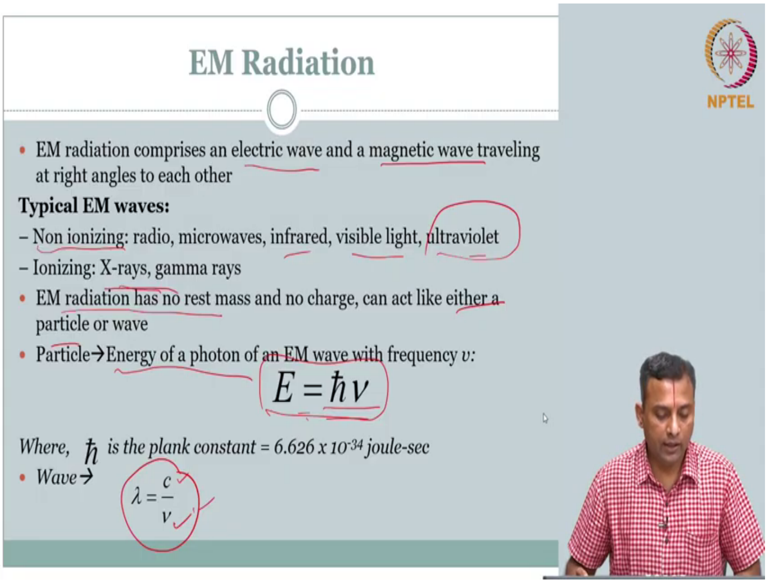
Introduction to Biomedical Imaging Systems
Dr. Arun K. Thittai
Department of Applied Mechanics
Indian Institute of Technology, Madras

Lecture - 12
EM Radiation

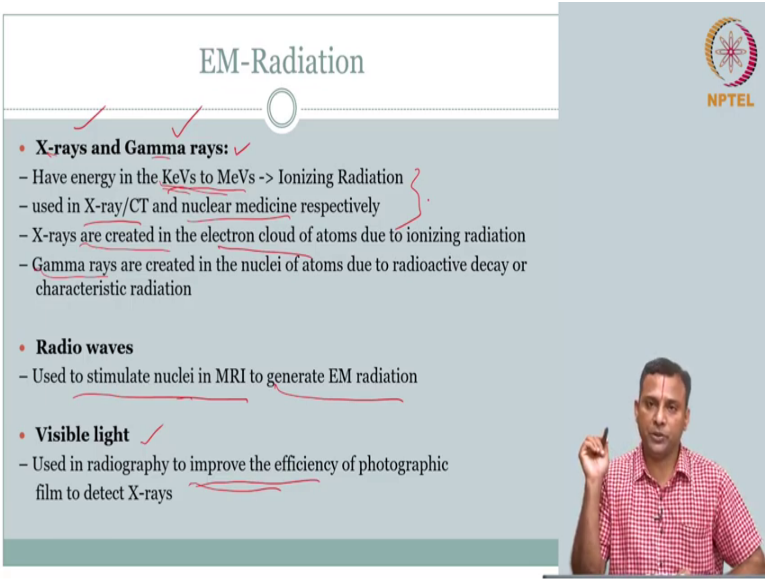
(Refer Slide Time: 00:17)



Before we proceed ahead with understanding the type of interaction that a electromagnetic radiation has with the material, let us quickly recognize you know we had this chart or the or this figure that showed the whole range of electromagnetic spectrum you know and some aspect of where it can be used was listed there, but it does not hurt us to just review one more time.

In the spectrum actually you see that we are in this specific ahmedical imaging systems, right in this particular course or this area what part of electromagnetic spectrum is used, and you will see that it is actually exploiting you know from your radio frequency wave to high energy right you have gamma, ok.

(Refer Slide Time: 01:11)



So, let us quickly look at that one more time before we start to talk about the interactions and that is there is a reason why I wanted do this because first and foremost the X-rays and gamma rays right if you look at the electromagnetic spectrum right. After the visible light as the energy increases you see that we will exploit X-rays and gamma rays in the modalities of X-ray CT in the first part and then later in the nuclear medicine right. So, we will use X rays and gamma rays.

So, these are high energy in kilo electron volts to mega electron volts and these are ionizing radiation. So, that is the reason we said we could think about the imaging medical imaging systems as based on ionizing or non ionizing, right. Non-ionizing we talked about MRI and ultrasound remember.

So, now, ok so, that high energy part the ionizing part we know where we are going to use and then on the lower side if you see you have your radio waves right which modality uses radio waves right imaging system. Well, radio waves are used in MRI. We said that it is MRI is to do with some magnetic resonance, what does radio frequency right radio waves have why is it used?

Well, it turns out to stimulate the nuclei right to spin one way and then to record the response. So, when you stimulate it, you again get another electromagnet. So, you get another radio frequency. So, radio frequency is heavily used in MRI both to stimulate and receive the response, ok.

Then of course, visible light visible light I mean apart from the intuitive thing right medical imaging system you want some radiologist or a practicing doctor to look at the image. So, you know visible light as useful right it is used in medical. In fact, all the modality, all the energy, all the different imaging system in the end your output is going to be in a visible range, right.

But, beyond that what do we mean? We mean that it is actually used when you have again recall what Roentgen did, right. He named it as X-rays because there was mysterious rays that were coming. He was working with Crookes tube and. So, he notice that the photographic film actually got spoiled due to some mysterious ray. So, he named it as X-rays. So, clearly X-ray can spoil a photography film.

But, to capture X-rays; that means, to detect X-rays you know by itself it is inefficient and therefore, in order to improve the efficiency you will exploit the visible light photons ok photons in the visible light region. So, we will ok so so much is clear. So, you can actually look at the different variety of electromagnetic radiation that will be involved that will have interaction with the body ok.

One thing to appreciate before we jump in, therefore, if you look at this from tick strict point of electromagnetic radiation interaction with body, right it does not really matter whether it is KE you know whether it is X-rays or gamma rays. Both are ionizing, both have higher energy here.

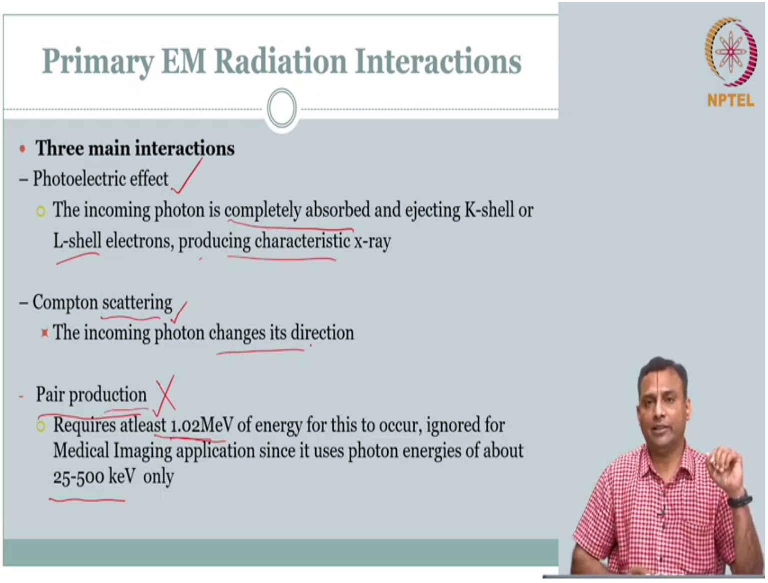
So, from the point of view of if you have to understand the interaction of the energies which is in this range with the tissue probably that is fine, there is not much distinction, but where the distinction between the different modality comes into picture is the origin of this energy.

So, in X-rays where is the origin we just saw right Bremsstrahlung and characteristic whereas, gamma is due to so, or in other words it is from the electron cloud where as gamma rays comes from the nuclear radioactivity from the nucleus remember. So, the point of origin is different for both the signals both the energies that is the difference. Otherwise their interaction is nothing, but it is a photon with that energy it is going to interact the material ok.

So, the creation is the difference. How you get this X-ray how you generate this X-ray how you generate gamma rays that is different, but once it is generated how it interacts with the body the ionization all that whatever we are going to cover now for X-ray specifically most of it can be borrowed right similar interaction happens for gamma rays as well.

So, we will differ gamma rays and the details of that when we get a nuclear medicine. For now we will talk about X-ray interaction with the tissue because that is what is important for us ok.

(Refer Slide Time: 06:36)



So, what are the I mean there are several levels of interactions you could talk about broadly there are three interactions of interest like you see here one is photoelectric another is Compton scattering all of these are you know we will go into the details. And, then there is pair production. So, these are some of the common three main types of interactions. In in fact, going forward we will rule out rule out the last one.

Pair production. So, these are all interaction of electromagnetic radiation with material. So, you will have pair production, but to have pair production it requires high energy; requires at least 1.02 mega electric volt. So, this one given that we are going to deal with our x-ray imaging system or even you know gamma rays we are not going to really go beyond this range like kilo electron volts hundreds of kilo electron volts.

And, therefore, for our purposes right for practical purposes in medical imaging we will not be bothered about pair production. Therefore, we will not cover this anymore. This is just for the completeness there are three types of interactions, for biomedical application we do not really worry about pair production. We just leave it at this stage and say that is not going to be encountered because of the high energy of the incident photon that is needed, ok.

So, now we will jump into the two other things. What is photoelectric effect, right? In some sense before because there are going to be several key names, unique names that come out right, but before you get that if you really look at it what we have covered right what we covered is particulate interaction with the material.

So, there we talked about roughly two things: one is the electron kicking out and then characteristic coming in characteristic radiation coming out. The other is the electron with energy goes near the nucleus right, but then it does not get annihilated and changes path reduced energy and that difference in energy comes out as again x-ray Bremsstrahlung radiation.

So, now, what is different? A difference is not a particulate that is carrying energy. Now, you have a photon with that energy. So, what are the guess that we can make already? Material is material. Now, instead of a particle that is coming in I have some energy coming in. So, what can happen? The same energy can do similar thing right the same energy can come in and then perhaps it can knock out the K shell electron, right.

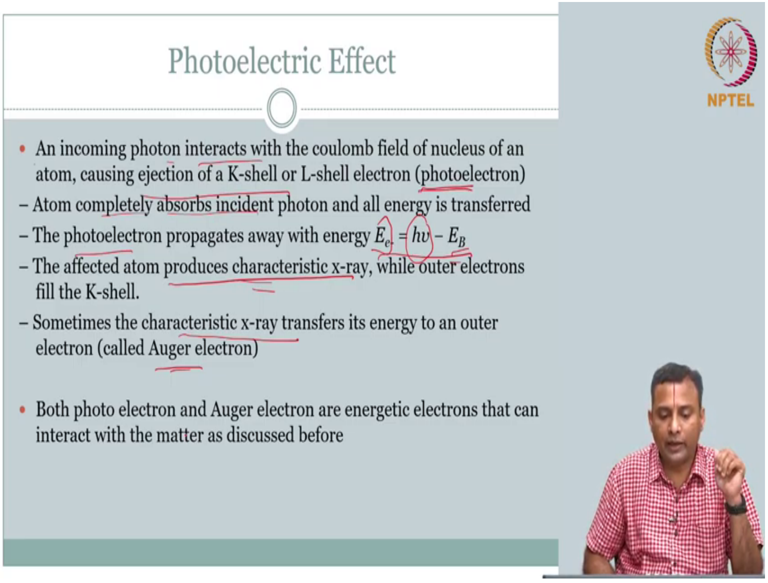
And, then after it excites or ionizes you have characteristic radiation that could that is one possibility. The other possibility is the energy is coming right the photon energy is coming maybe it bumps off the outer it does not really get into the core it just knocks off something right at the outer electron shell.

In which case what will happen? It will just knock that out reduces energy it will just go in a new direction. Intuitively this is very similar to what we did for charged I mean high energy particulate, right electron that is coming and interaction with the matter similar thing happens here.

So, incoming photon in photoelectric effect incoming photon is completely absorbed by the atom, that energy is absorbed and then that energy when atom is absorb that energy if it has greater than the binding energy it will kick the K electron out. When it kicks that or even L and then there is going to be characteristic x-ray produced, again that is a that characteristic x-ray is also going to be a electromagnetic radiation, ok.

But, of obviously, you can guess that it is going to be probably of a lower energy right that much is straightforward. So, if it is Compton scattering as the name suggests at least this name suggests; scatter means directional something to do with bouncing off in different directions that is why the scatter, right. So, the incoming photon changes its direction. So, it loses energy and changes direction.

(Refer Slide Time: 11:26)



So, let us go one step at a time. Let us talk little bit more on the photoelectric effect first and then we will talk about Compton scattering and then try to compare these two and make a final you know take home message of what is favorable, what is unfavorable, what is needed, what we need to maximize, what which effect we need to minimize, all that we will summarize, ok.

So, as we talk just now an incoming photon interacts with the so, think about it this way you have an atom, right. So, it has a core nucleus and then it has electron cloud. h mu comes in that comes in with x-ray energy. When it comes in it interacts with the coulomb field the electrical field that is there electron field that is there when it interacts what that that what does that mean is, it is losing energy. So, in fact, the hole of h mu is absorbed by this atom in this field, ok.

Once that field gets that energy if it has energy greater than the binding energy of K or L shell that electron is going to go out that electron is called as photoelectron because you have photoelectric effect. So, this electron is coming out because of photoelectric effect this electron is called as photoelectron. This photo electron can do what we studied before, right that is a electron which has energy. So, particulate it can go subsequently do whatever interactions we already covered for particulate, right. So, that is one thing.

So, the atom is completely absorbs incident photon and all energy is transferred. So, now, after the photoelectron leaves what will happen? This has to rearrange, right all the electrons now will rearrange because there is a hole in K shell that electron has left. So, there is going to be realignment exactly similar to what we covered already, right.

So, the photon so, rearrangement will take place, but the photon electron right the photo electron that propagates it went with a energy. What is that energy? h mu it came in this is your binding energy. So, whatever is came in minus the binding energy is the energy with which that photoelectron is going out clear.

So, after the effect after that what happens? The effected atom comes back to it is ground state when it tries to comes to it is ground state it releases energy and that energy right is in the x-ray range and we talked about why it is characteristic x-ray right depending on which electron, which shell is migrating and the rearrangement pattern ok. So, that is your characteristic x-ray.

So, now you have of course, characteristic x-ray will also be of lower energy right. So, now, you have both the photoelectron that can go and cause subsequent interaction and x-ray characteristic x-ray that can also interact further clear. So, very similar to what we did in the particulate, right. So, here also what can happen is this characteristic x-ray that is coming out right that characteristic x-ray on its way out from the atom can probably kick out the outermost atom or the or the electron in the outermost shell.

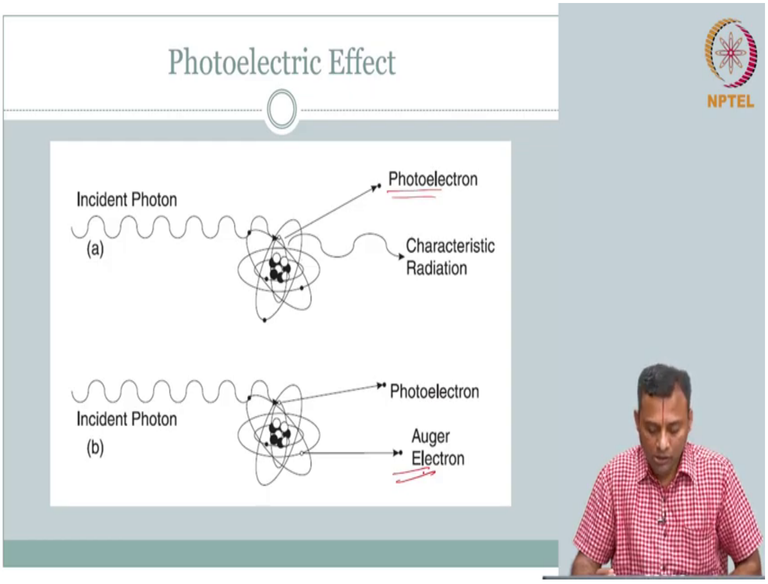
So, you have a characteristic x-ray that is produced in the photoelectric effect that characteristic x-ray energy that is when the photons with that is trying to leave the atom right coming out from the atom it may probably knock of the electron in the outermost shell because outermost shell you know the binding energy is going to be less, right. So, it is going to be weak. So, maybe it has sufficient energy to kick that atom.

So, sometimes the characteristic x-ray transfers this energy to the outer electron. So, what happens then? Then this electron gets that energy and it can move, right. So, it is an electron charged particle right electron that is going to move take some energy with it. So, this kind of electron is called Auger electron.

So, the interaction is going to be same electron with some energy it is going to interact with the material like we discuss. So, whether it is photoelectron or Auger electron their interaction with the material is going to be exactly same as what we already covered with particulate interaction. Only thing is now even when we have a electromagnetic radiation carrying x-ray that is interacting with tissue you can get these particulate radiations. So, here it is called us Auger electron.

So, essentially both Auger electron and photo electrons can interact with the matter in ways that we already covered right, ok. So, that is good. So, now, what we need to do ok photoelectric effect seems to make sense.

(Refer Slide Time: 17:01)

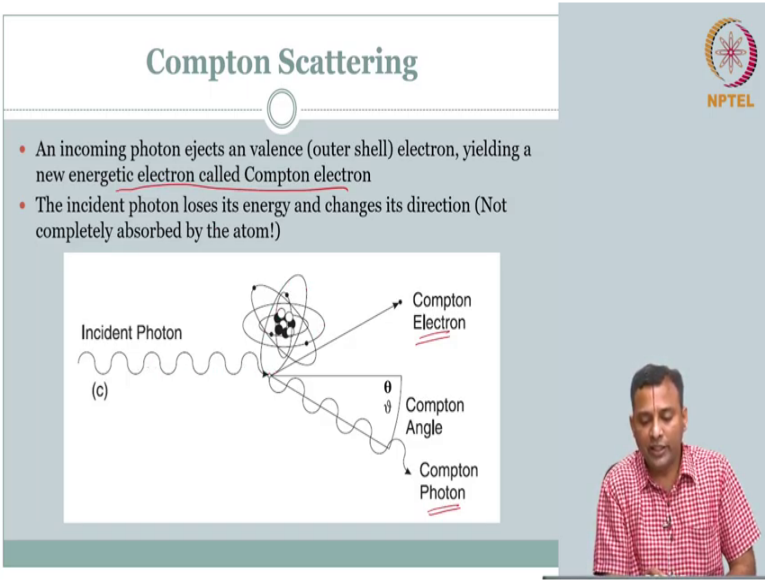


Let us just complete it with a picture. This is kind of a review right texts sometime might be boring. So, just quickly to review. So, you have a incident photon h mu some energy is coming in the X-ray range, this is your nucleus and these are your electron cloud. So, it knocks off, right it basically the full incident photon gets absorbed completely by the atom in this field and then it has enough energy greater than your K shell, then the K electron the electron in the K shell will be knocked out right, but it is given a name called photoelectron because of the process with which this electron was generated.

So, once that happens you know excited state, right this is ionized. So, it will basically now try to come back to ground state by rearrangement of the electrons from outer shell to inner shell and that gives you your characteristic radiation. Similarly, if you have the incident photon exactly do what we did here. So, much is so good, but in addition if this characteristic radiation right when it is coming out if it knocks out another electron on it is way of the same atom in the outer shell, then that election is called as your Auger electron clear.

After that Auger electron or photo electron are nothing, but these are electrons charge particles particulates with some energy that energy it is going to interact with subsequent atoms in the manner that we already covered, clear.

(Refer Slide Time: 18:56)



So, let us use the same sketch right to also talk about the other effect which is Compton scattering. So, here what happens? Incident photon comes, but notice it is not going into the coulomb field, right, does not go close here. But, it so happens that when it comes here it is able to hit a electron, share some energy to that electron and kick that outer electron you know release that outer electron.

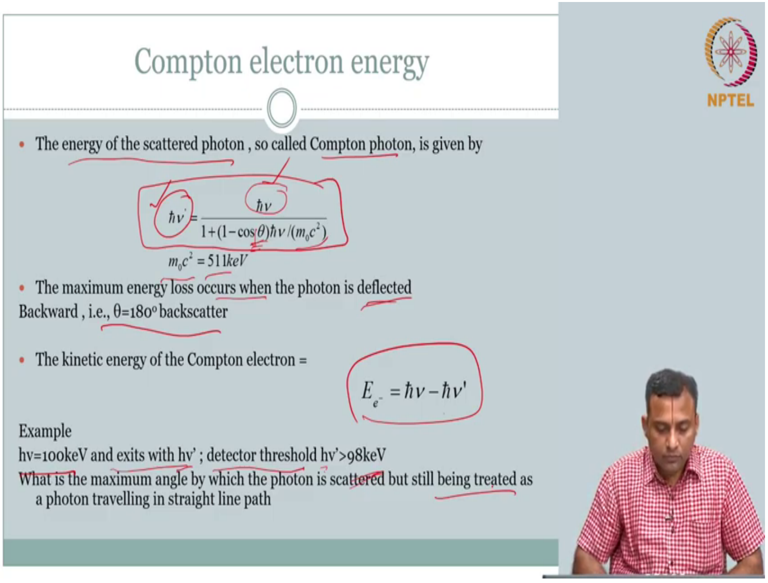
So, when you do that the incident photon loses energy to the Compton electron. So, it is now reduced energy and with reduced energy it after the deflection here right after taking it here with the new energy it reflects, it scatters to a different path. Here in the illustration if this was the original path it is deflected by angle theta and the electron that comes out because of Compton scattering is called as Compton electron.

After that this Compton electron could do the same thing. However, notice that the energy of the Compton electron is going to be small, but from a principle standpoint yes this is a particulate with the energy that can go do subsequent interactions. Likewise here you have Compton photon. What is Compton photon? It is still the photon, but then it is reduced energy due to Compton scattering.

So, Compton photon is the incoming energy that is reduced due to Compton scattering. So, it has lost some energy right in this interactions and it is reduced and it is the different path different angle now ok. So, Compton scattering is an incoming photon ejects a valance or the outer shell electron yielding a new energetic electron called Compton electron.

And, the incident photon is not completely absorbed by the atom. The incident photon with reduced energy it changes direction. So, it does not this is the key it is not completely absorbed by the atom and so, this can essentially go you know from here if the Compton photon has enough energy it can do photoelectric effect, right, it is just that after this it proceeds clear. So, that is for your Compton scattering.

(Refer Slide Time: 21:31)



So, what we would like to do is just before we proceed ahead let us look at this energy. So, because we should Compton scattering it has a new angle and it is reduced energy. So, is there a relationship that we can form between the incoming energy reduced that is your Compton photon energy and the angle at which it is getting reflected, right.

So, the energy of the scattered photon or the so called Compton photon is given by this equation. What do you see here? This is the incoming h mu right incoming photon, it had a h energy h mu; this is your Compton photon energy. Look at how these two are related there is this theta of course, the m not c square you can calculate that is your rest mass of your electron right based on that you can calculate that.

So, if you really look at it we know this energy is going to be less than this energy, but how much less depends on theta, ok. So, intuitively speaking if there is no change in path right then h mu will have h mu dash should be same as h mu right it has there is no interaction taken place it is not lost any energy unchanged path, right; 0 means it is not changed any path; that means, it probably did not interact and therefore, there is no energy lost therefore, you will get the same energy.

So, on a you know so, thinking in that spirit when will it have lost most energy? Look at this you have a 1 minus cos theta. So, it would have lost most energy when we have a backscatter what we call is backscatter 180 degree shift, right. So, when it comes back in the same direction, in that scenario you will have backscatter when you have maximum energy loss, right.

So, maximum energy loss occurs when the photon is deflected I mean it is actually deflected is you know deflected means it is a small angle, but we for explaining this it is like deflected, but the deflection is backwards 180 degree. So, it is essentially a reflection it comes back in the same direction, ok. So, which is call as backscatter 180 degree backscatter.

Why are all these important? We need to know this because in a moment we will actually do that we need to understand which phenomenon is favorable to our task. What is our task? Imaging that is we want to send the X-rays into the body the X-rays will interact with the body and I will receive right the X-rays that are coming out of the body. So, it is through transmission and based on what I am detecting I should comment on what is there inside the body, clear? That is the objective.

So, we need to now quickly understand what is favorable, what phenomenon is helpful for us, what is not, how to use minimize the bad guy, maximize the good guy right that we need to still do. So, of course, Compton angle is one thing and then what is the reduced energy? Reduced energy is; so, your Compton electrons will have a energy which is incoming minus Compton photon energy that energy is given to the Compton electron, ok. So, the kinetic energy of the Compton electron is the difference between these two.

So, one of the ways this will be useful is like I said we want to send the photon through the body and collect it when it comes to the other side. If you have Compton scattering then what is going to happen?

It is going take a different angle. So, I may sit on the detector thinking something is coming in this direction, but because of the interaction with the body if it goes there right that is not going to be helpful for me because I am not going to get it. I am not going to get the signal, right. I am not going to get the photon to make any sense of what it has interacted, right.

So, Compton scattering in that sense it will be helpful right to understand even if there is a what is the angle right beyond which my detector may not detect it. So, anything beyond that it is only the body that is getting all this ionization, but your detector will not get it because you are looking at the detector thinking it is going to come here, but because of Compton scattering it is going there, right.

So, you need to know what is an angle of this Compton scattering right until which you probably can detect even if it is at some angle it can detect, but if it is greater than certain angle maybe you are not going to detect you are just going to dose the patient, right. You going to have ionization, but you are not going to catch the photon to say you know what about the material that came through.

So, in scenarios like that it probably very useful to calculate this angle. So, I am not going to do that here this is a simple substitution that you can do. So, typical scenario is you have incoming photon right with some energy of 100 kilo electron volt. And, then we also say that it exits it exits from the material with a reduced energy of h mu dash.

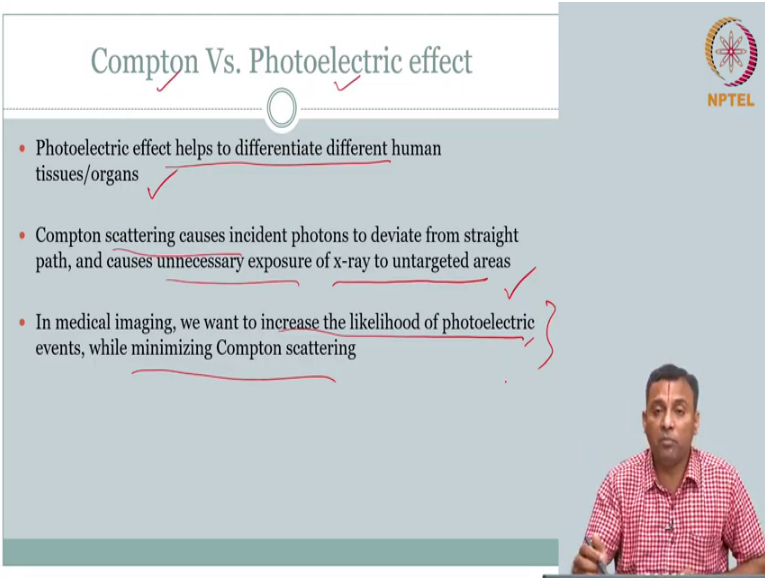
So, now, we are also saying that the detector threshold of h mu dash. So, if the detected energy of h mu dash if it is greater than 98 kilo electron volt; so, you are sending in 100 you are receiving 98 after the photon has gone through the medium.

You say that if I am able to capture 98 kilo electron volt, then whatever scattering has happened the angle of Compton scattering is acceptable until then you are ok because you are you are capturing the signal 98 kilo electron volt. Anything beyond that you will have to look at design aspects.

So, the question is what could be that maximum angle if this is the scenario. So, I am not going to do it now because it is straight forward. So, you will do it, what do you do? You are given h mu, you are given h mu dash, right. You given h mu you are given h mu dashed, you know m naught c square you have to find out theta, ok. So, if you do that what is the maximum angle by which the photon is scattered, but still being treated as travelling in straight line path if you calculate it will turn out to be about 26.4 degrees.

So, essentially even if it is deflected right straight line path is 0, 0 degree. So, even if it is deflected by in this case about 26.4 degree you will still be able to catch the photon in the detector when it is coming through. So, you can say that it came through the straight line anything greater than that probably is not going to be helpful from your signal detection point of view, ok.

(Refer Slide Time: 29:37)



So, now let us just compare the two effects, right. What do I mean by compare the two effects? See you do not have control over any of this it is all statistics right population based. So, you send some energy remember, when I say send some energy h mu that h mu is not like discrete that you can. So, it is coming from x-ray tube and we saw in the previous lecture basically you get Bremsstrahlung you get a population right.

So, you have different energies that come. In fact, sometimes you also have characteristic x-rays energy that is coming in. So, you have a host of different energies that are coming in. So, different h mu's that are coming in. So, in that sense different h mus are coming different energy levels are coming it has to interact with the body.

So, there are two prominent interaction that we are worried about – one is Compton, the other is photoelectric which one does what is you know which condition favors or which factors favor each of the effects and which effect are we interested in what is our task right that is what we want to do here when we compare.

So, photoelectric effect helps to differentiate different human tissue organs. What does that mean? Why is that statement made ok? So, the idea is this right you are sending energy it is going through it is I am just using simple chest x-ray kind of example that you are probably familiar. Similar concept works for CT as well. So, right. So, we will not complicate that.

So, simple chest x-ray that you are familiar, you went and stood in front of x-ray tube. X-ray photons came in and behind you there was a detector. So, that was detecting the x-rays that come out. So, what does photoelectric effect do? That means, you have energy that is coming in. The energy is now deposited in the tissue and the remaining energy comes out. So, it is the relative distribution of which location can stop how much x-ray that is what you see as the image in your x-ray, right.

So, in that sense, photoelectric effect what does it do? Photoelectric effect the energy is absorbed by the material. So, different material can have different for the same energy that is going in different material can have a different level of absorption, loss in the signal. I am not using the word attenuation yet right just to give a feel. So, it is you have a energy that is reduced.

So, it depending on the material the amount of reduction will take. So, the remaining will come out. So, it is this differential materials ability different material has different ability to have this photoelectric effect right absorb the energy to different extents. That is what you want to map. So, you want to maximize photoelectric effect.

So, if there is no interaction whatever you send whatever comes out, then you are not going to tell anything about the medium, right. Or other extreme I send everything and everything is lost inside around I do not get anything outside, then also you cannot really comment about because your output is 0, right. So, you cannot really tell what is there inside in the body.

So, there is this idea that photoelectric effect helps because of this differential attenuation by the tissue materials to the for x-ray energy. This photoelectric effect which basically says that the photon is going to interact with the tissue, the material, the you know the cloud that is going to be helpful factor for us, right that is going to be our clue signal how does it interact with the material.

If it interacts with the material then by measuring that signal I can comment about the material right. So, that is photoelectric effect helps in that.

Then, what about Compton scattering? Compton scattering as we already talked about right scattering causes incident photon to go into a different direction. So, it deviates from the straight line path. So, in some sense it is unnecessary exposure will be happening; in the sense that I send the photons it does campton Compton scattering.

So, I am thinking I am going to get the photon energy through my body to the other side whereas it got deflected inside the body. It goes all over the body and exits the body from some other angle. Then although all the interaction, absorption, ionization everything took place I am not able to even catch the signal, right. If I do not catch the signal I cannot really get anything about that tissue or the material.

So, essentially you would have irradiated the tissue with x-ray energy, but that energy interaction with the tissue that signal is not coming out, that signal is scattered everywhere. So, that is what we mean by exposure of x-ray to untargeted areas. So, now, it may go into other direction and cause some ionization in some other organ, ok. So, that is a.

So, in some sense you can look at it this is the signal that we are interested, this is a effect that does not contribute to a signal in fact, it contributes to difficulties, right. So, this signal is kind of your noise, ok. So, in medical imaging we would like to increase the likelihood of photoelectric effect while minimizing Compton scattering. A very important we should know what we are going after, ok.

So, in some sense it is very intuitive, right. So, let us take an example how do I engineer this. I now that we have this knowledge how do we exploit? I mean the simplest case let me tell you what happens if I know how to increase the likelihood of photoelectric events what does that mean I want the photons to get absorbed by the coulomb cloud the atom cloud, right. So, what happens if I what happens if I say look on increase it increase the probability.

So, that it actually is completely absorbed by the material that is nothing comes out. From a medical imaging point of view we might not favor that because we need something come, but then if you actually cleverly look at it maybe there is a way in which if I am the I am I do not want to be affected by the ionizing radiation, then I can have a material in front of me which maximizes photoelectric effect to the extent that all the n the x radiations that ionizing radiations that come right get absorbed in the material that is placed in front of me. That way I would not get any radiation, right.

So, mean it is just knowledge. So, if you if you know that that is why if you go to scan room right operator will going to do all that he will have safety because you are gone there to take a chest x-ray.

He does not want to get exposed to ionizing radiation that is sits in another room is one thing, but even then you will see that they will put some jacket led jacket. Why? Because they want this energy to get absorbed by the led jacket they do not want to get ionized, they do not want this ionization to go to their soft tissue.

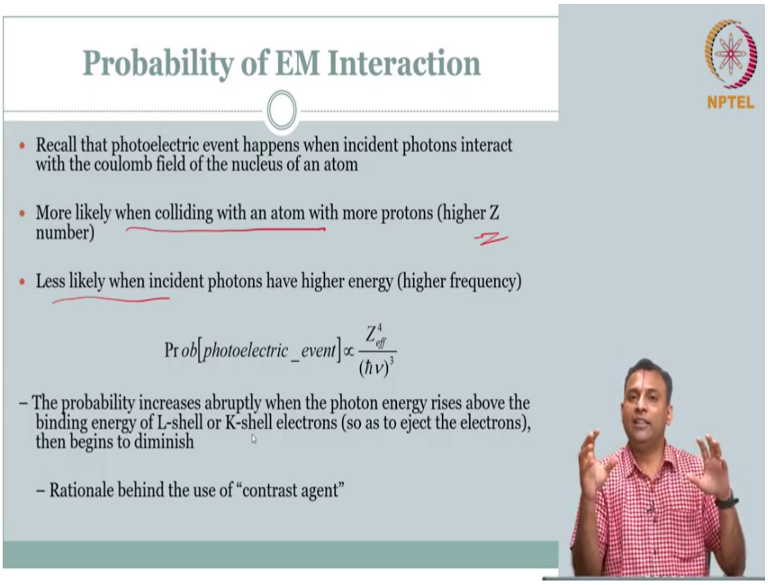
Likewise minimizing Compton scattering; if you know how to minimize Compton scattering that is beneficial like just the example that we saw the angles are coming. So, we can calculate either how do minimize the Compton scattering because from perspective of dose is one thing the other perspective is also giving contributing to the noise ok, because I am probably looking at some signal coming straight through, right.

So, I am looking at my detector is looking at some h mu that is supposed to come straight through whereas, now that is my signal of interest, but now because of Compton scattering something else happened and that one comes at an angle and hits here. So, while I am looking at here something else come and hit me here. I will not know I will say it came from here. So, basically this is noise this is corrupting my measurement.

So, it is undesired, right. I want to minimize that. So, I can then in that sense come up with schemes so that I can prevent, right Compton scattered photons to come. So, I can have some ways mechanisms through which if the signal is coming from if the photons are coming at a certain angles, right I would have material so that will stop the photons hitting the detector, ok.

So, knowing this is very important because we will then strategically use this to our advantage ok.

(Refer Slide Time: 39:24)



So, that means, we will spend a little more time on understanding what do we mean by increasing the likelihood or decreasing the likelihood, right. So, it is all probabilistic. So, intuitively to think about it we are interested in photoelectric when does photoelectric effect happen or you have a energy you know photon with X-ray energy coming in it is interacting with the cloud of electors, is the key is it has to interact with the electron cloud or the coulomb field, right.

So, when does that happen? Well, without knowing much I can say if the field is big right then the I maximizes the chance the field is strong then I maximize the chance. So, that means, if I have more protons then I am going to have equal number of electrons. So, more the protons, more the electrons, more the electron cloud. So, I maximize my chance right very straightforward extension of what we know from the definition of photoelectric effect.

So, more likely; so, more likely when colliding with an atom with more protons. So, that means, if it is a higher Z number, right then you have maximizing the chance. So, it is all very first order rule of thumb kind of. So, we are not going to derive the details because these are all fields you know whole physics they were doing all this. So, we are not going to do that.

We are going to appreciate the rational of yeah, photoelectric effects is it is you know it is interacting the energies h mu is interacting with the coulomb field. So, if there are more electrons the strong field, then there is a higher chance of h mu interacting, ok. So, we will only say that you need a higher Z number. In fact, we exact order we will put, but rule of thumb is directly proportional right which order we will talk about.

So, what we also can guess is less likely when incident photon have higher energy why is it very guessable. So, let us go back to our example like you said it is a Layman's example, but maybe the message will be sent. So, recall how we said I am the electron I have lot of energy I am running right and there are 15 of you there they are there, ok.

So, when I go if I have lot more energy what is going to happen? Am I going to with relations to the people who are standing there. If I have way too much energy compared to the people, there I will not probably interact with them when I go through them they will all fall apart and I will proceed further.

When is the chance of me interacting with them? When my energy is not so much it is greater than there so that you know I will have some energy to give right if I do not have energy if I have energy less than theirs then probably I will go I cannot penetrate them I will come back. But, the idea is I am ionizing radiation. So, I have enough energy. So, I am going there. So, what will happen? If I go there if there are many of them I will interact with them, I will push them nudge them slightly right and then I will go further.

So, there is going to be interaction the chances of interaction goes up if the energy is not weight too much. So, if the energy is weight too much I would not interact with them. I will just run through they will all fall apart I will keep going. So, I would not lose much energy in that sense, right.

So, what is the fun? I send some energy through. It does not interact with the tissue. It comes out, what is the fun? Right. I do not get anything from that. So, less likely when the incident photons have higher energy, ok. So, you have to look at some energy level that is conducive for maximizing the probability. So, from a interaction perspective from a probability perspective, one is directly proportional, other is inversely proportional ok.

So, the exact order is like here probability of a photoelectric given to take place depends on the fourth power of Z effective. So, why is this Z effective? I talked about atom, but you have some compound some molecule. So, you have several different kinds of atoms perhaps. So, Z effective is the effective average of all the atoms that are there all the different types of atoms that are there h mu cube.

So, for tissue it is about Z power 4, but if the interaction is with some material which are heavy atoms then they say it is Z power 3, but for our purpose we will take that probability of photoelectric event is proportional to 4th power of Z effective by h mu the energy that is incident right cube of that. So, lesser the energy more the density of I mean you have more the atomic number, then your chances are increasing ok.

Beyond that there is one more detail. The probability increases abruptly. So, this is fine, but the probability increases abruptly when the photon energy rises about the binding energy. So, all now we said ok h mu is going in, it is interacting fully absorbed right, but if it turns out that this h whatever you are sending the h mu is sufficient or it is close to this binding energy just greater than your L and K.

Then suddenly what happens is this energy is able to overcome the binding energy of the K electron, right. So, the probability of the effect taking place increases, ok. So, the probability increases when the photon energy rises above the binding energy of K electron right because then suddenly you have many electrons that K – shell electron becomes a right you can eject them, ok. And, then of course, after that it will start to diminish.

So, when you have a energy such that it is close to the K shell, L shell binding energy you have maximize the photoelectric effect. So, here again how do naturally probably you cannot do much right we are composed of certain material. So, they have characteristics how do you; how do you maximize all this? Engineer all this that is where they do.

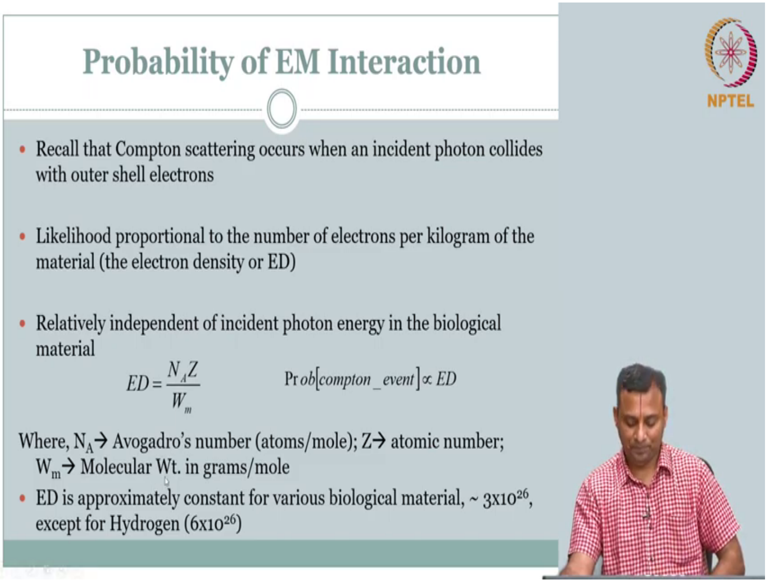
If you can engineer a material right if you have engineer material so that its K shell or L shell binding energy is within the range of the diagnostic X-ray energy that you are sending in.

If you can engineer such a material, then probably the activity of that material will go up. Where do they engineer? You look at something called us contrast agents. We will not cover that here, but you know sometimes contrast agents are these are agents that are there to generate contrast such way. So, you inject. So, you have your angio right when you go for ray dye you would have versed they will inject and dye and then do a CT or a X-ray, right.

So, what does that do? That is a material that material is sent in which is carefully engineered so that its K shell, L shell is just above the those that the X-ray tube energy that is used in that imaging system so that when that goes in suddenly that will behave very differently compare to the rest of the tissue, so that you can clearly spot where all the dye is going you will see the contrast it out compare to the rest very easily. So, that is why it is called as contrast agents.

So, you will look at when you do contra when you do contrast agent angio you will see several you know vascular picture in CT. Those are all high contrast very clear for that reason, ok. So, that is for your probability of your photoelectric effect.

(Refer Slide Time: 48:25)



So, then what about probability of your Compton scattering, ok. What we know is Compton scattering when the energy comes in it interacts with the outer shell or interacts as an it knocks the outer shell and then reduces the energy and it goes in another direction. So, when can you maximize that? I mean likelihood is if you have more electrons the chances are that it encounters a electron at the outer level before it actually goes into the it is attracted by the nucleus right or it goes towards the K electron.

So, that means, you have to maximize the electron density, ok. So, likelihood proportional to the number of electrons per kilogram of the material or the electron density. What is electron density you have right number of atoms in a mole and then your Z and then your weight in mole. So, you have now Avogadro number right you have you have heard of Avogadro number at number of atoms in a mole, right and then you have your Z.

So, that tells you number of electrons in an atom you can get that and then you have your weight, ok. So, with that you can have electron density. So, it is directly proportional to or the likelihood is related proportional to your electron density. So, probability of your Compton event is directly proportional to your electron density.

And, in this case it is real I mean at least for I mean these are all there are a lot of physics that are there behind several aspects of which with respect to for example, energy, but for the energy that is encountered in human interactions right here for biomedical applications in that range it is found that relatively the probability of Compton scattering right there is relatively independent of the incident photon energy. So, we do not have to worry.

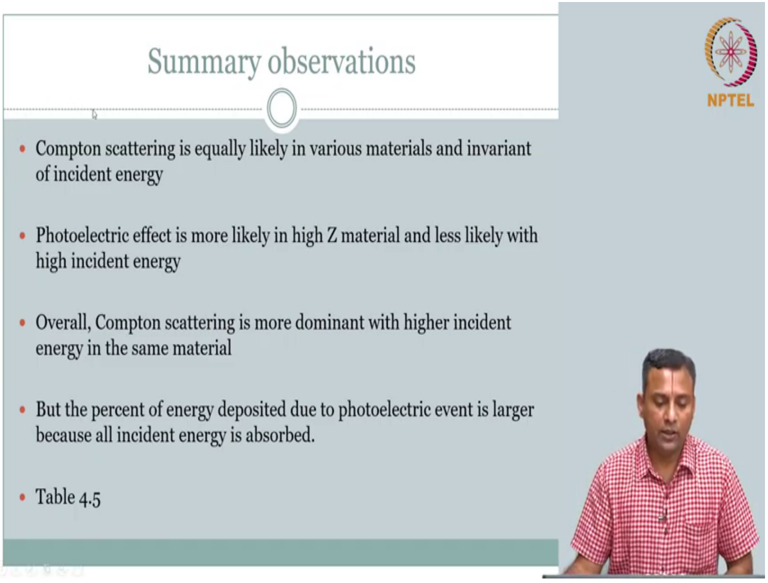
So, good news is that, bad news is also that; bad news is irrespective of the energy you are going to or you are going to have Compton scattering it is something that is not desired right. So, you are going to have that your respective of whichever energy you are using. At least photoelectric effect we can maximize ok if I put an contrast agent I can tune the energy so that it is the K and L so, I can maximize my signal. Whereas here it does not depend on the energy and therefore, it is always going to be there ok. So, that is a downside as.

These are just the whatever I listed N A is the Avogadro number which is the atom per mole, Z is the atomic number and then W m is the weight in grams per mole, ok. So, that is for your Compton scattering.

So, let us kind of wrap up like we looked at the probability we looked at what is signal, what is favorable, what is unfavorable, what should be maximize, what should be minimized. So, ED electron density is for biological tissue right approximately constant for all the material except for hydrogen which is 6 into 10 power 26, rest of them are all 3 into 10 power 26.

So, the essence is right you are going to have Compton scattering this independent of the material that you are going to see, ok.

(Refer Slide Time: 52:19)



To summarize, Compton scattering is equally likely in various materials and invariant of incident energy. So, you see so, you have to live up with the noise as it is just noise if from a signal point of view you may say it is noise, but actually your if you really think through whatever physics we have covered, it is just not that it is just unnecessarily a dosing the patient, right.

Because it is not your it is not even coming out to help you, but then it does you know is there inside the body it is exiting somewhere. So, it is actually a problem.

So, photoelectric effect is more likely in high Z material and less likely in high incident energy. So, this kind of gives you because intuitively what we may feel at least without much thought first you send more energy maybe it will help, right. No that is not going to happen because your signal is not going to number of photons should increase, but it should be an energy where this maximum interaction can take place that is key.

So, do not get confused with the example that we did yesterday, in introduction I said root is a signal to noise ratio right specifically. There we talked about square root of n, then I said you can increase the signal to noise ratio by sending in more photons more photon is different from energy of the photons. If you send higher energy it does not help right. So, it is not that is what this means.

So, overall Compton scattering is dominant with higher incident energy in the same material. So, you see the disadvantage. So, if you have a higher energy that you are going to use, not only that your minimizing the photoelectric effect you also increase the Compton scattering, ok.

And, also what would be interesting to compare is what is the percentage of interaction. So, if I send the energy in a given material how much of it is Compton scattering, how much of the photons do photoelectric effect that is one way of looking at it that is a number percentage of times that one is happening the other. The other way to look at it is interactions might be same, but amount of energy that is deposited right that is another issue.

So, there is a table in the text which is table 4.5 of prints and links that and you will see there quickly that the percentage of interactions Compton scattering is more, but the energy depositor right due to Compton scattering is less compared to the photoelectric effect.

In fact, whereas, you look at it you will notice that even a 60 percent of the interaction can be Compton scattering something like that, right. But then your amount of energy that is deposited will still your photoelectric effect will contribute to significant deposition.

So, look at the table 4.5 that tells you that it is probably in some sense it is understandable. Compton scattering they you have many interactions, but the energy that is deposited in the tissue is less whereas, in photoelectric effect because the principle of photoelectric effect is the energy is absorbed by the atom, right it come. So, naturally even though the number of interactions of photoelectric is less compared to Compton the energy that is deposited will be more in photoelectric, ok.

So, we will stop that here. We will now proceed further as to how do we now start to write the interaction we talked about loss in energy. So, how do we write the loss in energy, how do we write the in terms of photons and then attenuation all that. So, that we kind of get little more detail into this quantifying this interaction, right, we know the effects; next question is how do we quantify that how do we describe that with some numbers some equations, right. So, we will stop here and we will continue from there next.

Thank you.