrons which are giving away all their energy in one impact. And that is why those x-rays are of maximum intensity or that is those x-rays are of minimum wavelength.

So, if we now try to calculate what should be the short wavelength limit. So, we know that those electrons such electrons transfer all their energy into the photon. So, the energy of this photon $E = eV$, E is the charge of the electrons and V is the accelerating voltage under which these electrons are travelling. And that we can equate it with h nu max, h nu is again the energy of the x-rays that is coming out, h is the Planck's constant, mu is the frequency of those that x-ray beam.

So, we can write this lambda SWL that is lambda short wavelength limit equals lambda minimum that is the minimum one. So, and that is obviously by virtue of this relationship between the frequency and the wavelength. So, this is some constant here the constant is C that is the speed of the light and this by nu max that means we can write hc by eV. Lambda SWL = hc by eV.

And when we put all of these values like hc and E we get a relationship between the accelerating voltage or tube voltage we get this relationship. The relationship between short wavelength limit, lambda SWL and the accelerating voltage.

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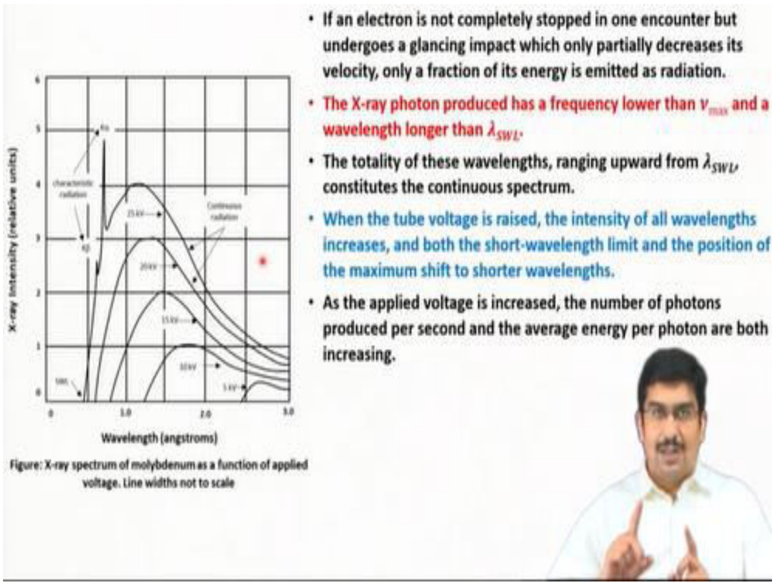

So, this is very important relationship to understand the variation or to understand this curve again. Now, so this says that basically what if we increase this accelerating voltage and it is shown here for a molybdenum anode, molybdenum target or molybdenum anode and now if we consider that this, so all of these are basically showing at different, different tube voltage this continuous spectrum curves we have collected.

So, all of these are showing and lambda SWL but that lambda SWL is varying with tube voltage and as we understand that it is inversely related. So, basically what is happening if I use a smaller voltage the lambda SWL is larger that means lambda SWL is a happening at a up to a much larger wavelength there is no measurable x-ray intensity. If we increase the tube voltage then lambda SWL is shifting towards left.

That means lambda SWL is shifting to a smaller and smaller wavelength value. That is the kind of relationship we have. Now what is happening here? So, as we already said that electrons not completely stopped in one encounter but it is going through undergoing this glancing impact and then in that is producing these x-rays of continuous spectrum. And definitely then those x-rays which are produced by such electrons which are continuously going through scattering elastic and inelastic interaction.

They will produce x-rays with a lower frequency and a longer wavelength. And these will constitute the continuous spectrum and when tube voltage is raised that is what is happening, we have already discussed that. This intensity or our first effect that it will have when we increase the tube voltage that it will shift the lambda SWL towards the left at a shorter wavelength. And second thing what it will do increasing the tube voltage is that.

It will increase the intensity of all the beams. That means at any given any particular wavelength if we consider if we increase the tube voltage then that will increase the intensity of the corresponding x-ray beam and that is again it is easy to understand that means the electrons increasing the tube voltage means we are now the electrons are carrying more amount of energy.

So, when that electron those electrons are now able to generate a far intense x-ray beam of different wavelengths. All the wavelengths are changing but like the energies of the electrons are also correspondingly changing that means the intensity of the electrons at a given wavelength will increase as the tube voltage is increased. So, these are the 2 things that the tube voltage is causing towards this electron or towards this x-ray that is generated.

Or this tube voltage if the tube voltage is raised the intensity of all wavelength increases and the short wavelength shifting to the lower side. Also, one more thing will happen that means the maximum in the continuous spectrum. So, up to this limit this is the maximum in the continuous spectrum the maximum will also shift towards lower and lower wavelength because the electrons are now carrying more amount of energy.

And that means the x-rays that is produced they will also have much higher or much higher energy and the maximum x-rays. That means these are possibly so these are these are the kind of electrons which are stopped may not be within one impact but may be within 2, 3, 4, 5 impact, very few impacts. And then since they are carrying more energy now the x-rays that is produced will also have correspondingly higher energy.

And that will be reflected in number in their shorter wavelength. So, the maximum will shift to shorter wavelength. The lambda SWL will shift to shorter wavelength and the intensity of the extreme that is produced or the number of extra photons that is produced will also be much higher if the tube voltage is increased, applied voltage is increased.

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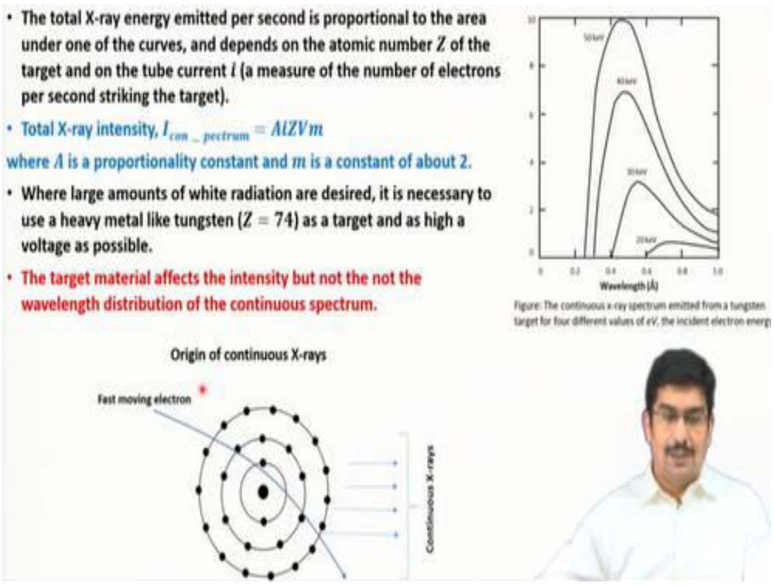

Now the total x-ray energy emitted per second in this process this in the continuous spectrum. So, when we are getting the continuous spectrum, the electrons are getting accelerated electrons are deaccelerated. So, in the process the x-ray energy that is emitted per second this is proportional to the area under any one of the curves. So, this continuous spectrum curve if we integrate this curve, we will get the x-ray energy total extra energy emitted per second.

This total extra energy will depend on the atomic number of the target metal that is used and also the tube current. Tube current means the number of basically the number of electrons that is hitting the striking. So, it will depend on two things, number one is the atomic number of this metal atom. Because that atomic number; basically is responsible for stopping the electron.

So, if we have a heavier metal let us say if we have a tungsten in comparison to a lighter metal. Then the tungsten since it is a heavier metal it has a very heavy positive nucleus it will be effective in stopping the electrons or in other way the if it is not stopped under one impact if it is undergoing some elastic and inelastic interaction. Then a heavier electron or heavier nucleus or heavier atom will be able to extract more amount of energy from this interaction from individual interaction.

It will able to extract more amount of energy. So, that means this will the atomic number will also depends and this extraction of energy is the source of electron. Source of the x-ray generation. So, x-ray energy will also depend on the atomic number of the target atom because of this philosophy. And it will also depend definitely it will also depend on the how many number of such electrons are hitting the target.

So, if we increase the number of electrons in the beam that means more and more electrons are coming and hitting. The target more and more x-ray signals will also be produced. So, finally the intensity of this continuous spectrum that we can relate it to this AiZVm, where A is a proportionality constant, m is another constant of about 2. The variables here is i, Z and V, V is again the accelerating voltage, i is the current.

And current means total number of electrons heating and Z is the atomic number of the element. So, from this what we can understand that is the as an anode material we need to have an heavy metal as heavy as possible. And usually tungsten is used for this, sometimes we can have target metal as a tungsten or moly or that kind of metals are used as a target metal.

And also, another important point as we already discussed most of the energy is going here as a heat that means that target metal also should have a very high melting point. So, from both of this perspective both of this consideration moly or tungsten are better choice as a anode material here. But one thing is important that this target material affects the intensity but it does not change the wavelength distribution in the continuous spectrum.

So, that means if I use a tungsten here, if this is a moly and this is a tungsten. So, they will have their own characteristic spectrum or continuous spectrum. That means they will have their very typical relationship between the x-ray intensity and the wavelength and that is very much characteristic of the anode element which is used. This can be changed definitely; the shape of these curves will change due to the tube current.

If I increase the tube current this all of these curves will be coming towards the left. But this typical shape of the curve will not change unless I change the target anode material.

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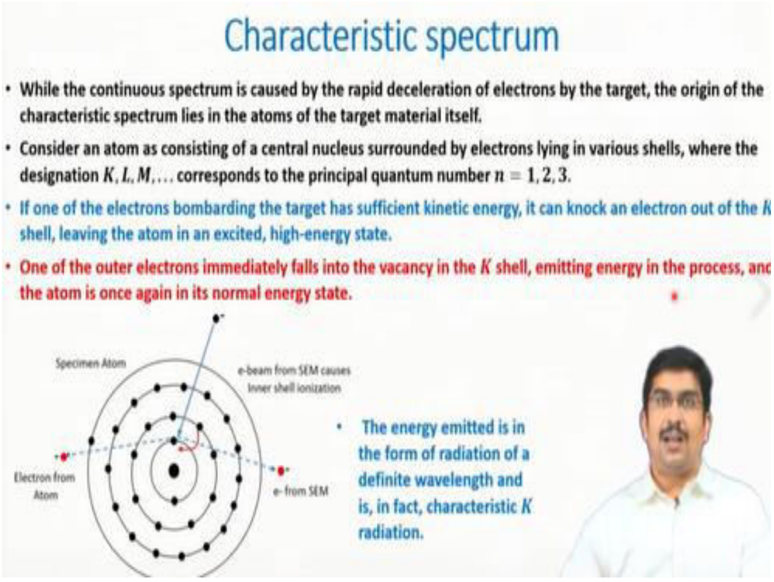

That is what it is. So, we will stop here and we will continue with this characteristic spectrum in the next class.