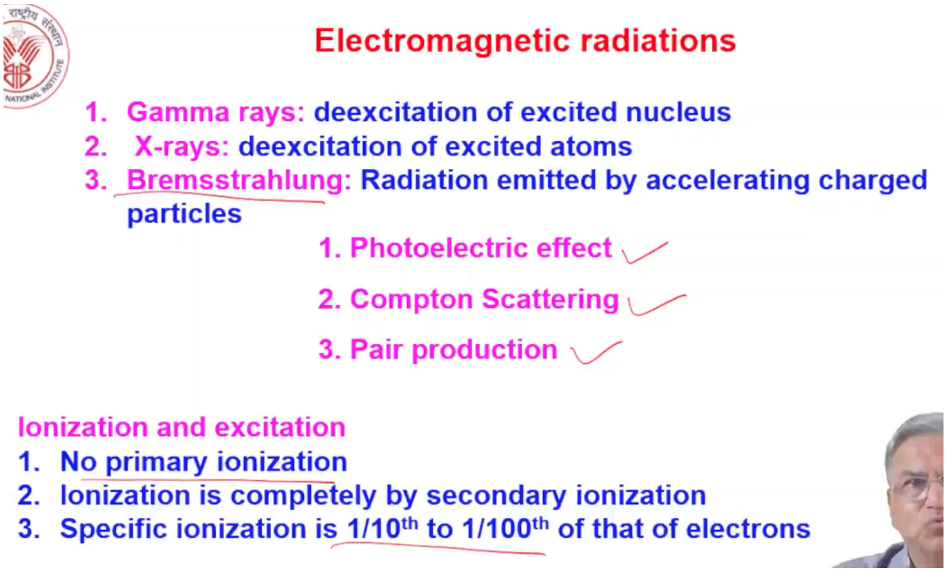
Interaction of electromagnetic radiations and neutrons with matter

B.S.Tomar

Homi Bhabha National Institute

Lecture-8, module-2

Dear students, so far we have discussed the interaction of heavy charged particles and fast electrons with matter. Today we will discuss the interaction of electromagnetic radiations with matter.



Electromagnetic radiations

1. Gamma rays: deexcitation of excited nucleus
2. X-rays: deexcitation of excited atoms
3. Bremsstrahlung: Radiation emitted by accelerating charged particles

1. Photoelectric effect ✓
2. Compton Scattering ✓
3. Pair production ✓

Ionization and excitation

1. No primary ionization
2. Ionization is completely by secondary ionization
3. Specific ionization is 1/10th to 1/100th of that of electrons

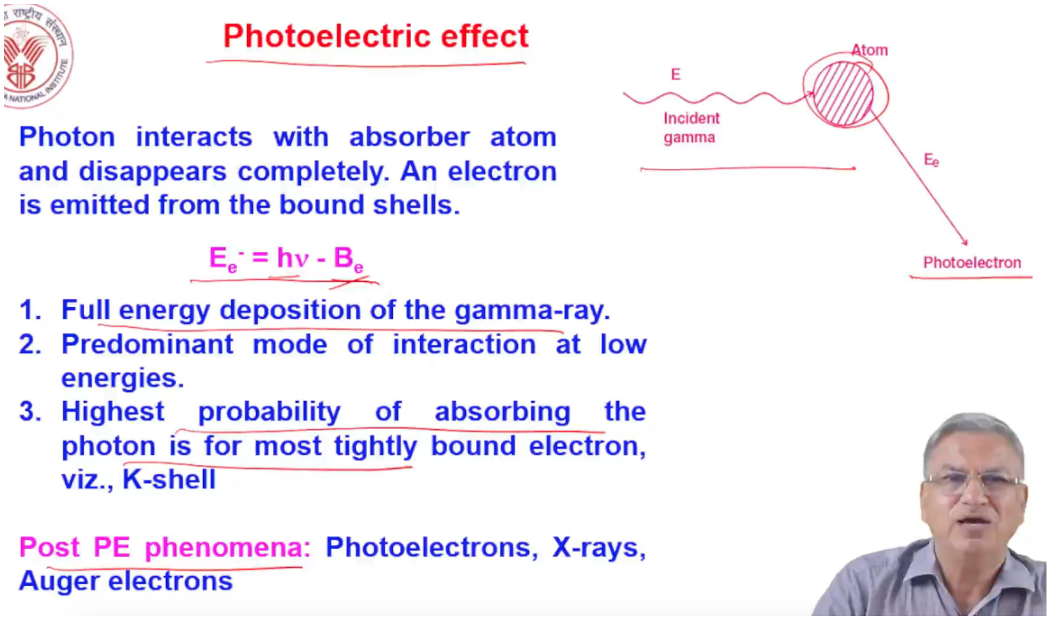
So, electromagnetic radiations essentially comprise of gamma rays and X-rays. So, gamma rays, as you know already, appear from the de-excitation of the excited nuclei, whereas the X-rays come from the de-excitation of excited atoms. In addition to this discrete gamma rays from the decay of excited nuclei, we also have Bremsstrahlung which we discussed during the interaction of beta particles with matter. And this Bremsstrahlung essentially have a continuous spectrum starting from zero to the end point of beta spectrum or fast electron energy.

Now, the Bremsstrahlung you know already that when the accelerated particles moving, see if it is accelerated in the vicinity of a nucleus, then it emits a Bremsstrahlung radiation. So, all of them, all interactions, all the types of radiation, gamma rays, X-rays and Bremsstrahlung, they are electromagnetic radiations and the interactions with matter are same. So, we will call them mostly in terms of gamma rays. So, gamma rays predominantly interact by three modes, the photoelectric effect, the Compton scattering and pair production.

So, the major deposition of energy in the gamma ray detector, which essentially we will see how they manifest in the gamma ray spectrum, comprises of these three processes. And since the gamma rays are photons, they will not cause the ionization directly in the medium. But by these three processes, photoelectric effect, Compton scattering and pair production, ultimately, the net result is ionization and excitation. By secondary means, they will produce electrons, which in turn will cause ionizations. So, there is no primary ionization in the interaction of these gamma photons with the matter.

It is mostly by secondary ionization, whatever electrons are produced, as we will discuss very soon in these three processes, they will cause ionization and therefore, we get the secondary ionization. Another important point is that since the gamma rays are photons, so their specific ionization is very small compared to that of electrons. So, their ranges are very high. So, about one tenth to one hundredth of the electrons, they will cause very less specific ionization, means the per unit thickness in the medium, how many ion pairs they can produce, that is called as the specific ionization, number of ion pairs produced per unit thickness. So, that is very small.

And that is why the gamma rays or even the x-ray, they all travel a long distance in any material. But then we know, we will discuss very soon that the ideal materials, which can stop the gamma rays effectively and so they are the ones which are used to stop these gamma rays. So, let us discuss the main three processes, what is the mechanism, what are their manifestations in the gamma ray spectrum.



Photoelectric effect

Photon interacts with absorber atom and disappears completely. An electron is emitted from the bound shells.

$$E_{e^-} = h\nu - B_e$$

1. **Full energy deposition of the gamma-ray.**
2. **Predominant mode of interaction at low energies.**
3. **Highest probability of absorbing the photon is for most tightly bound electron, viz., K-shell**

Post PE phenomena: Photoelectrons, X-rays, Auger electrons

The photoelectric effect, all you all know from the Einstein's theory of photoelectric effect, when the photon interacts with an atom as a whole, so it is not with the electron, but it is with the absorbed atom as a whole, then in the vicinity of the atom, the photon disappears, it is completely absorbed. So, it can also be called as photoelectric absorption.

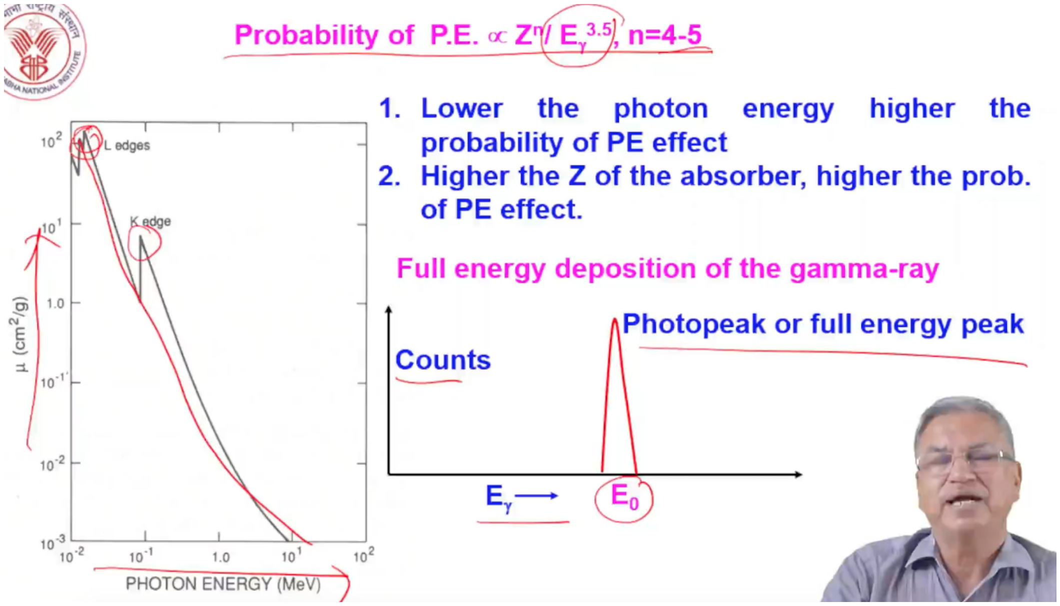
And so the atom gets excited and the excited atom loses its energy by emission of electron. In the case of photoelectric effect, probability is maximum for emission of the highest bound electron. So, that means the case electron has highest probability of emission provided the energy of photon is more than the binding energy of that particular electron. So, essentially the effect of photoelectric effect is to release one electron from the atom and the kinetic energy of the electron will be the initial energy of the photon minus the binding energy of the electron in that shell. So, this is the schematically shown here, the incident photon comes, it is absorbed by the atom as a whole.

So, the important point is that the momentum of the photon, say photon has the momentum E by C that is balanced, that is it has to be conserved and that is conserved by the atom as a whole. So, all the momentum is taken up by the atom as a whole and so the excited atom that emits the electron from the K shell or L shell depending on its energy. So, it is important for the conservation of momentum that the electron which is closest to the nucleus is participating in the photoelectric effect. And the electron that is produced we will be calling as the photoelectron. The photoelectron energy as you can see if we have a 1 MeV gamma ray and binding energy of electron maybe about few tens of eV to keV, then the electron will be coming out with a very high energy and so that electron can cause subsequent ionization in the medium.

So, this process of photoelectric effect essentially leads to full energy deposition of the gamma ray. Gamma ray is lost, so all energy of gamma ray photon is deposited in the material in form of electron and the electron will stop now in the medium. So, essentially it will cause ionization. The photoelectric effect is the predominant mode of interaction at the low energy of photon as we will very soon see the dependence of the cross section for this process, the energy of the photon and the Z of the absorber material. And as I mentioned that for this momentum conservation the shell closest to the nucleus is excited so that electron coming from the K shell has a highest probability.

So, the highest probability of absorbing the photon is for most tightly bound electron that is K shell. So, if the energy of the photon is more than the K shell binding energy, then it is the predominantly K shell electron that is emitted. Now, so what essentially has happened, there is a hole in the K shell, electron has been emitted. So, the post photoelectric effect, what happens, it is a hole in the K shell, then the electrons in the higher shells will jump down to the lower shell and in the process you will see the X-rays being emitted and subsequently when it comes to the valance electrons then instead of X-ray emission the Auger electrons may also be emitted. So, as a result of the photoelectric effect, we have photoelectrons, X-rays and Auger electrons being emitted and all these X-rays again will cause photoelectric effect, their energies are much smaller.

So, they will be having much smaller ranges and so all of them ultimately deposit energy in the medium and you get the full energy deposition in the substrate.



Probability of P.E. $\propto Z^n / E_\gamma^{3.5}$, n=4-5

1. Lower the photon energy higher the probability of PE effect
2. Higher the Z of the absorber, higher the prob. of PE effect.

Full energy deposition of the gamma-ray

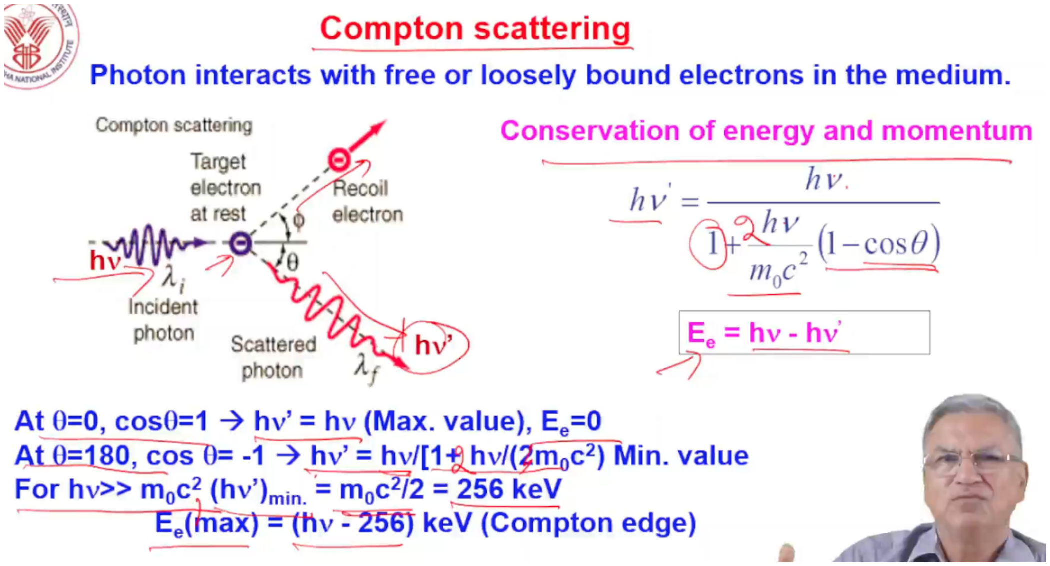
So, the probability of the photoelectric effect depends heavily upon the Z of the observer, Z^n, where Z is the observer atomic number and this n value is quite high, 4 to 5. Whereas it is depending upon the energy of the gamma ray in inverse way, as $E^{-3.5}$. So, these dependences have come from the electromagnetic theory and so we will not go into details how this relationship has been arrived at.

But the point to note is that the probability of the photoelectric effect highly dependent upon the Z, higher the Z, higher the cross section for the photoelectric effect and lower the energy, higher the probability for photoelectric effect. So, what I have shown here is in the, this as a function of energy of the photon, the cross section or the what we call as the attenuation coefficient for the photoelectric effect, it is coming down with energy, you can see here. So, higher the energy, lower the probability of photoelectric effect. For a particular Z, for a particular atomic number, you can see here, so this is the K shell, this is the L shell and so on. So, what happens that in general, that cross section should come down with energy, but whenever the photon energy matches with the K shell binding energy, there is a jump in the cross section for photoelectric effect.

Similarly, whenever the energy of the photon is close to the L shell binding energy, then there is a jump in the cross section. And so, the cross section for photoelectric effect will have edges at the respective shell binding energies. So, the photoelectric effect is one process that leads to complete deposition of the energy of the photon in the detector system. And so, the typical spectrum, you can see here, what happens, suppose this is the counts versus energy of the gamma ray, then if the energy of the photon was E_0, then it will lead to a sharp peak. Ideally, it should be a delta function, sharp line, but the detector has its own resolution.

And so, it becomes a Gaussian peak. So, there is a broadening in the peak, the gamma ray. So, but this is what, so there is no other effect of manifestation of the photoelectric effect in the gamma spectrum, except that suppose this is the ideal material, the detector is ideal material. So, the x-rays are emitted and x-rays might escape it. So, there will be x-ray escape peaks.

Particularly, it happens in sodium iodide, which we will discuss subsequent lectures. The iodine is one of the components of sodium iodide and the iodine x-ray might escape from the detector system. And so, there will be a peak full energy minus iodine K x-ray that is called the iodine x-ray escape.



Compton scattering

Photon interacts with free or loosely bound electrons in the medium.

Conservation of energy and momentum

$$h\nu' = \frac{h\nu}{1 + \frac{2h\nu}{m_0c^2}(1-\cos\theta)}$$

$E_e = h\nu - h\nu'$

At $\theta=0$, $\cos\theta=1$ → $h\nu' = h\nu$ (Max. value), $E_e=0$

At $\theta=180$, $\cos\theta= -1$ → $h\nu' = h\nu/[1+2\,h\nu/(\cancel{2}m_0c^2)$ Min. value

For $h\nu \gg m_0c^2$ $(h\nu')_{min.} = m_0c^2/2 = 256$ keV

$E_e(max) = (h\nu - 256)$ keV (Compton edge)

Another process of the photon interaction is Compton scattering. And as the name itself implies, it is a scattering. So, it is like an elastic scattering between the photon and the loosely bound electron. So, here, the electron that is participating in Compton scattering is either a valance cell or almost loosely bound electron. So, there is a collision between a photon, photon comes, strikes the electron and the photon is emitted at theta degree, the electron goes at phi. So, it is like the elastic scattering between the photon and the electron. And the energy of the incident photon is shared by the scattered photon and the required electron.

So, you can set up the equations for the conservation of energy and momentum of the photon before and after the collision. But that we will not go into, this is a very simple derivation you can set up. So, finally, we want to know what is the energy of the photon that depends upon the angle at which the photon is emitted. And so, the hν', the energy of the Compton scattered photon is given by

$h\nu' = h\nu/[1+ h\nu/(2m_0c^2)](1-\cos\theta)$

where m_0 is the rest mass of electron, c is the speed of light. And so, accordingly, the energy of the electron will be $h\nu$ - $h\nu$.

So, the energy of the incident photon is shared between the electron and the scattered photon. So, the manifestation of this you will see in this, when we see what happens at $\cos\theta = 0$, when $\theta=0$, $\cos\theta = 1$, and then so this term becomes 0. So, you have

$h\nu' = h\nu$

So, that means at 0 degree, the photon goes undeflected, there is no electron energy at 0, when the photon is scattered at 0 degree. But when the photon is scattered at 180 degrees, the $\cos\theta$ is -1 and you put here the value of $\cos\theta$ bearing term becomes 2.

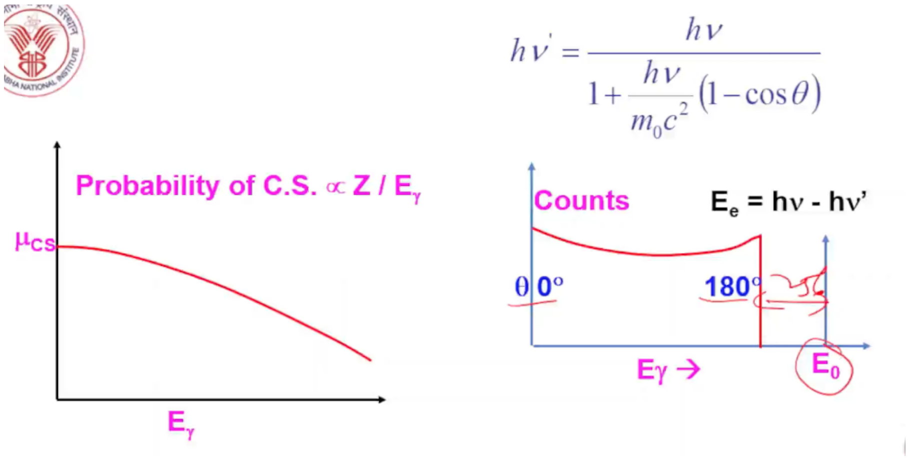
$h\nu' = h\nu/[1+ h\nu/(2m_0c^2)]$

So, it should be $2h\nu/m_0c^2$. So, at 180 degree, this is the minimum value of the scattered photon energy.

Now, let us do some simplification. If the gamma ray energy is much higher than the rest mass energy of the electron, m_0c^2 means 0.511 MeV. In that case, you can actually substitute this term you can neglect. So, it becomes $h\nu'$ will be $m_0c^2/2$, this will get cancelled with this, m_0c^2 will go in the numerator and it becomes $m_0c^2/2$. m_0c^2 is nothing but 0.511 MeV or 511 KeV, half of it will be 256 KeV. So, at 180 degrees, the gamma ray photon energy is very high, then you will find that there is something called as a compton edge, because the energy of the electron will be $h\nu$ - 256.

And so, at an energy, full energy of the gamma ray -256, there is a peak, that is called the, it is not a peak, it is a hump, so that is called the Compton edge. So, it is a typical feature of Compton scattering, which we will see in the subsequent slide, you can see here. The Compton edge, this is 256, if the photon energy is much higher than the rest mass energy of the electron, that is 511 KeV. So, you can see here, depending upon the scattering of the photon at 0 degree or 180 degree, you get a continuum in the gamma spectrum, as a result of Compton scattering, this is the full energy. So, Compton scattering does not lead to the full energy deposition.

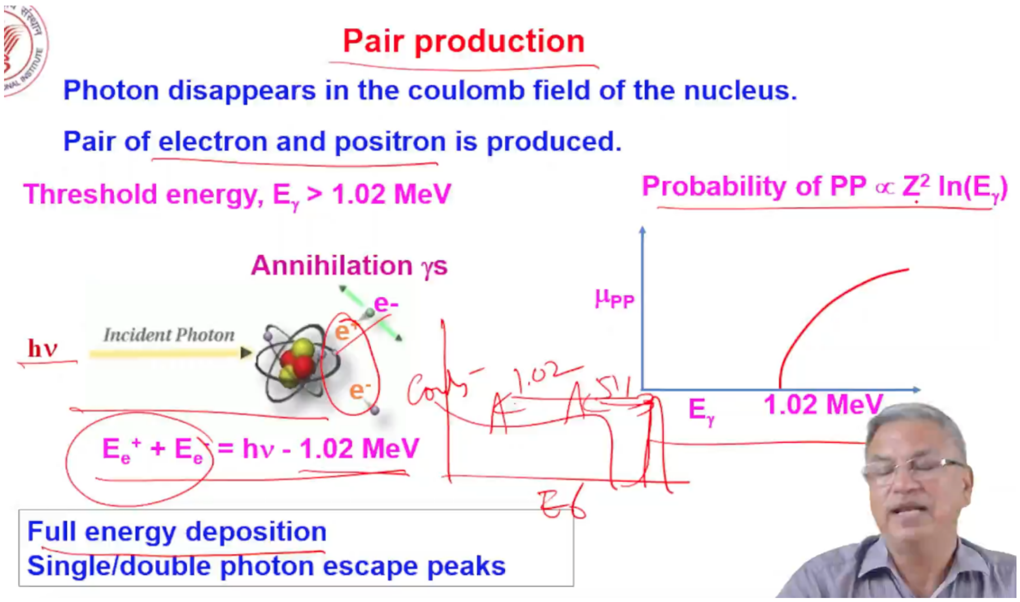
But what happens, if your detector is very big in size, then the Compton scattered photon can further undergo photoelectric effect or Compton scattering, and then you can have full energy deposition, because, even the Compton scattered, here we just assume that the photon is scattered out of the system. But if the photon can further interact with the medium, then it can lead to full energy deposition.



$$h\nu' = \frac{h\nu}{1+\frac{h\nu}{m_0c^2}(1-\cos\theta)}$$

Probability of C.S. ∝ Z / E_γ

And the probability of the Compton scattering has a mild dependence on the Z of absorber and the energy of the photon. So, here what is shown here is the energy dependence of the photon. So, as the energy of the gamma ray increases, the photoelectric Compton scattering cross section decreases with the energy. But it is a very mild dependence.



Pair production

Photon disappears in the coulomb field of the nucleus.

Pair of electron and positron is produced.

Threshold energy, $E_\gamma > 1.02$ MeV

Probability of PP ∝ $Z^2 \ln(E_\gamma)$

$E_{e^+} + E_{e^-} = h\nu - 1.02$ MeV

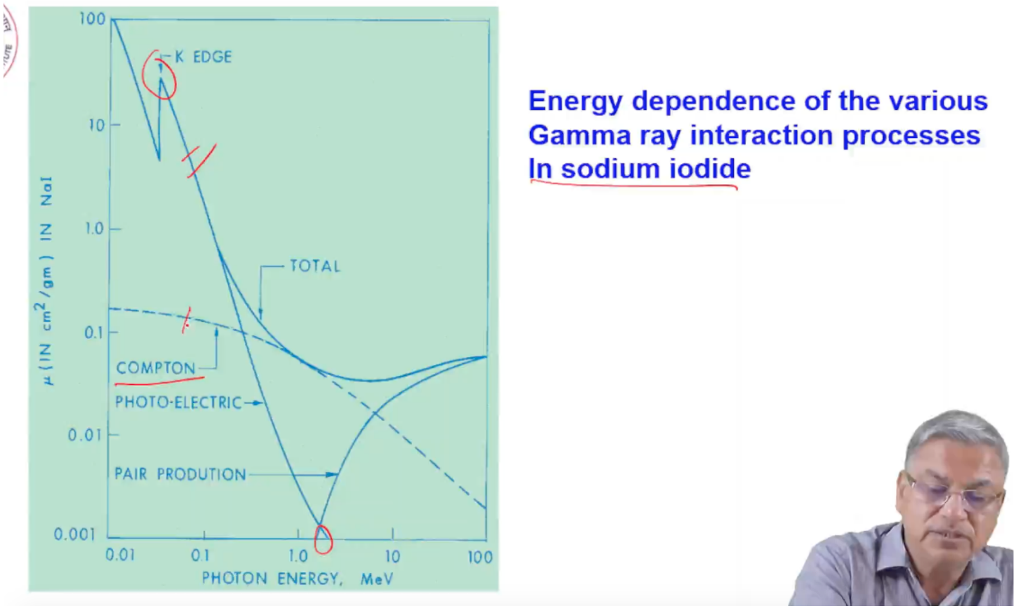
Full energy deposition
Single/double photon escape peaks

Now, the third process is pair production. So, essentially, in this process also, the photon is completely lost. The photon is like, you know, absorbed in the Coulomb field of the nucleus, and the energy of the photon is used in producing a pair of electron and positron. So, this process is seen schematically here, that the incident photon comes in the vicinity of the nucleus, and the energy of the photon is taken up by the nucleus. And instead of that, the photon, it is like, you know, the inverse of the annihilation of the gamma ray, the pair of annihilation of the positron with electron.

So, a pair of electron and positron is produced, and the energy of the photon is now going into the energy of the positron and electron. But to create the pair of electron and positron, you require the rest mass energy of the pair that is 1.02 MeV. And so that is the threshold for this pair production process.

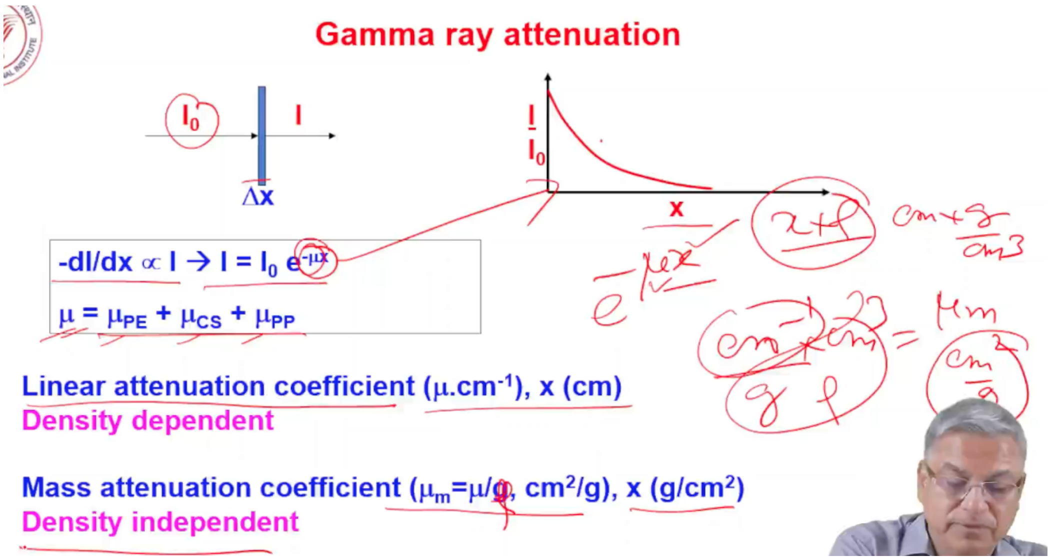
The remaining energy actually hν -1.02 goes as the kinetic energy of the electron positron pair. This positron will get thermalized in the medium, and it can meet another electron in the medium and annihilate with the electron when it is thermalized to give you two 511keV gamma rays, which we discussed in the interaction of positron with matter. The net result of pair production, as you can see here, you will have a high energy electron and two 511keV gamma rays. And then these two 511keV gamma rays can further interact in the medium, either they can get deposited in the system, or they can escape or so. So, if the detector is large enough then either there can be full energy deposition, or one of the 511keV may escape, this is called single escape peak, or both the gamma rays, this 511keV gamma ray photons may escape from detector, that is called the double escape peak.

So, what you will have here that suppose this is the gamma ray peak. So, this is the full energy, then you will find, and this is the Compton, this is the photo peak, you will see the single escape and double escape peaks on the gamma spectrum because of this 511. And this is 1.03, corresponding to single escape and double escape. So, what happens that when the pair production takes place, so you can immediately make out that since the gamma energy is higher than 1.02, pair production will be dominant process. So, the probability of pair production is varying with the energy of the gamma ray and the Z of the absorber in this fashion, $Z^2 \ln(E_\gamma)$. Here the E dependence is shown, but there is a threshold for the pair production. And as you go on increasing the energy of the photon, the pair production probability increases. So, at let us say 2 MeV, 3 MeV, you will find pair production will dominate the interaction of gamma rays with matter.



Energy dependence of the various Gamma ray interaction processes In sodium iodide

So, the net cross-sections for all the processes, the photoelectric, the Compton scattering and the pair production are shown in this slide here. So, you can see this is the photoelectric effect, you can see the K edge and it is going down after 1 MeV or so, actually this is for the sodium iodide. So, it is interacting with sodium and iodine in the material. Then the Compton scattering is you can see here Compton scattering, this is photoelectric effect. So, it is coming down as 1/E and the pair production is going up beyond 1.02 MeV. The net result of these processes is the cross-section for the whole process interaction will be, it will come down and then again start going up. So, this is the way the gamma ray photons will interact with the medium and when the gamma ray is traveling through an absorber.



Gamma ray attenuation

$-dI/dx \propto I \rightarrow I = I_0 e^{-\mu x}$

$\mu = \mu_{PE} + \mu_{CS} + \mu_{PP}$

Linear attenuation coefficient (μ.cm^{-1}), x (cm)
Density dependent

Mass attenuation coefficient ($\mu_m = \mu/\rho$, cm^2/g), x (g/cm^2)
Density independent

So, how does the intensity of the gamma ray change with the thickness of the absorber material that I have tried to illustrate here. There is an incident gamma ray photon of intensity I_0 is passing through a thin slab of the absorber material and the transmitted intensity is I. Then the decrease in the intensity of the gamma ray -dI/dx thickness is proportional to I.

Why this has come? Because in this case of gamma ray where the gamma ray photon is interacting in one step, either it will undergo photoelectric effect or Compton scattering or pair production, in one event itself the photon is removed from the incident flux so that process follows, like radioactive decay, radioactive atom decays and so you have an exponential decay with time. In the case of this interaction of gamma ray in one interaction itself the photon is disappearing from this beam intensity and so you have the first order rate law and the solution of the differential equation is

$I = I_0 e^{-\mu x}$

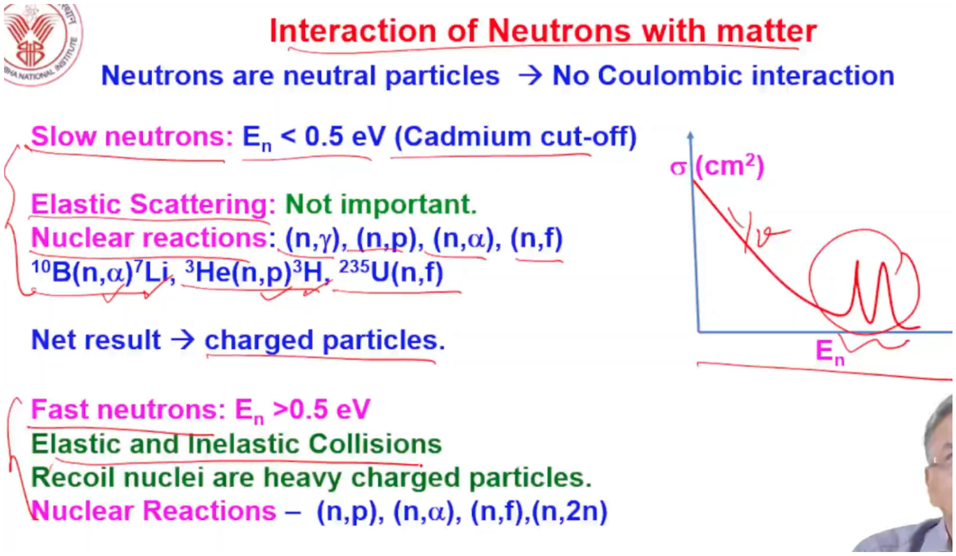
that is what I have tried to show here that the ratio of the transmitted to the incident intensity is exponentially decreasing with the thickness of the absorbing material. As the thickness is increasing the transmitted gamma ray intensity is decreasing. And so you can see this μ you can get from here by fitting this equation and that μ is the total attenuation coefficient.

So we are not trying to break up them but this μ whatever we get is a sum of the three attenuation coefficients, μ is called the attenuation coefficient. How does the gamma ray get attenuated? So μ photoelectric effect, μ Compton scattering and μ pair production, the sum total of this is the total attenuation coefficient. Now see the attenuation coefficient will define two types of attenuation coefficient. One is the linear attenuation coefficient. Mind you the quantity in exponential $e^{-\mu x}$, the μx has to be dimensionless quantity anything in exponential is dimensionless quantity.

So if x is in thickness in centimeter, μ will be in centimeter inverse. So that is what is this is the x is linear in thickness in centimeter, μ is called the linear attenuation coefficient. But in the interaction as I discussed earlier also, suppose you have a one inch thick material with pores inside and same thing you can compress the thickness becomes one centimeter but the density is different. So the density normalized thicknesses are called mass dependent thicknesses. And so the density independent mass attenuation coefficient can be obtained by dividing the linear attenuation coefficient by the density.

So if you multiply the thickness by the ρ density of the material it will be cm^{-1} into gm/cm^3 equal to gram per cm^2. So this is a density 1/ρ, this is the μ. So it becomes μ_m that is centimeter square per gram. This is called the mass attenuation coefficient. So if you write the thickness in gram per centimeter square, so you multiply the thickness by density x into density is centimeter into gram centimeter cube, this is called the dependent thickness.

So normally in this interaction, so we will always talk about density dependent thicknesses and so we have that. So then this becomes independent of density of the material. So whatever value you get μ_m, it is independent of the density. Whereas this attenuation coefficient linear 1 depends on the density of the material.



Interaction of Neutrons with matter

Neutrons are neutral particles → No Coulombic interaction

Slow neutrons: $E_n < 0.5$ eV (Cadmium cut-off)

Elastic Scattering: Not important.
Nuclear reactions: (n,γ), (n,p), (n,α), (n,f)
$^{10}B(n,\alpha)^7Li$, $^3He(n,p)^3H$, $^{235}U(n,f)$

Net result → charged particles.

Fast neutrons: E_n >0.5 eV
Elastic and Inelastic Collisions
Recoil nuclei are heavy charged particles.
Nuclear Reactions – (n,p), (n,α), (n,f),(n,2n)

Now I will just touch upon the interaction of neutrons with matter. Neutrons are also neutral particles, they are neutral particles, so they do not have any coulombic interaction with the material, but they will undergo scattering, elastic scattering, inelastic scattering or nuclear reactions. And that is how we make use of these interactions to detect the neutrons. In the case of neutrons, so we can classify neutrons into slow neutrons or fast neutrons. In fact, there are other classifications like epithermal neutrons, when there are some regions of energy of neutron where there are high resonances like here I have shown here. The cross-section for the neutron induced reactions fall as we increase the energy of neutron.

This is called 1/v law, velocity of the neutron is increasing, so the cross-section is decreasing. So thermal neutrons, the neutrons of low energy are more reactive than high energy and somewhere in the middle around 1 to 2 electron volt, there are resonances in the cross-sections, whenever the nucleus is matching with its energy, its energy. So what we want to show is that thermal neutrons are more reactive and so many times to detect neutrons, we need to thermalize the neutrons. So we will discuss the interaction of slow neutrons and fast neutrons little bit separately.

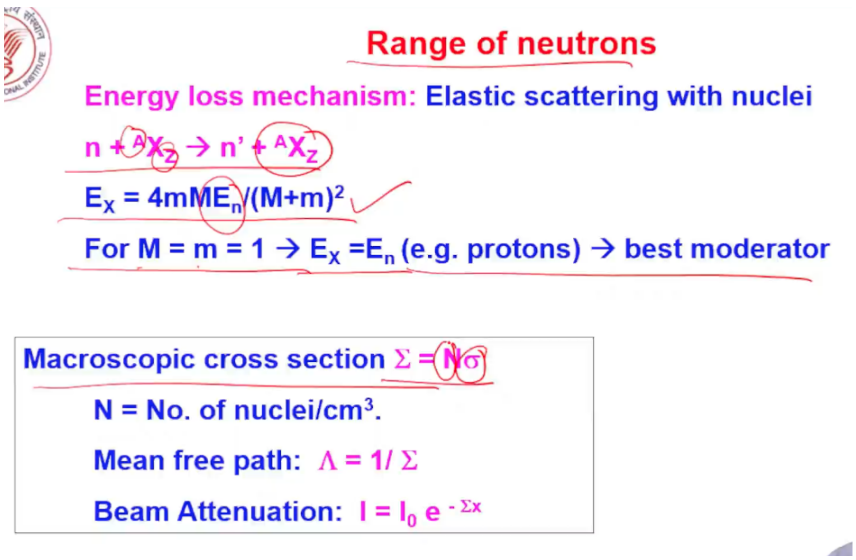
Slow neutrons are highly reactive and why it is called cadmium cut-off, the energy of neutron less than 0.5 electron volt is called cadmium cut-off because at 0.5 electron volt, cadmium has got this kind of resonances and so if you put cadmium, then the neutrons are totally absorbed by this cadmium. So that's called the cadmium cut-off, means the energy which is absorbed by the cadmium. So if you wrap a sample by cadmium, then low energy neutrons are all absorbed by the cadmium.

You will see only the fast neutrons. So the thermal neutrons, though it will undergo elastic scattering, but that is not important from the point of view of detecting the neutrons. The slow neutrons will predominantly undergo nuclear reactions, it can be neutron capture and gamma, it can be neutron induced reaction proton emission followed by, preceded by neutron capture, n,alpha or fission, neutron induced fission. So you can see detectors based on boron, BF_3 gas, where boron-10 interacts with the neutron to give alpha and lithium-7. So these are the charged particles. They will be detected; they will be depositing energy in the medium. Similarly $^3He(n,p)^3H$ reaction. So the tritium and proton, they are the charged particles. Similarly the $^{235}U(n,f)$ giving fission fragments which are charged particles. So the net result of the nuclear reactions by neutrons with different detector materials will be the production of charged particles which will interact with the, like heavy charged particles and deposit their energy in the substance.

The fast neutrons can also undergo inelastic collisions apart from elastic collisions and they can excite the nuclei or they can undergo nuclear reactions. So when it is undergoing elastic scattering, we have recoil nuclei like a neutron can interact with the proton and knock it off from the place. So we can have the heavy charged particles as a recoil nuclei or the fast neutrons can also undergo nuclear reactions like (n,p), (n,alpha), n,f (neutron induced fission) and (n,2n) types of reactions. So these neutrons detection can be done using the nuclear reaction. In fact, mostly the neutrons are detected using the nuclear reactions. And what is the range that neutron, how much distance they can travel like they are neutral particles.

So the energy loss mechanism is based initially only on elastic scattering or inelastic scattering. So if a neutron is colliding with a nucleus of mass number A, atomic number Z, then it can just give a kinematics you can set up and like we did in the case of heavy charged particles and electrons, the energy received by the recoil nucleus will be $4mME_n/(M+m)^2$. This is the same formula we derived before for the heavy charged particles. So same thing applies here. Now let us assume that for protons, the protons and neutrons are relatively same mass.

So $M = m$. And so if you put the value here, then you will find the energy of the recoil will be energy of the neutron. So that means what? With the proton when the neutron is interacting, neutron can give all energy in one single collision. Like in the case of fast electrons, fast electrons will give all energy in one collision. So when you want to reduce the energy of neutron using a moderator, the proton or the hydrogen material is the best one. So that is why you will find water is used as a moderator in the reactors. There are other problems with the water, so we use heavy water.



Range of neutrons

Energy loss mechanism: Elastic scattering with nuclei

$n + {}^{A}X_{Z} \rightarrow n' + {}^{A}X_{Z}$

$E_X = 4mME_n/(M+m)^2$

For $M = m = 1 \rightarrow E_X = E_n$ (e.g. protons) → best moderator

Macroscopic cross section $\Sigma = N\sigma$

N = No. of nuclei/cm^3.

Mean free path: $\Lambda = 1/\Sigma$

Beam Attenuation: $I = I_0 e^{-\Sigma x}$

Now finally the cross-sections, this is called the microscopic cross-section. When a neutron is interacting with the nucleus, we call cross-section as σ. But when a neutron beam is passing through a material, we call capital sigma (Σ) is called macroscopic, where n is the density, nuclei per cc, number of nuclei per cc or number of atoms also you can say per cc in the material. And so this Σ is like decay constant of a neutron. Like when we have the beam attenuation of the neutron, you can see here that the neutron beam is going, then I_0 to I. The neutrons also will follow the similar type of expression, $I = I_0e^{-\Sigma x}$, where this Σ is the macroscopic cross-section. And many times we associate a mean free path, that means what is the distance travelled by the neutron without interacting with the material, that is 1/Σ. So these are in fact used in the reactor physics when the neutron economy is being discussed, how the neutron is diffusing in the detector system, these concepts become important in that. So I will stop here and subsequently discuss the detection of radiations by different means. Thank you.