Nuclear Astrophysics

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Lecture - 36

Detectors - II

Welcome students to today's lecture on the continuation of discussion on experimental aspects of nuclear astrophysics. In the previous lecture I have discussed in brief ionization chambers, characteristics of gas field ionization detectors, organic scintillation detectors starting from the history of spinthariscope. In today's lecture I will continue the discussion on nuclear radiation detectors mainly inorganic scintillators and semiconductor detectors. And I will summarize by comparing with the ionization chambers. And if time permits, I will discuss one of the experimental techniques to measure the nuclear reaction cross section.

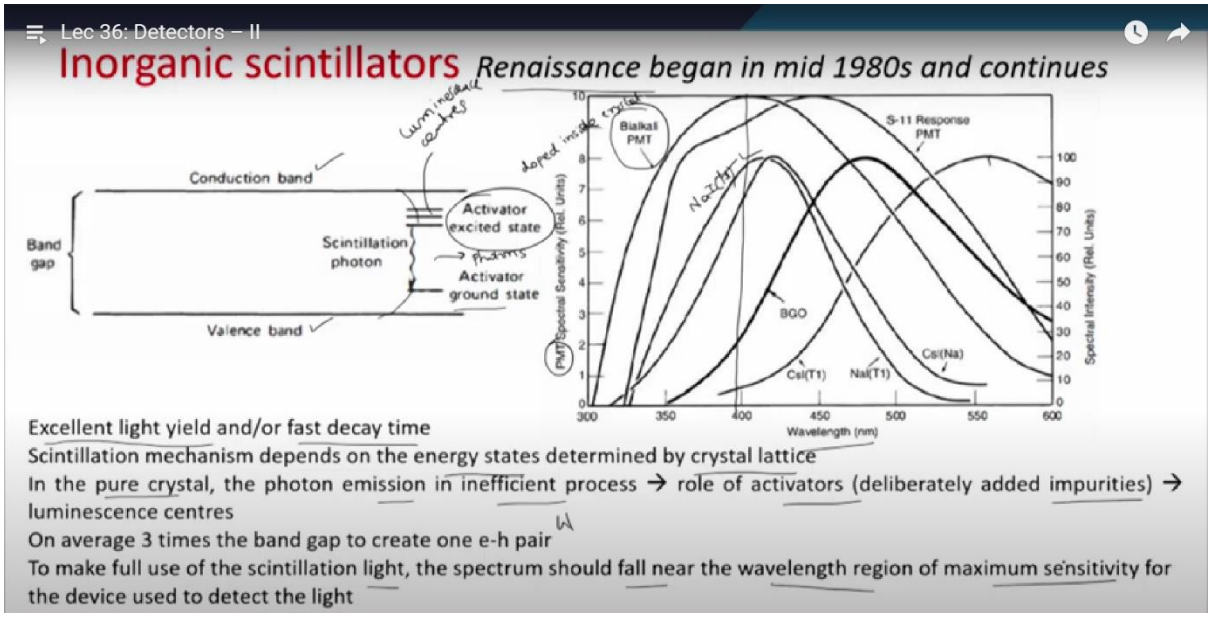
So, here you can see the band diagram for inorganic scintillators. Here we have replaced the medium of detection from gas to solid. Though we know that sodium iodide doped with thallium was in use since 1940 actually, the renaissance began in mid-1980s and still it continues. So, in inorganic scintillation crystals when transition takes place from conduction band to valence band then the emission of photons is not an efficient process. That is the reason, activators are used to dope inside the crystal. The activators sit in between conduction and valence band. As activator excited states because of these electrons from conduction band to the activator states and holes from the valence band the recombination leads to the emission of photons. So, we have activator ground states, we have activator excited states. The transition gives rest to the emission of photons which is an efficient scintillation process.

So, without the presence of activators many at times it is not required always. For example, if you take cerium bromide and there are a few scintillators which does not require any kind of activities. But most of the times in the field of inorganics scintillators it is important to dope with activators which makes the emission of photons during the recombination of electrons and holes in the visible region.

And this visible region the optical photons, that means photons in the visible region they can be easily sensitive with a photosensor like photomultiplier tube, silicon photomultiplier or avalanche photodiode. There are many photo sensors. So, the basic principle of inorganic scintillator is explained in this slide. Now the optical photons emitted from this crystal have to be coupled to an efficient photo sensor.

What kind of photo sensors have to be used? For example, the widely used photo sensors are bi-alkali photomultiplier tube and if you see the spectral sensitivity of the PMT on the y-axis wavelength on x-axis. There should be an agreement or matching between maximum

wavelengths of the photons emitted by this scintillation crystal. And thus, maximum wavelength for which the PMT spectral sensitivity is maximum. The wavelength for which PMT has maximum sensitivity.



Then we can have a better combination as a detector. So, it is important to choose an appropriate photomultiplier tube. For example, in this diagram you can also see the Caesium Iodide whose maximum wavelength is about 550. So, for this bi alkali PMT is not very much suggested. Whereas for this Sodium Iodide if you see the Sodium Iodide emits photons whose wavelength is varying like this. The maximum wavelength is around 420 nanometres and even for bi alkali PMTs the maximum wavelength is about 420 nanometres. So, this is how one has to choose the photomultiplier tube for efficient detection of optical photons emitted by a scintillation crystal. So, the combination of crystal and PMT plays very important role for its use in measuring the nuclear radiation emitted during the nuclear reaction relevant for astrophysics.

The advantage of inorganic scintillators is because of its high density. The light yield is really good; it is much better than organic scintillators. And many times you will also come across fast decay time. And the mechanism of scintillation depends on the energy states determined by the crystal lattice. For example, if the energy states determined by the crystal lattice if they allow then there is no need of any activators.

Whereas in the case of Sodium Iodide if you see Thallium doping is very much required. In the pure crystal as I said the emission of photon is an inefficient process that is why role of activators comes into picture. That means impurities are deliberately added which act as the luminescence centres. So, basically these are called luminescence centres because they are causing the emission of light. If you see the value of w that means energy required to create 1 electron hole pair. Normally on average it is 3 times the band gap. The remaining energy goes into the non-transitional processes. So, that is the reason we see the w value of inorganic scintillators is much higher than the semiconductor detector. And it is of the order of w value in the case of ionization chambers. And in order to use light emitted by the scintillator the

spectrum should fall near the wavelength region of the maximum sensitivity for the device used to detect the optical photons.

Let me quickly provide you the basic information of sodium iodide doped with thallium because it is widely used detector in the field of nuclear astrophysics. So, it is important for you to understand the role of activators and the role of sodium iodide doped with thallium. What are the properties which makes them useful for studying the nuclear reaction measurements? So, in 1948 Hofstadter he demonstrated that the crystalline sodium iodide, in which a small amount of thallium iodide where iodine is mainly responsible for the interaction with the gamma rays. It has been added in the melt and this thallium iodide plays role not only for the iodine but the thallium acts as an activator. So, that light emitted from the crystal comes into the visible range. And when thallium iodide is added to sodium iodide Hofstadter has seen that the light output is really good when compared with the organic materials.

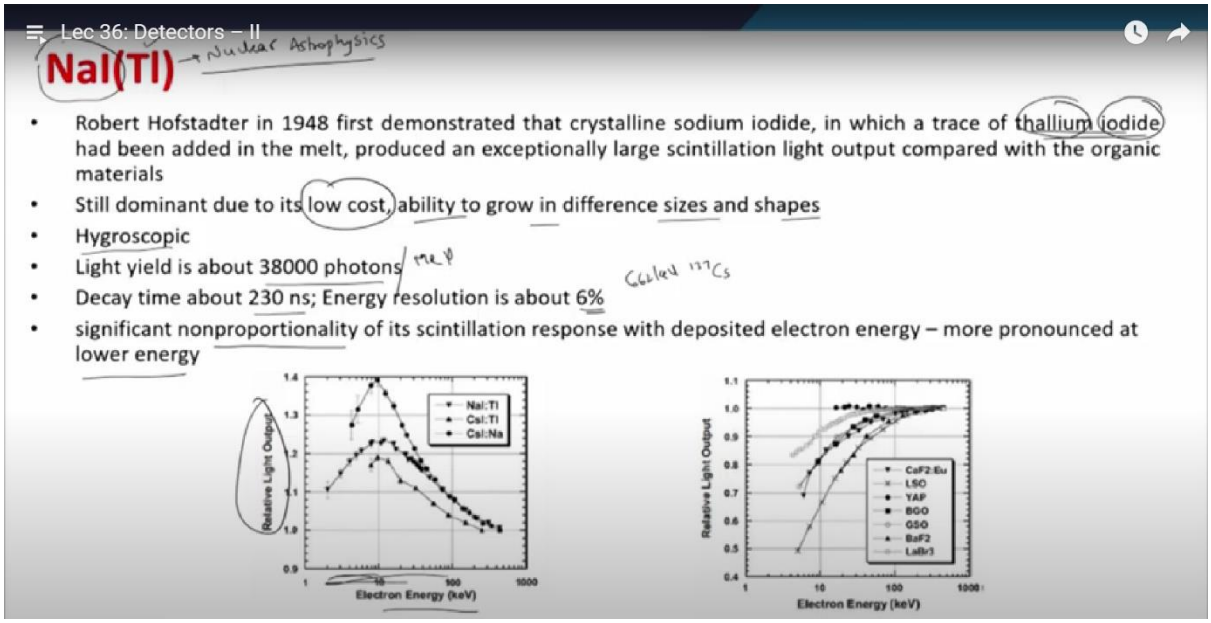
And even now the sodium iodide doped with thallium is dominant because of its low cost. That is one of the main reasons and the time-tested sodium iodide detector is still under use because of the reasons like low cost and ability to grow in different sizes and shapes. You can grow into straight conical hexagonal and different shapes. One can get using crystal growth methods like Bridgeman method.

Low-cost large volume because large volume crystal is useful for the detection of high energy gamma rays. However, it is hygroscopic. One has to pack the crystal within some material like aluminium otherwise, it will go bad. And the light yield is about 38,000 photons per MeV. The decay time is not excellent but it is perfectly all right 230 nanoseconds and the energy resolution is about 6%.

So, whenever I quote any number for energy resolution so it has to be understood that it is for 662 keV emitted by Caesium 137 nucleus. In one of the previous lectures, I have explained the decay scheme of widely used gamma source that is caesium 137. So, energy resolution of a detector when it is mentioned unless energy is mentioned otherwise it corresponds to the energy of 662 KeV because energy resolution is strong dependent of gamma energy.

So, with change in energy, energy resolution also changes. So, whenever you come across energy resolution value it corresponds to the 662 keV gamma rays. Significant non-proportionality, so, when I say non-proportionality, it means the relation between the number of photons emitted and the amount of energy deposited because of various reasons it is not proportional always. So, this non-proportionality is significant in the case of sodium iodide mainly at low energies.

So, it is not very much important for us because the gamma rays of our interest they are above 1 MeV kind of thing. This diagram shows the variation of light output versus electron energy. Now you can ask a question. This inorganic scintillator is mainly used for the gamma rays because it is hygroscopic and we are encasing inside some metal. It cannot be used for the detection of charged particles and it is not very sensitive for the neutrons as well.



So, mainly it is used for gamma rays. So, if I want to show the variation of light output it has to be with respect to the gamma rays. Why it is electron? Not very difficult to get the answer. See gamma rays interacts with matter; it could be gas, liquid or solid via three processes as I said in the previous class photoelectric effect, Compton and pair production. And the outcome in all these three processes is electron. So, the energy of the gamma is transferred to the electron fully or partially.

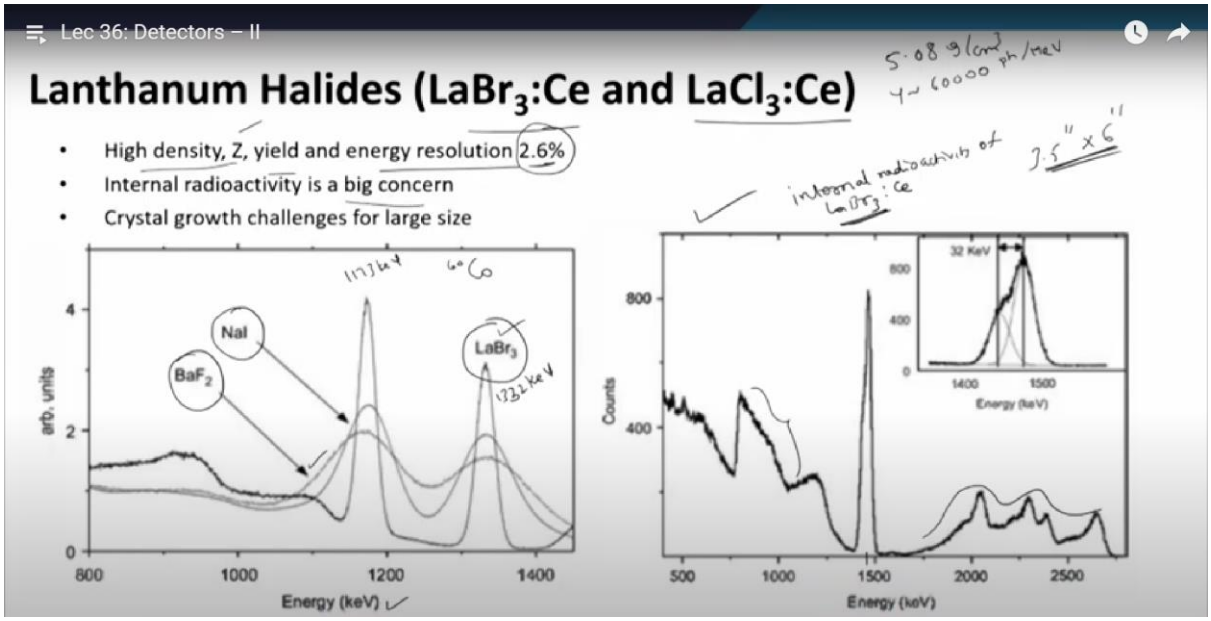
And it is the traversal of electron in the crystal which is responsible for the production of scintillations. It is the passage of the electron within the crystal. This electron is coming from a gamma ray which has transferred its energy partially or fully to the electron to the bond are loosely bound electron in the crystal. So, this electron while losing its energy it creates further electrons and holes whose recombination gives rise to the emission of optical photons.

So, that is the reason on the x-axis I have plotted the electron energy. And you can see mainly in the low energy like 1 to say 100 keV the non-proportionality is very high. And after 100 keV are say 3-400 keV the non-proportionality is not very significant. And for crystals other than sodium iodide, caesium iodide we can see the relative output how they are changing from 1 to 1000 keV. So, the non-proportionality is prominent in the case of sodium iodide and caesium iodide especially at the lower energies of electrons.

Now this slide shows you one of the advanced scintillation detectors that is Lanthanum Halides. They have very good density like 5.08 grams per centimetre cube and the yield is about 60,000. See sodium iodide has about 36,000 photons per MeV. So, in this case it is about 60,000 photons per MeV and it is very much resistant with respect to the temperature and mechanical strength is also very good.

This figure shows the comparison between barium fluoride, sodium iodide doped with thallium and lanthanum bromide. So, the ability to separate two peaks. So, here the energy is keV so, it is 1173 keV and this is 1332 keV. So, the source used here is cobalt 60 whose decay scheme I

have explained in one of the previous lectures. So, cobalt 60 is another widely used gamma source in the laboratory which emits two gamma rays in the cascade.



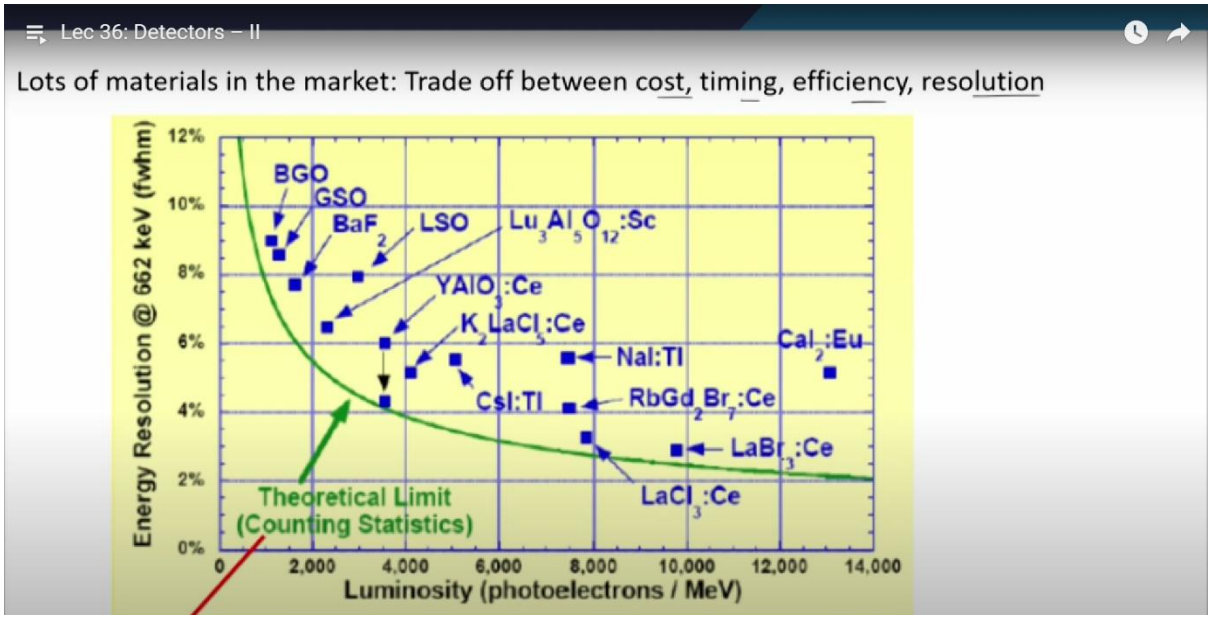
Of course, sometimes we are interested in measuring the angular correlation between these two gamma rays as well. But here in the spectrum of barium fluoride, sodium iodide and lanthanum bromide you can see. Lanthanum bromide supersedes sodium iodide which supersedes barium fluoride. So, the advantage of barium fluoride is basically it has a high density. So, its efficiency is higher than the sodium iodide but resolution is very poor.

So, depending on the application the choice of scintillation detector comes into picture. And this diagram shows the internal radio activity of lanthanum bromide. So, as I said the contaminants like actinium, they emit alpha and gamma rays especially around 1.4 MeV and, in this region, and beyond 1.4 also. So, this radioactivity from the contaminants present inside the lanthanum bromide crystal becomes a significant source of background.

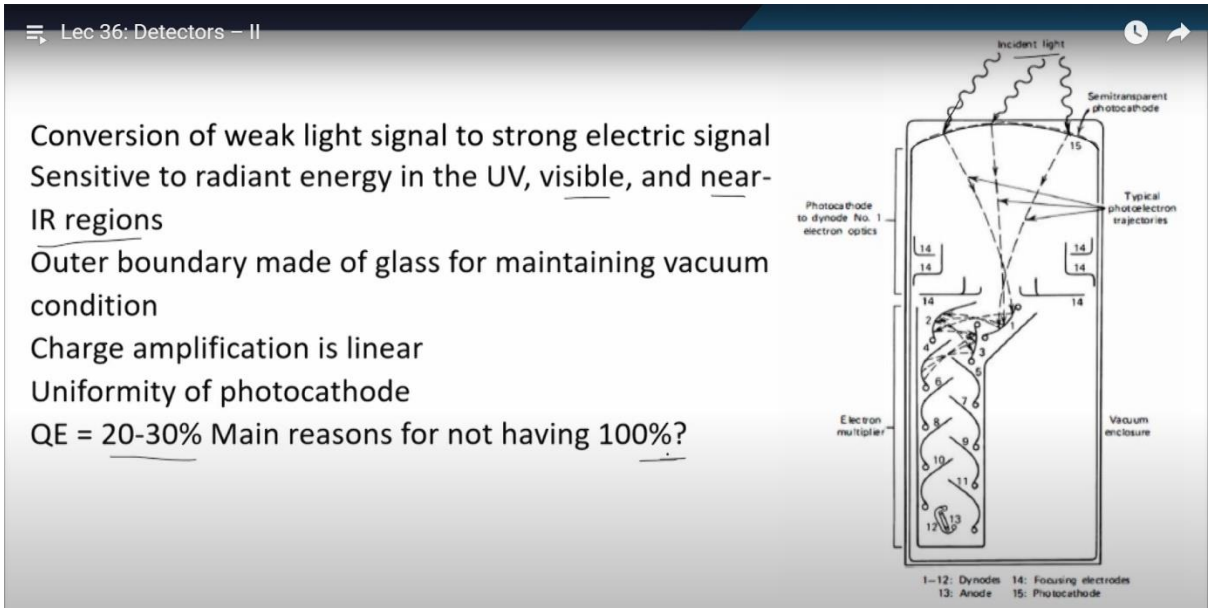
So, one has to take care of this background as well even though the detector is shielded properly. So, presently the size available for lanthanum bromide is like 3.5-inch diameter and 6 inch. So, beyond this because of the anisotropy related properties it is difficult to grow the crystals in large size. So, that is one of the disadvantages of lanthanum bromide to have in large volumes whereas sodium iodide can be grown in large volumes.

But it suffers from the light yield and resolution and also efficiency. So, as I said, high density effective atomic number is also quite good and yield and energy resolution for the small lanthanum bromide crystal people have reported a resolution of 2.6%. So, see the resolution of sodium iodide is about 6% and so, for lanthanum bromide it is about 2.6 to 3.2%. So, there is a factor of two in terms of energy resolution.

And as I said internal radioactivity is a big concern and crystal growth challenges are there for growing them in large size.

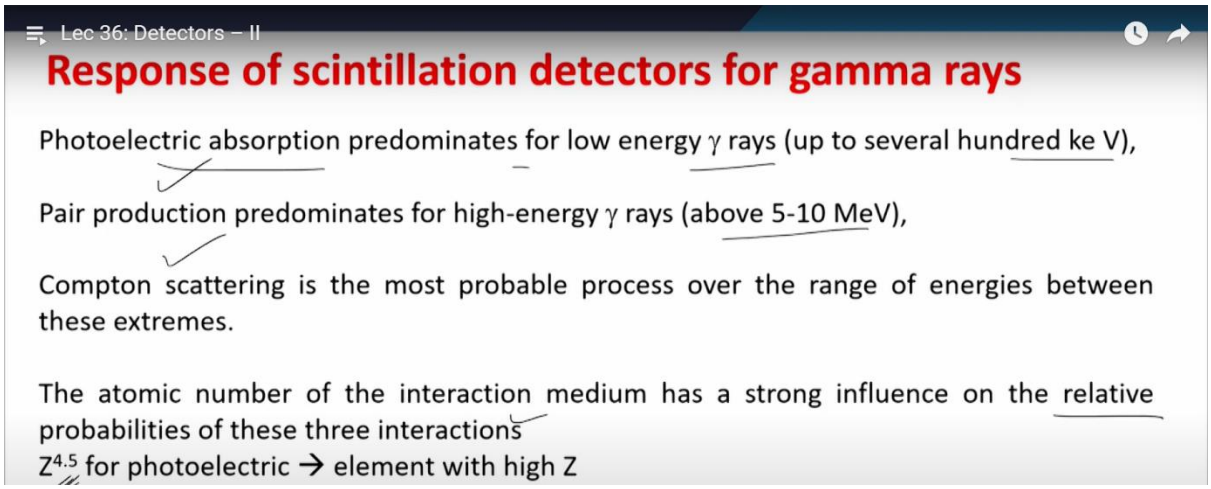


So, there are lots of materials in the market. There is a trade-off between cost, timing, efficiency and the resolution and there is a theoretical limit. No crystal could reach the theoretical limit like lanthanum bromide, which little bit comes to this theoretical limit and lanthanum chloride. And one crystal is there YAlO3 Ce this comes after certain conditions close to the theoretical limit in terms of resolution.



So, now this photomultiplier tube is basically conversion of optical photons into signal electrical signal. How it works? So, this incident light falls on the photo cathode and it converts into strong electric signal by multiplying the electrons. And here at the photocathode the conversion is taking place with the help of photoelectric effect and sensitive to radiant energy in UV, visible and near IR regions.

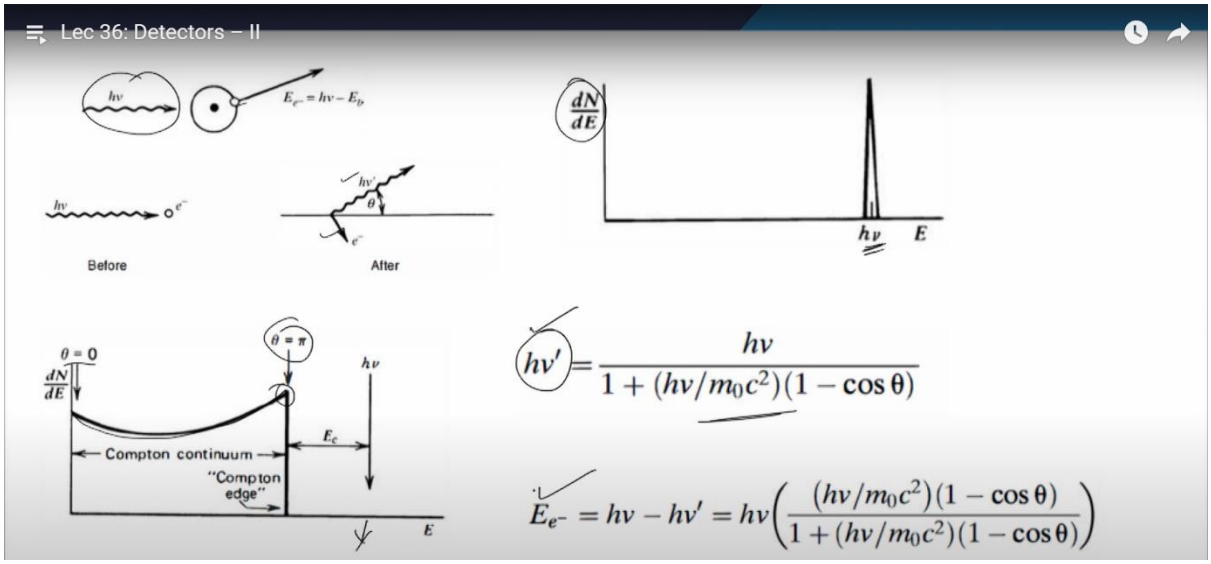
And outer boundary of this PMT is made of glass for maintaining the vacuum condition and the amplification is linear and the uniformity of photocathode also plays important role and quantum efficiency is not 100% it is 20 to 30% and there are reasons for not having 100%. Please guess why photocathode cannot convert the optical photons to electrons fully. And the W is higher than in the gas field and semiconductor detector.



Now let me discuss the response of scintillation detectors for gamma rays. And as you know photoelectric absorption predominates for low energy gamma rays say up to several 100 keV. And if you go to high energy, say above 5 MeV pair production comes into picture and in between these two ranges you have Compton scattering. And the role of atomic number is very well known of the interaction medium on the relative probabilities of these interactions.

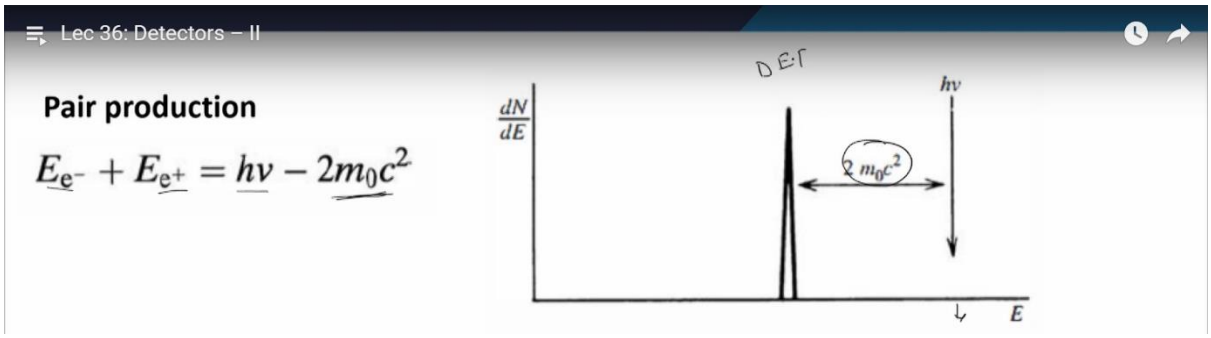
So, for a photoelectric effect element with high Z is preferred. So, element with high atomic number possess high photoelectric effect probability because it is given as Z to the power of 4.5. So, this is the reason high Z materials are preferred for allowing the photoelectric effect to happen when gamma rays interact with those materials.

So, here you can see incident photon ejects the electron. So, I am discussing the interaction of gamma with matter in detail and here you can see the energy deposited is h nu. So, if it happens with large number then dN by dE completely occupied with h nu only. But if it is Compton



scattering and applying conservation of energy and momentum one can derive the energy of the scattered gamma and recoil electron.

And the energy of the scattered gamma ray is given by this well-known relation. And the range of energies of electrons from theta = 0 to theta = pi give rise to curve called as Compton continuum. And the edge is called as a Compton edge and h nu is the place where full energy deposition takes place and the energy of the Compton scattered gamma ray is given here. And energy of the recoil electron is given here. One can easily derive by applying the conservation of energy and momentum.



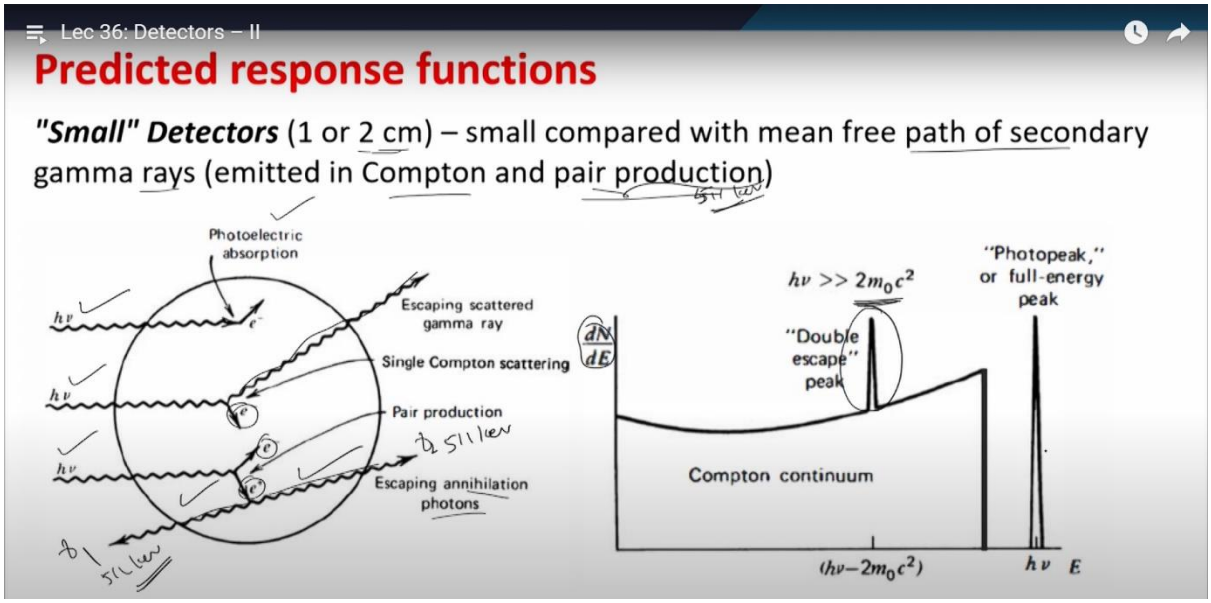
And in pair production you know the energy of the electron and positron should be in such a way that it is equal to the incident energy - two 511 keV gamma rays. So, that is the reason you will get a peak which is left to the full energy by an amount of 2m0c square. This is also called as double escape peak.

And let me quickly explain the predicted response functions of the detectors for gamma rays and neutrons. Because in nuclear astrophysics many times the proton capture reactions or neutron capture reactions leads to the emission of gamma rays. So, these gamma rays are mainly detected by scintillation detectors in particular sodium iodide and nowadays lanthanum bromide, cerium bromide detectors they are also in use.

Other than scintillation detectors it is the semiconductor detector which is in use. So, how scintillation detectors respond to the gamma rays. Let me start by assuming different sizes of scintillation detectors. So, let me start from small to large and then intermediate. So, here we need to take into account all physics processes which are happening in the crystal when gamma ray interacts with it.

For example, if you take a size of say 1 inch by 1-inch cylindrical detector or 2 inch by 2-inch cylindrical detector. Of course, that is small compared with the mean free path of the secondary gamma rays which are normally emitted in the Compton scattering and pair production. Because pair production we have 511 keV gamma rays. So, this diagram shows you the small size detector in which the h nu gamma photon can undergo photoelectric effect.

This gamma can undergo Compton scattering and Compton scattering can happen once or more than once. So, in single Compton scattering it is undergoing scattering only once and the gamma ray which is undergoing scattering is escaping from the crystal. So, that is what I mean by single counter scattering. So, here you have recoil electron and this gamma is escaping from the crystal. So, the same gamma if at all it undergoes pair production you have electron and you have positron.



And this emits 511 keV gamma rays in both directions. So, this we are calling as escaping annihilation photons. And here the response of the crystal if it is less than the 2 m 0 c square and more than 2 m 0 c square. One should be able to draw the spectrum. So, when I say energy spectrum what does it mean? It is the distribution of energy of the gamma rays. So, when I say spectrum, it is the distribution of energies.

So, energies on the y axis and the number of gamma rays on the x axis so, it is otherwise. So, energy of the gamma ray on the x axis and the number of gamma rays with that particular energy on y axis this dN by dE. And in case the energy of the gamma rays is much more than the 2m 0 c square. So, pair production take place and you can expect double escape peak. You can always ask why not single escape peak of course, it can happen.

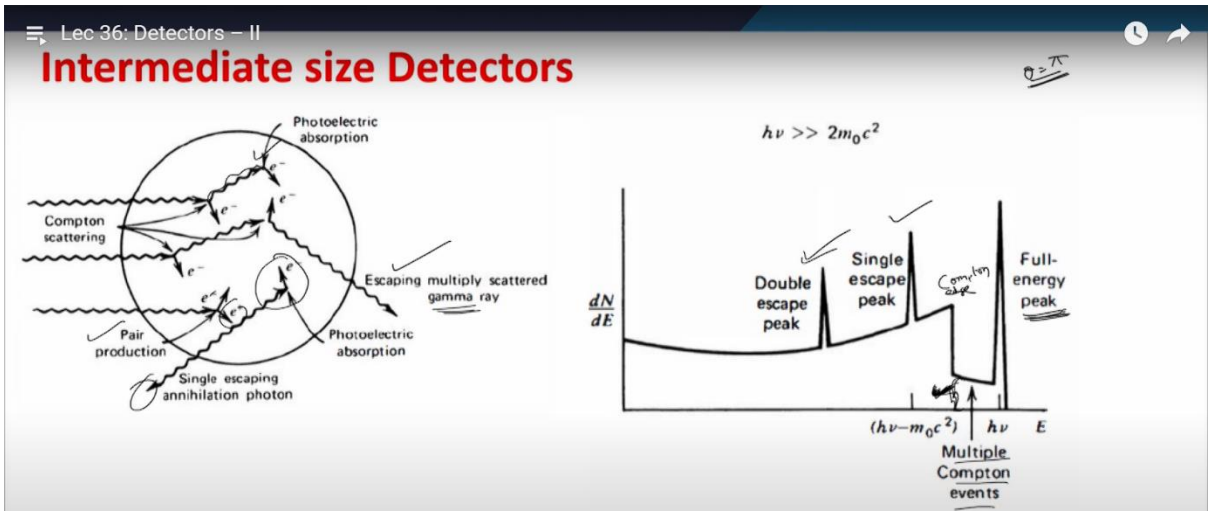
But here we are assuming that detector size is small. So, the absorption of 511 keV gamma within the crystal we are ignoring. So, in this slide if you see two gamma rays are escaping gamma 1 and gamma 2 whose energy is 511 keV so, this energy you are losing. So, this double escape peak is happening h nu - 2 m 0 c square.

So, continuing this for intermediate size. So, photoelectric absorption as it is and the Compton scattering happens in such a way that first Compton scattering happening here and second counter scattering happening here. So, multiple Compton scattering happening here. And overall, they are absorbed within the crystal and sometimes due to multiple Compton scattering also the final gamma ray can escape.

And in the pair production sometimes the electron and position when they are produced one 511 keV can escape from the crystal another 511 keV can be absorbed within the crystal. Considering all these processes what kind of spectrum we can assume. See remember in this particular case in pair production one 511 keV is absorbed. Why? Because the size we are assuming as bigger than in the previous case.

And due to multiple Compton scattering also we have increased the probability for a full absorption of energy. So, here you have single escape peak and also double escape peak. So,

in single escape peak we are assuming one gamma ray is escape peak. And in double escape we are assuming 2 gamma rays are escaping because of the pair production. And now you can see here multiple Compton events. So, there is a difference here. I am drawing like this.



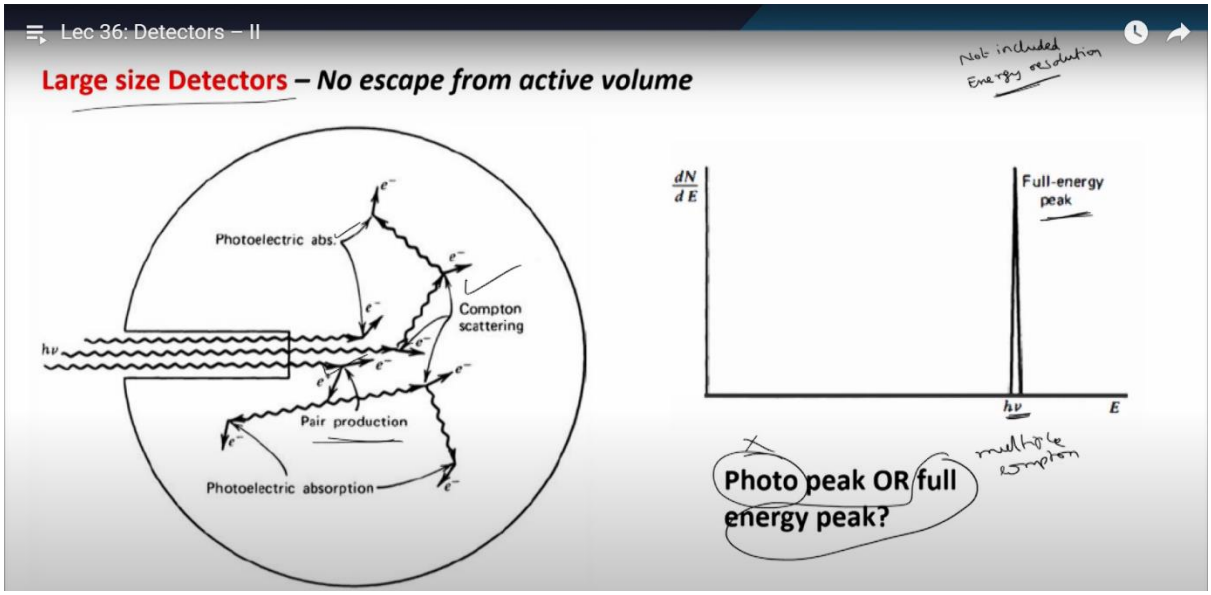
So, what is this? Because of the multiple Compton scattering other than theta is equal to pi energy corresponding to theta is good pi. If it undergoes Compton scattering again it can deposit more energy. And that comes in between Compton edge and full energy peak. And due to multiple Compton scattering if full energy is deposited like in instalment but full energy is deposited. It comes under the photo peak. So, now this peak is no more because of the photoelectric effect.

It could be due to the photo, it could be due to the multiple Compton scattering also. So, it makes sense to use the word full energy peak instead of photo peak because photo peak normally it refers to the peak arising due to the photoelectric absorption only. So, it is always better to use the word full energy absorption peak. When, you are aware that the crystal size is enough to accommodate the multiple Compton scattering.

Now if I go to the large size detectors you see nothing is escaping from the detector. Many times, it can happen, in the nuclear reaction if the gamma rays of interest are less and if you have enough money and if you buy large size crystals so you are not allowing the gamma rays to escape from the crystal. Then what kind of spectrum you expect? See in photoelectric absorption in Compton scattering in pair production in all manners.

Whatever electrons and positrons are emitted and whatever further interactions are taking place nothing is escaping from the crystal. So, full energy is deposited by each gamma ray within the crystal. So, it is quite easy to expect the shape of the spectrum in this case. So, we can get full energy peak at the energy corresponding to the incident gamma the energy corresponds to the incident gamma ray. Now here in all these slides I have not included the energy resolution.

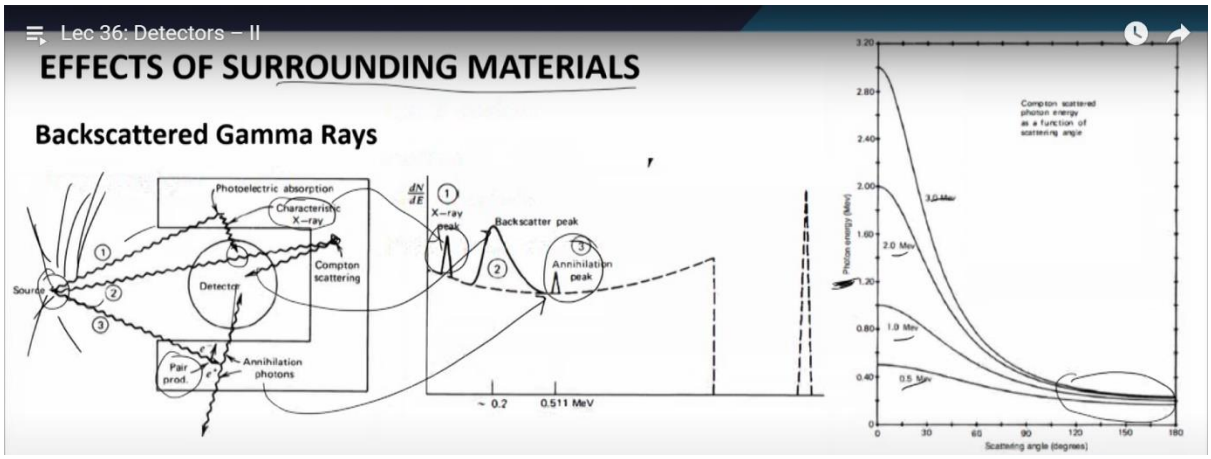
Just for the sake of simplicity I wanted to highlight the effect of size of the crystal on the response of the crystal for gamma rays. So, that is what I am trying to explain in these slides. So, as I said let us go for full energy peak because not only photoelectric effect you have



multiple Compton scattering also. And you have for in photo I mean pair production also it is giving rise to the emission of 511 keV gamma rays which are again deposited within the crystal.

Now one of the important aspect of the experimental setup how the surrounding materials will influence the response of the detector. For example, if you consider here some say source it could be due to nuclear reaction it could be due to target or simple radioactive source in the laboratory like caesium cobalt sodium. When gamma rays are emitted in all directions and they are also falling on the surrounding materials.

So, there is a high chance that they undergo absorption within the surrounding material and they can emit the characteristic x-ray because of the photoelectric effect and this x-ray can enter the detector. And this detector will detect the x-ray and these gamma rays it can pierce through the detector because most of the atom is empty remember. So, sometimes electromagnetic radiation may not deposit any energy in the crystal and to go to the surrounding material undergoes Compton scattering.



And scattered gamma ray can come back to the detector. So, all these scenarios are possible and if the energy is sufficiently high it can undergo pair production within the surrounding material. And it can emit annihilation photons and these photons can enter into the detector.

So, there is always a good possibility that detector detects the radiation not only from the source but also the radiation emitted by the surrounding materials.

So, if you plot photon energy versus scattering angle at different energies you can see that at higher angles the value of the scattered energy is almost constant. Now you can see here the spectrum looks something like this. You can have extra peak corresponds to character x-ray peak and back scatter peak because of this Compton scattering and inhalation peak because of this annihilation photons. So, this is how the materials surrounding the detector can influence the response of the detector.

Now let me discuss the response to neutrons. How neutrons interact with matter? So, we have seen charged particles interact with matter via ionization and excitation that is Coulombic interaction. Gamma rays being electromagnetic in nature they cannot take part in Coulombic interaction. So, electromagnetic interaction covers photoelectric Compton and pair production mainly. But neutrons they have mass but they have no charge.

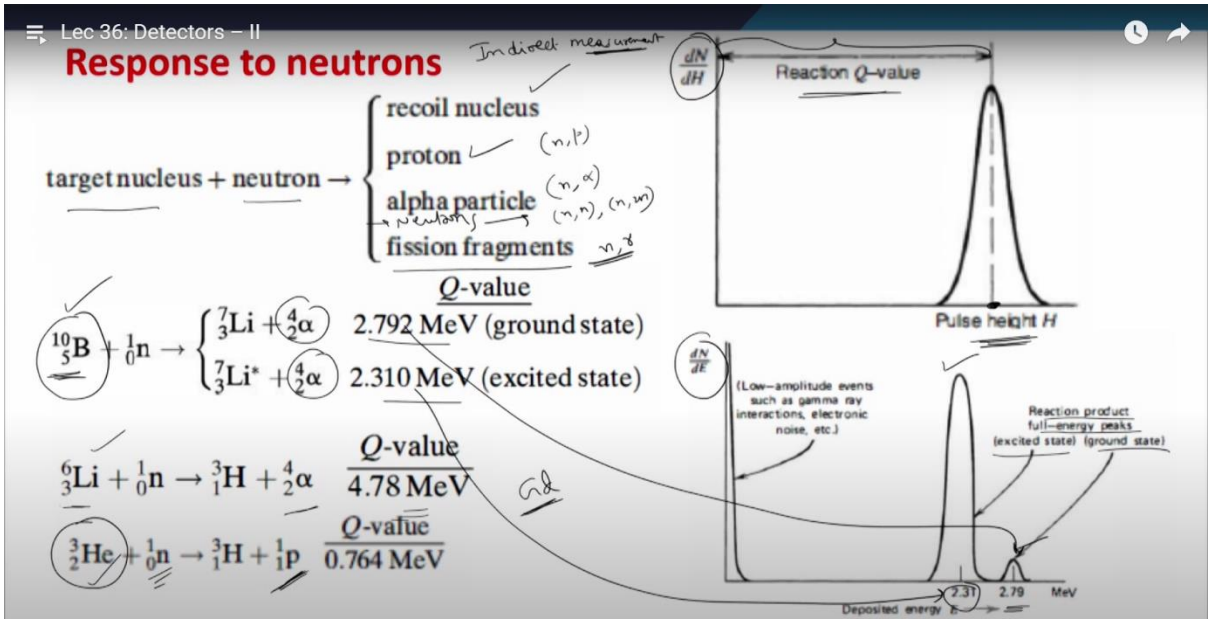
So, what kind of interaction neutrons will have with matter? We can divide into two types. Number one, scattering it could be elastic or inelastic. Number two absorption. Do you remember? Nuclear fission process in which slow neutron gets absorbed by uranium 235 nucleus and you have uranium 236 compound nucleus just by absorbing 1 neutron U 236 is undergoing fission. It is disintegrating. You have fragmentation so much is the effect of one slow neutron on a few nuclei like uranium 235.

So, the absorption of neutron may lead to the fission. And sometimes the absorption may lead to the emission of neutrons one or more than one. Sometimes the absorption may lead to the emission of charged particles and sometimes the absorption may lead to the emission of gamma ray. Because neutron induced reactions are important in the nuclear astrophysics already, I have discussed. So, it is important to study those reactions which emit the neutrons.

And who get moderated and initiate reactions for the synthesis of elements beyond iron peak. So, if you want to understand the nuclear reactions which are emitting neutrons then you need to use the detectors for detection and measurement of the neutrons. What kind of detectors you use? As I said it participates in scattering and absorption. So, you take those materials which have high absorption cross section or which have high scattering cross sections.

High absorption cross section and high scattering cross section so let me give you a few examples. So, as I said, a target nucleus + neutron can give rise to recall nucleus as part of scattering and it can give rise to proton that means n, p. And sometimes it can emit n alpha and also it can emit neutrons. So, it can emit n, n n, 2 n and fission fragments and in this fission fragments also many times you will get the emission of n and gamma.

So, the distribution of neutrons energies versus energy if you see it is strongly influenced by the reaction Q value because the kind of reactions I have explained it shows that the pulse height happens which depends on the reaction Q value. For example, boron has very good thermal neutron I mean it is a very good absorption cross section for neutrons. See when I say neutrons in general you should be in a position to divide into two types like thermal neutrons and fast neutrons.

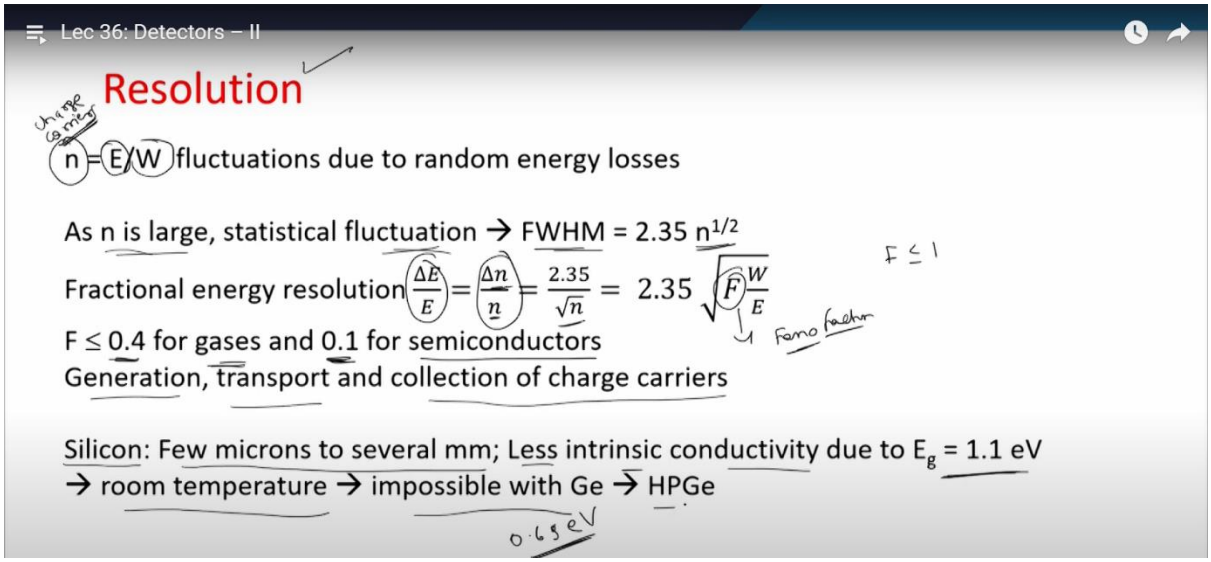


And the materials which are good for the detection of fast neutrons most probably they are not good for the detection of thermal neutrons. Because the change in the energy when we go from slow to fast neutrons changes the cross-section value as well. So, in this particular case I am discussing one of the important neutron absorber that is Boron. It gives alpha particles of two different energies and you detect these alpha particles.

So, you can see here 2.31 and you can see 2.792. So, dN by dE number of neutrons per n unit energy. And reaction product full energy peaks for excited state of lithium 7 gives rise to 2.31. And if the compound nucleus formed because of neutron + boron 10 decays to the ground state of compound nucleus. It gives rise to this 2.79 alpha particle. So, the detection of alpha particle is helping us to detect the neutrons. So, it is indirect measurement.

So, even gamma rays also. Gamma rays they are transferring their energy to the electrons and electrons are charging particles. And I have just already discussed how charged particles interacts with matter even because of neutrons. If they emit charged particles again this interaction of charged particles with matter comes into picture. And another nucleus which has good absorption cross section for neutron is lithium 6 which emits alpha particle.

And here the Q value is quite high 4.78 MeV and neutron + helium one of the important component for the detection of neutrons, mainly thermal neutrons. It gives recoil protons and by measuring the recoil protons we will get the signal and boron, lithium, helium and nowadays people are using gadolinium. So, all these are very good detectors for the thermal neutrons. And for fast neutrons the widely used component is chlorine which has very good absorption cross section for the fast neutrons.



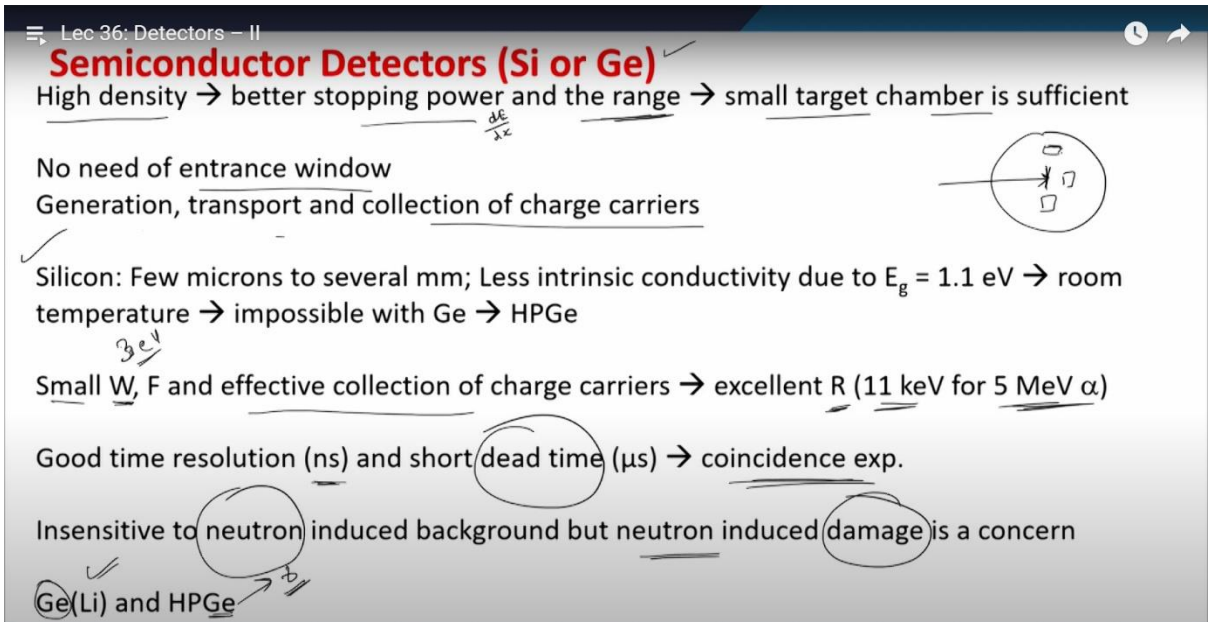
Now let me discuss the concept of energy resolution. One of the important properties of detectors see incident energy, if it is E and energy required to produce 1 electron hole pair or when one electron ion pair is W you can find out the number of charge carriers. See because of the random energy losses though the incident particle has same energy because of the difference in the energy loss mechanisms there is a randomness in the energy loss.

That leads to the fluctuations in the number of electron hole pairs or number of electron ion pairs produced. See remember this is the number small n which plays important role in measurement of the energy. So, as normally n is very large so, the statistical fluctuation can be approximated by Gaussian distribution with full width half maximum given by 2.35 square root of small n. And because n is function of energy so fractional energy resolution is nothing but fractional value in terms of delta n and n.

And delta n is nothing but 2.35 square root of n divided by small n which gives rise to square root in the denominator. And it gives rise to 2.35 W by E, where from this F comes into picture? This is called as Fano factor. See Fano has demonstrated that whatever the fluctuations we are expecting in the number of charge carriers. In reality it is not that much it is less. So, it is less than or equal to 1. For example, if you go to the gases like argon, it is like 0.4 and for semiconductor it is 0.1.

Here you see Fano factor is 0.1 for semiconductors and 0.4 for the gas. So, this less value of the semiconductor also is the advantage for the semiconductor. How? I will discuss in the next slide. And the generation of the charge carriers, transport of the charge carriers and efficient collection of the charge carriers plays important role in designing the detector. For example, in case of silicon normally the sizes are not in centimetres. You can see it is of the order of microns to several mm.

Because it has a less intrinsic conductivity because of the gap band gap 1.1 electron volts it can be used at room temperature. Because at room temperature the; energy is not sufficient for the electrons to go to the conduction band. So, which is not possible with the; germanium because of its less band gap. That is why it is important to cool the detector with the liquid nitrogen. So, that is the reason we go for high purity germanium detectors.



So, let us discuss more about the semiconductor detectors. So, the density is of course higher than the ionization chambers. So, I am comparing with now ionization chambers, gas field detectors. So, because of the high density the stopping power is also good, that means dE by dX. The energy loss per unit length is also quite high. So, the range is very small. So, one can have small size detectors and there is a possibility to go for small target chamber.

So, that in target when the incident beam reacts with the target material you can keep the charged particle detectors. Of course, vacuum has to be created within the target chamber. So, because of the range small value of the range of the charged particle. Now I am discussing about the importance of semiconductor detectors for charged particles. So, unlike gas field detectors there is no need of entrance window.

So, this is where the straggling within the entrance window can be avoided. And as I said the efficient generation transport and collection decides the sizes of the detectors. And of course, this is some kind of repetition the silicon and HPGe already I have discussed this. Now this is important the small value of W. It is of the order of 3 electron volts in case of semiconductors. Do you remember the value of W in the case of gas?

It is about 30 electron volts so, 10 times difference. So, W value is less so, E by W if you take n will be more. So, more charge carriers are created and under the influence of electric field and because of the less size there will be efficient collection of the charge carriers. This gives rise to the value that we are looking for excellent resolution. In terms of energy for 5 MeV alpha particle the energy resolution is of the order of 11 keV.

And the time resolution also quite good for semiconductor detector that is in nanosecond dead time. Particles are continuously falling on the detector. So, before second particle interacts with the detector active volume, sometimes the detector will die for some time. During which it cannot consider the second event. So, this is called as dead time. The dead time is quite high in the case of gas field detectors whereas in the case of semiconductor detectors it is quite less.

And because of this reason coincidence experiments prefer the use of semiconductor detectors. One of the interesting thing, is that semiconductor detectors cannot detect the neutrons they are

insensitive. However, the major problem is neutrons can damage the crystal by changing the crystal properties and inducing the lattice defects. So, if you are using the semiconductor detectors ensure that neutron sources should not be in the surroundings.

And another semiconductor detector that is germanium widely used detector for nuclear astrophysics studies is germanium doped with lithium. And another way is you cool the germanium crystal to low temperature using liquid nitrogen. And this is one of the widely used detector for studying the nuclear reactions with the measurement of gamma rays because of its excellent resolution. Actually, nobody can match HPGe in terms of energy resolution.

Why energy resolution is very high in the case of germanium? Because of less W value and less Fano factor value. And why we need to cool the germanium detectors? Because at room temperature the thermal fluctuations can induce the noise because of which the data that we want to acquire will be polluted. So, it is very important to cool the germanium detectors. So, with this let me close today's lecture.

And let me discuss one interesting experimental technique in the next lecture. Thank you very much for your attention.