Neutron Scattering for Condensed Matter Studies
Indian Institute of Technology, Bombay
Lecture – 09A

Keywords: Gas detectors, Nuclear reactions, ionization region, proportional region, Geiger counters, Electron shower, photoelectric absorption, Compton scattering, Pair production

Hello, welcome to the lecture on detectors in this series of lectures on Neutron scattering techniques. I have discussed various components that are required right from tailoring the beam in the reactor core to the beam falling on the sample. In the last leg of this description, I will narrate to you how neutron detectors work because this is important for understanding various neutron scattering techniques. How we design them and how we use various detectors in different kinds of sources? So, with this brief introduction let me get to the topics that I covered (so far, on neutron beam design).

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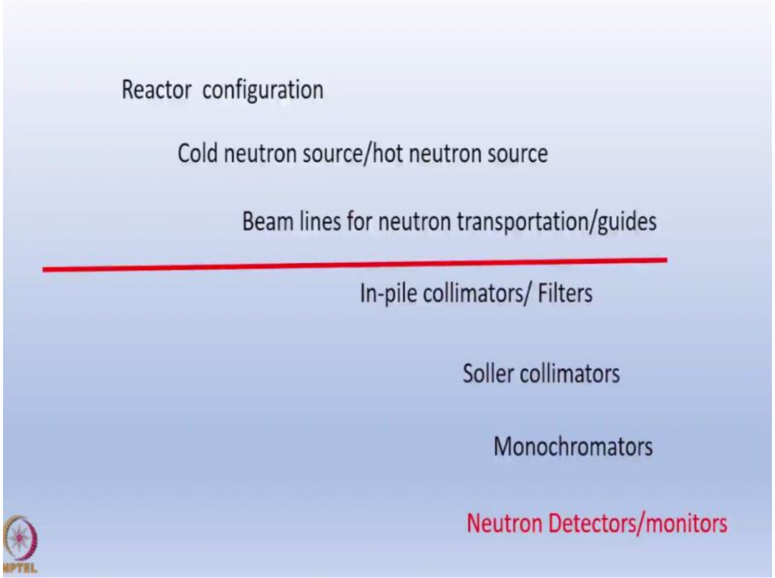

Regarding neutron beam design, I started with reactor configuration. I discussed with you how beams are made in the reactor and then how they are tailored to hot or cold ranges using cold or hot neutron sources by using moderators at cryogenic temperatures like liquid hydrogen, deuterium (~20 K), methane (~ 100 K) or by using hot moderators like a graphite block at 2,000° C.

I discussed with you how the beam lines are designed to take these neutrons out and also the neutron guides that act as optical fibers for neutron. I am harping (on guides) because they can take neutrons far away from the source to neutron guide halls. I also showed you the guide halls photographs. Afterwards, I discussed beam tailoring inside a beam line using in pile collimators as well as using filters.

In-pile collimators restrict the geometry of the beam and the filters remove certain undesirable neutron energies with good transmission for the desirable neutron. Then I discussed soller collimators. Soller collimators are collimators which can bring two contradicting requirements together, that is we need a large beam for neutrons, something like 5 cm ×5 cm (say in Dhruva) but at the same time we need good angular resolution for the beam to define our wavevector $\vec{K}$. Using Soller collimators, the beam is broken into vertical slits and these vertical splits are separated (by slits) as narrow as 1 mm distances and the length of the collimator is typically around say half a meter which dictates what is the resolution in defining the $\vec{K}$. At the same time, the beam remains large because the entire soller collimator covers a wider beam. Then I discussed one of the most important aspects in (preparing) the neutron beam, the monochromators. The monochromators actually select the neutron energy from a polychromatic beam, often after filtration because by filtration you can remove the high energy unwanted background-creating fast neutrons (and) then we select the desirable wavelength by Bragg-Scattering.

There are other kinds of monochromators I will discuss later. In general, the monochromators are silicon, germanium, pyrolytic graphite and they allow you to choose the desirable wavelength or energy (of the neutrons) depending on the Bragg angle that you choose for the monochromator.

Now comes the last piece of devices which are neutron detectors and neutron monitors. For counting neutrons, in a scattering experiment you need to count the number of neutrons that are being scattered and for that we need neutron detectors. In this lecture I will be describing to you the neutron detectors.

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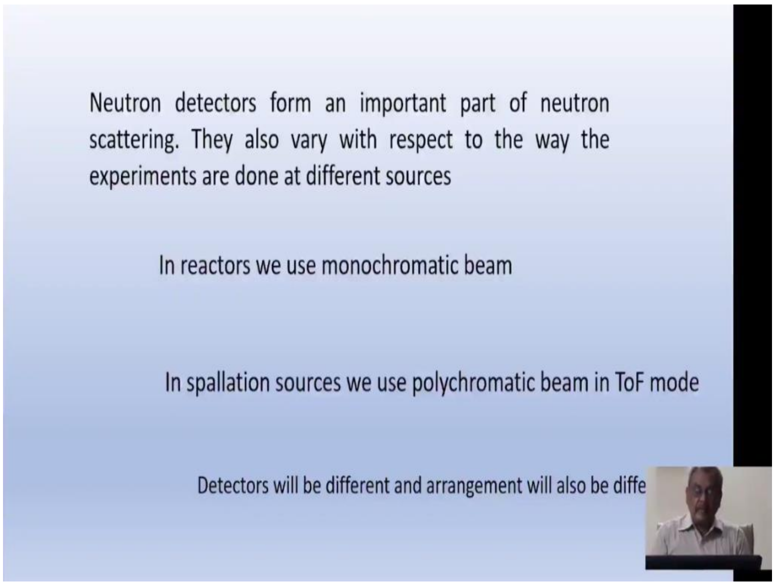

Neutron detectors are an important part of neutron scattering because that is the final device which gives me the scattered intensity. But the neutron detectors vary with respect to the way we do the experiments. As I mentioned earlier, at present day, we have, not just nuclear reactors but also the spallation neutron sources and spallation neutron sources use the different kind of spectroscopy called time of flight spectroscopy which we will discuss later. Whereas reactors use what is known as monochromatic neutron beam and then the spectroscopy is (done) with respect to monochromatic neutron beam. In case of spallation neutron sources, we use time of flight with respect to polychromatic beam. Detectors will be different for different kinds of experiments. So, I will briefly mention to you in this lecture mention how the experiments are done and how the neutron detectors work.

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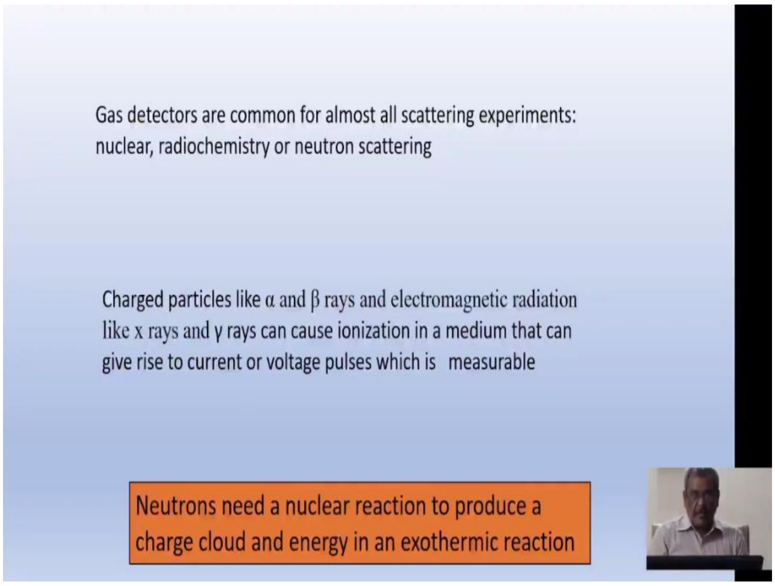

We are all familiar with gas detectors and gas detectors are omnipresent in almost all scattering experiments. We are aware of nuclear experiment in radiochemistry and also in neutron scattering, (the topic) which we are discussing now. Many of us during the master's days have done nuclear experiments and did counting (of radioactive particles) and we have used Geiger-Mueller counter.

I know that many of you have done experiments using Geiger-Mueller counter. Now regarding radioactive materials, charged particles such as alpha rays or beta rays are coming from the nucleus and also there are gamma rays and extranuclear x-ray. All these charged particles and the electromagnetic radiation can cause ionization in a medium and ultimately the detector's role is to convert it to current or voltage pulses which can be measured.

Every time a charged particle like alpha or beta ray comes inside the detector it is detected and finally registered as a count. Now interestingly alpha rays and beta rays are charged rays. Alpha rays are (ionized) helium nucleus and beta rays are electrons but it is coming from the nucleus and x-rays is an electromagnetic radiation of wave length typically around 1 to 10 Å. All these can cause ionization (in a medium). But neutron is a neutral particle. So, it needs to be converted and for that our detectors have to be special unlike other detectors., We need a nuclear reaction to produce a charge cloud and energy in an exothermic reaction and that can be detected in a (neutron) detector.

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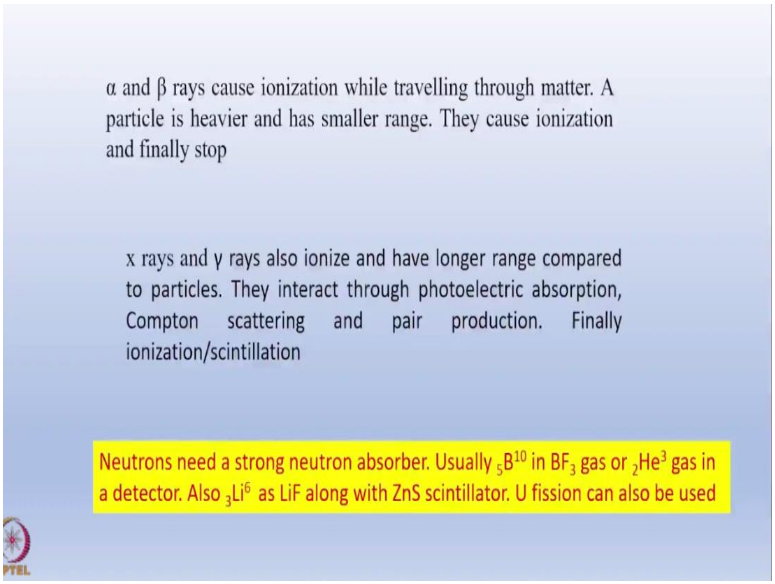

Alpha rays and beta rays cause ionization once they enter a gas medium. I am primarily talking of gas detectors, but it is also true for solid medium. Alpha rays have very narrow range (in a medium), beta rays will have longer range (in a medium) because alpha particles are heavier, beta particles are lighter. Lighter particles travel longer distance, heavy particles travel lesser and (both of) them can cause ionization and finally stop in the medium.

Through ionization, charge is produced which is counted. X rays and gamma rays also ionize (a medium) but have longer range compared to particles (like alpha and beta) and we are aware that they interact through photoelectric absorption, Compton scattering and pair production. Photoelectric absorption is basically absorption of an x-ray in an atom and then a photoelectron comes out in the process when the x-ray is absorbed.

Compton scattering is when you take the photon picture and the x-ray or gamma ray undergo momentum conserving scattering process. Pair production happens when the gamma ray has energy more than 2 × 511 keV because this is the rest mass of an electron. Electrons and positrons are produced in a pair production (process) and these are charged particles which can be again be counted and finally it causes ionization or scintillation. I will talk about ionization first, scintillation later.

For neutrons we need a strong neutron absorber like $_5B^{10}$ and $_2He^3$. $_5B^{10}$ in form of gas in BF_3 or $_2He^3$ gas in a detector. $_2He^3$ is an isotope of the He which is much more expensive than normal $_2He^4$, but an extremely important component of neutron-based experiment because helium detectors are used heavily.

And Li^6 as an isotope of Li along with ZnS scintillators it causes a (nuclear) reaction, interacting with neutron and produces one tritium and one proton. Uranium fission is where neutron causes breaking up of nucleus and also produces charged particles with high energy, that can also be used (for neutron detection). But usually when we use fission, the efficiency of the detectors is not so good and they are used as monitor detectors.

I will come to on monitor detectors later. Right now, know that they are used in low efficiency detection. However, when you want to have more than 80% detection efficiency, in a scattering experiment, the neutrons which has gone in (the detector) and produced a charged cloud, there we use mostly gas detectors and in spallation neutron sources, scintillation detectors are also used. First, I will discuss the gas detectors.

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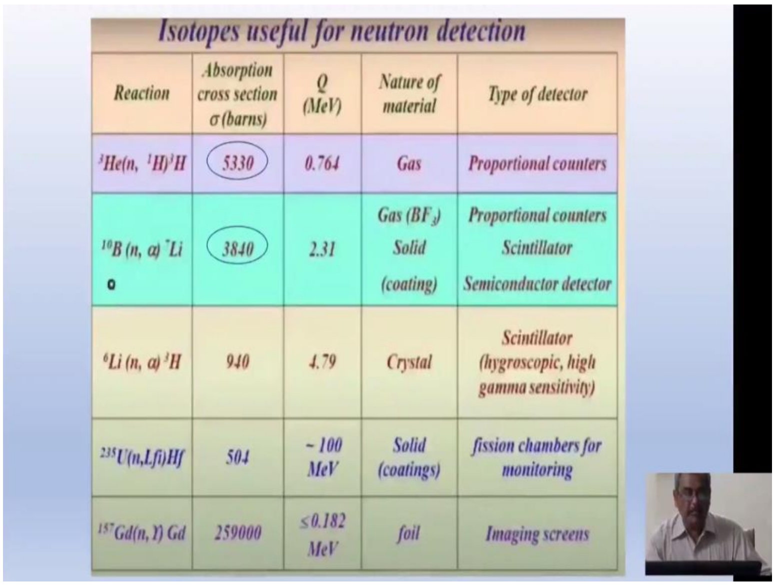

Isotopes useful for neutron detection

Reaction	Absorption cross section σ (barns)	Q (MeV)	Nature of material	Type of detector
$^{3}He(n, ^{1}H)^{3}H$	5330	0.764	Gas	Proportional counters
$^{10}B(n, \alpha)^{7}Li$	3840	2.31	Gas (BF_3) Solid (coating)	Proportional counters Scintillator Semiconductor detector
$^{6}Li(n, \alpha)^{3}H$	940	4.79	Crystal	Scintillator (hygroscopic, high gamma sensitivity)
^{235}U(n,Lfi)Hf	504	~ 100 MeV	Solid (coatings)	fission chambers for monitoring
$^{157}Gd(n, \gamma)$ Gd	259000	≤0.182 MeV	foil	Imaging screens

I have given a table here for the (nuclear) reactions. So, let us check the reaction or He-3 with neutron which is, ${}_{0}^{1}n + {}_{2}^{3}He \rightarrow {}_{1}^{1}H\ (proton) + {}_{1}^{3}H\ (tritium)$. Both proton and tritium are charged particles and when they move through the gas, they produce ionization. Similarly, the reaction with B^{10} is, ${}_{0}^{1}n + {}_{5}^{10}B \rightarrow {}_{2}^{4}He + {}_{3}^{7}Li$.

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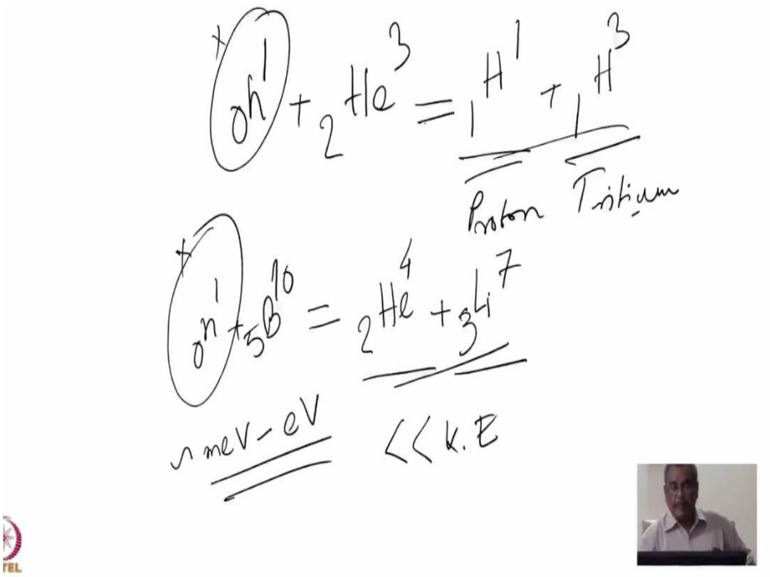

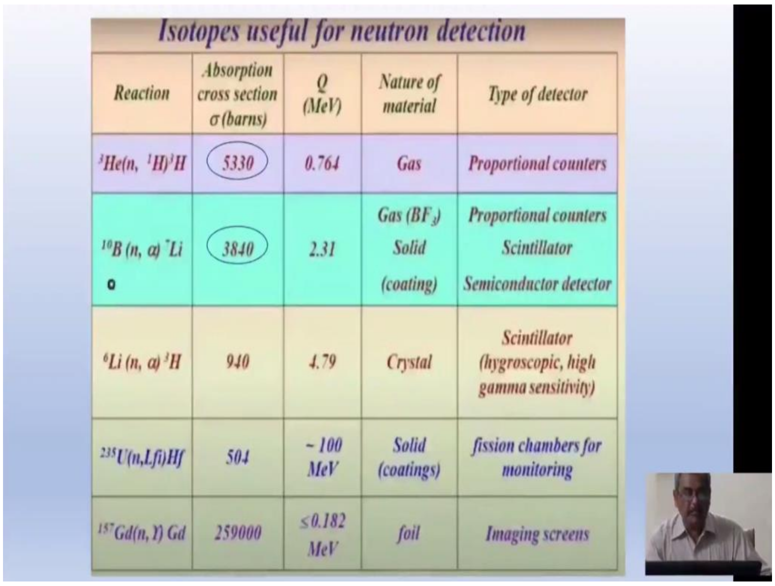

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Actually, boron-10 is acting like a sensor by converting neutron to charged particle. These particles come out with some kinetic energy of the charged particles and they produce a charged cloud which is detected (in turn). But we must remember that the neutron energy in most of these reactions is of the order of meV- eV. They are much less than the kinetic energy of the products (nuclei). So, detection of neutron does not give us the energy of the neutrons because ultimately the charged clouds are produced by the products and not by the neutron itself. So, no way we can find out the neutron energy (directly). But you can detect them and for finding out the neutron energy the techniques, I will come to later.

Similarly, with Li^6 isotopes the neutron can interact and produce tritium. Gadolinium gives neutron to gamma conversion and we can detect them (the gamma) on a photographic plate.

So, they are also used for imaging techniques in a foil (form) and I have given the absorption cross sections. You can see that helium has a very high absorption cross section of 5,330 barns (1 barn = 10^{-24} cm^2.

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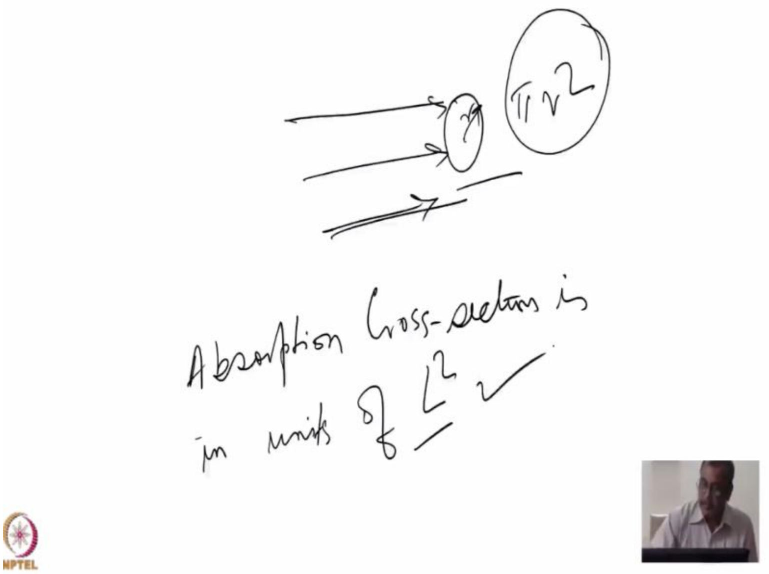

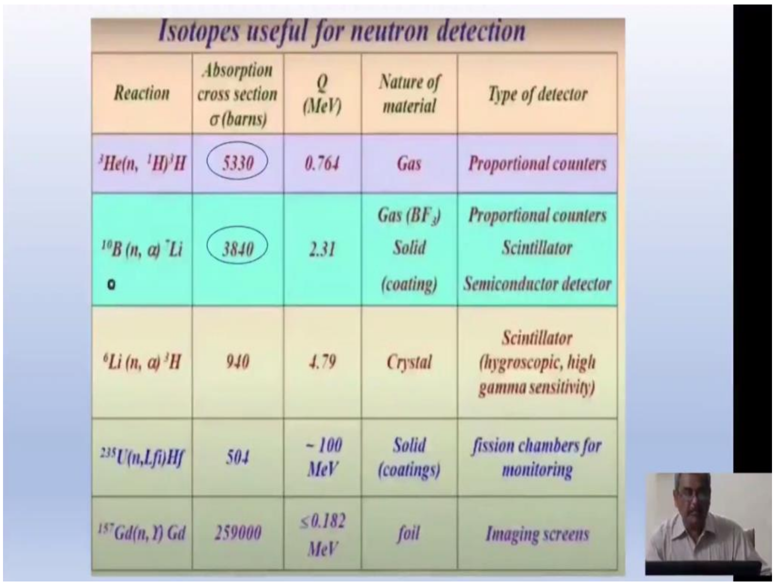

Isotopes useful for neutron detection

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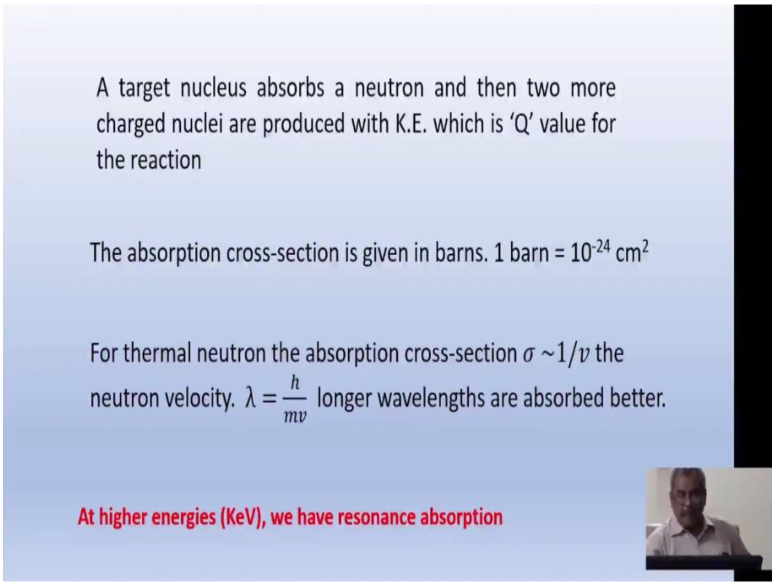
¹⁵⁷Gd(n, γ) Gd	259000	≤0.182 MeV	foil	Imaging screens

Always we talk about scattering cross section in terms of area because classically you can see if you have a disc of radius r (in the path of a neutron) it gives a resistance of πr^2 in the path of a beam. Absorption cross section is in units of length square always. I have given it in barns. I have also listed the exothermic energy in reactions. For example, 764 keV in case of He^3, in case of Boron it is 2.31 MeV and similarly the energies are given in case of fission we have of the order of 100 MeV. He^3 and BF_3 are used in the gas mode mostly as gas detector. Boron - 10 can also be used as a solid coating; the alpha particle and the lithium can cause tracks of charge in the coating and they can used as scintillation detectors. Then Li-6 can also be used as a crystal, the fission chambers can be solid and Gadolinium can be used as foil which will produce gamma rays (for detection). (Refer Slide Time: 17:58)



Hence, basic principle (of detectors) is that target nucleus absorbs a neutron and then two more charged nuclei are produced with kinetic energy shared between them which is Q value for the reaction. This is not proportional to the neutron energy as I told you earlier. This Q value is fixed and it does not depend on the energy of the neutron. The absorption cross section as I mentioned just now is in barns.

For the thermal neutron the absorption cross section σ is (proportional) to $1/v$ where v is the neutron velocity, and neutron wavelength is given by h/mv. Longer wavelengths have slightly larger absorption cross section in the thermal range. At the higher energy ranges i.e. in keV, we also have resonance absorption because these energies can match with the nuclear energies in the shell model and then (neutrons) can be absorbed through resonance absorption, which means higher absorption probability at certain resonance energies.

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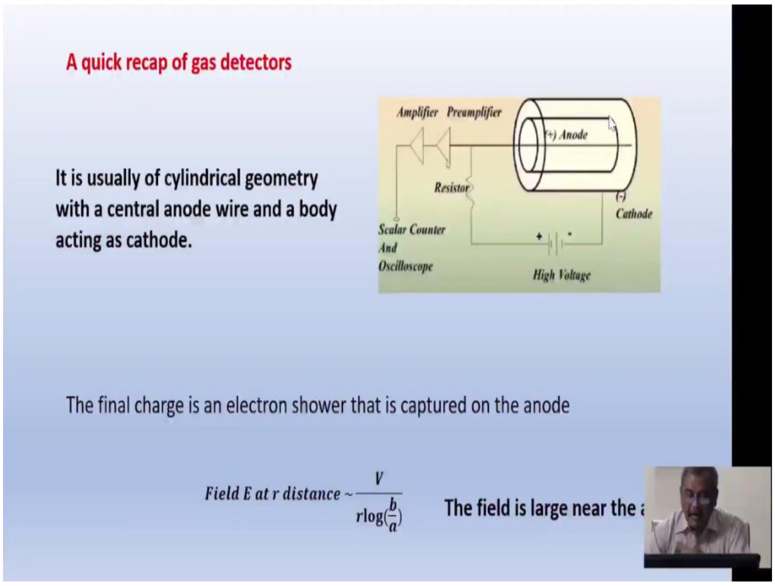

Now, I will quickly give you a recap of a gas detectors. A gas detector is usually of cylindrical geometry. I am saying usually because I will show you later that in case of some of the position sensitive detectors, they can be also of square geometry. In case of cylindrical geometry, you can see that there is a central wire known as anode on which the charge is collected, there is a body which is usually grounded and it is a cathode. The charge that we collect finally is mostly electrons and electron shower come and heats the anode. The anode of the detector is connected through preamplifier-amplifier (combination) to the counters. This is important that in a cylindrical geometry it is easier to engineer (the assembly). For two coaxial cylinders, one is anode wire and the other is cathode, the field at a distance (from the cylinder axis) is given by $\frac{V}{r\log\frac{b}{a}}$. So, the field is larger near the anode.

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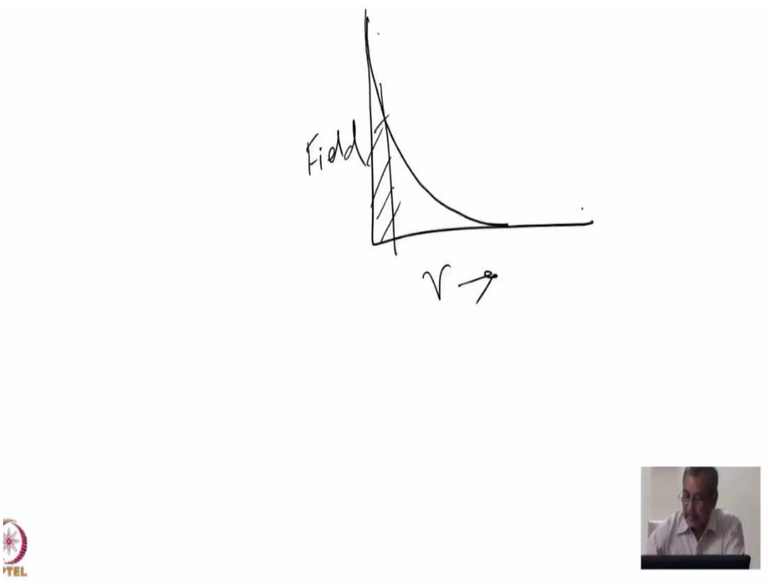

That means, if I plot the field as a function of distance *r* from the center considering the anode is of (nearly) zero diameter, then it falls drastically like this. The field is very high near the anode and it falls quickly as we go out in the detector. So, if the field is high near the anode and it is less when we go out to the cathode, the charge cloud which is produced close to the anode is collected.

Let me just now bring it to your notice that there are various regions when we increase the voltage in a gas detector and it looks like the one drawn here.

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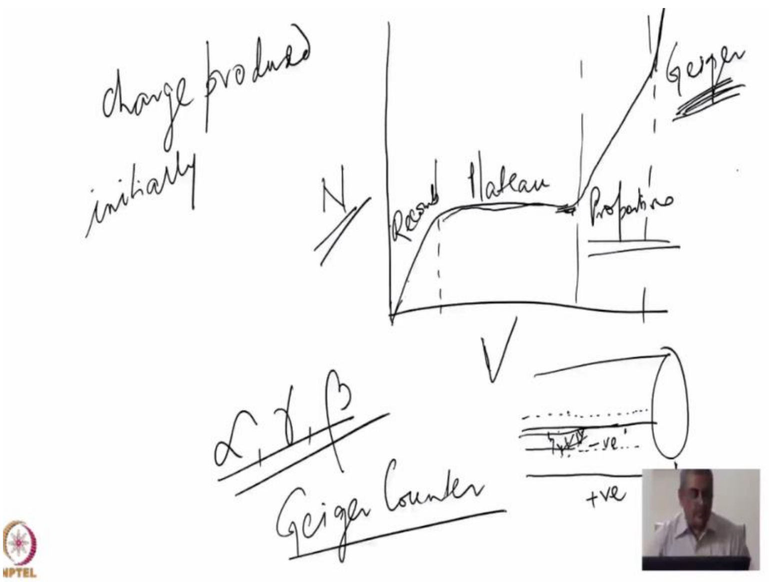

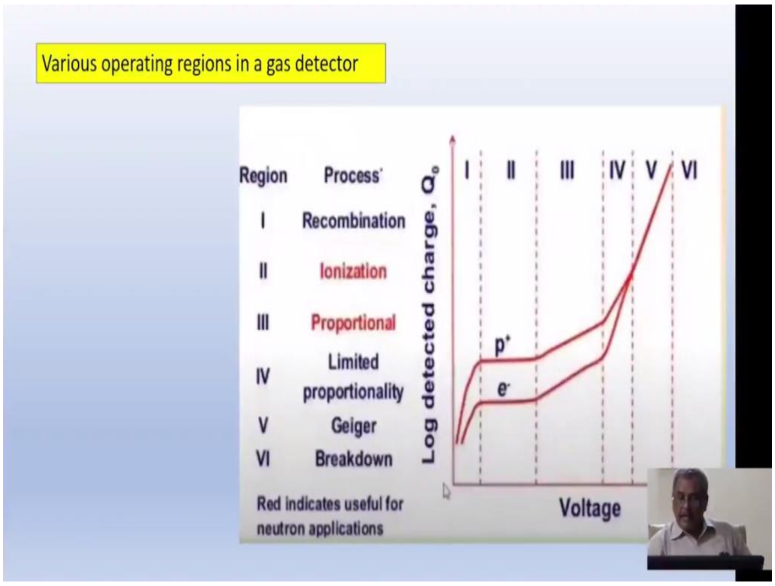

First you have the recombination region, as we increase the voltage (across the anode wire and the cathode body). In recombination region charged particles are produced after absorption of neutrons caused ionization in the medium. In this (voltage) range you are collecting those ionized particles (ions and electrons) in the cathode and the anode. As we increase the voltage, the number of charges collected increase because at lower voltages there is a probability that these electrons and ions may recombine and then I will lose them. As I increase the voltage the field increases, acceleration towards the anode increases and so ultimately start collecting all the charges (produced) and we reach a plateau. So, we do collect all the charges (produced initially) in the plateau region.

The positive ions go towards cathode and the negative electrons move towards anode wire. When I increase the voltage further then the number of particles that are collected are proportional to the voltage because now there is a multiplication. Let us consider the electron and for the time being forget the ions. The electron has entered the high field region over here (near anode wire), and then here it starts producing showers. So, there is a multiplication (of charges). One electron entering here might give a million electrons after the shower and they are collected here (on the anode). That means the number collected here increases as you increase the voltages. Hence, the detected charge in the detector increases in this region because there is a proportionality with respect to the voltage (applied). This region is proportional region. Please remember that here I am talking about the number of charges collected at the detector and not the number of neutrons.

But if I keep on increasing the voltage then this proportionality is lost and we go to something called Geiger region. In the Geiger region, it is not proportional to the incident energy. In case of neutron anyway the incident energy is that of the charges that are produced (in nuclear reaction). In the Geiger region we can just count the particles, but you cannot find out their energy. Whereas in the proportional region you can get a voltage pulse which is commensurate with the energy of the particle and we can detect the energy of the particles once we calibrate our detectors. In the Geiger region, we just count and we call it a Geiger counter.

We are generally in the ionization (region)and the proportional region for neutron detection, But I must mention here that when I say the detected charge is proportional to the energy of the particles we can find out energy of gamma rays and beta rays etc. in this detector in the proportional region because they directly create the ionization whereas in case of neutrons it is first a nuclear reaction which is independent of the energy of the neutron and then the Q value of the reaction is known beforehand and it is same.

Hence, we do not try to find out neutron energy from a detector directly. This plot shows various zones in a gas detector where you are detecting the particles. This is the recombination region, the plateau where you are collecting all the initial charges. Then the number of charges collected at the detector increases proportional to the energy of the incident charged particles which is total electron as shown here and then we go to a Geiger region where it is not proportional. This is a quick recap of the gas detectors. For neutron also we use gas detectors such as BF_3 or He^3.

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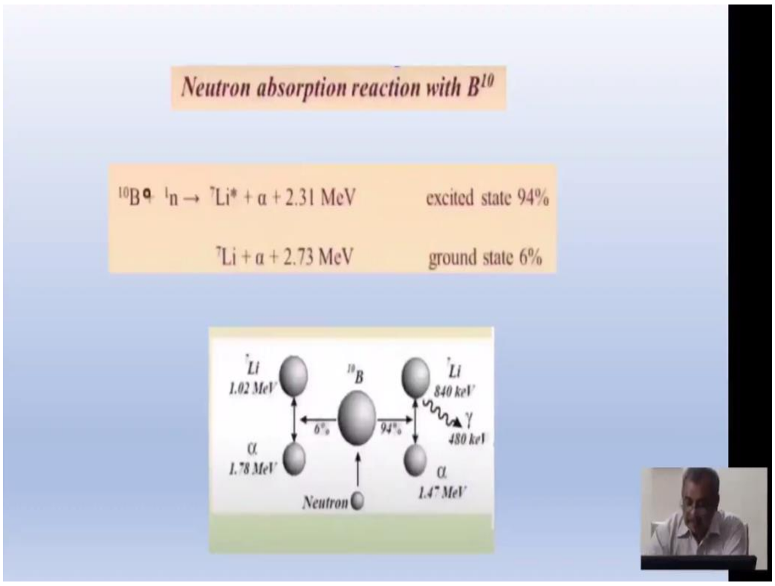

Just to remind you, B^{10} absorbs a neutron and creates Li and alpha particles, and 2.31 MeV energy where Li is in the excited state with 94% probability while in 6% of cases Li is in the ground state and the energy produced in 2.73 MeV. This energy is shared by the lithium and alpha (particle).

Here, pictorially I am showing this. 94% goes to an excited state lithium then it gives out a gamma ray because it comes from excited state to the ground state and the 6% is directly produced in the ground state and this energy of 2.73 or 2.31 MeV is shared between the two products of the nuclear reaction where the heavier one has lesser (kinetic) energy and the lighter one has got more (kinetic) energy.

And that is we know very well from classical mechanics that here the neutron energy or direction (of its travel) is immaterial because these energies (of the products) are much higher compared to the neutron energy which is typically in meV-eV region. But once these are produced then basically the entire energy is shared by them (the products) and they travel in the opposite directions.

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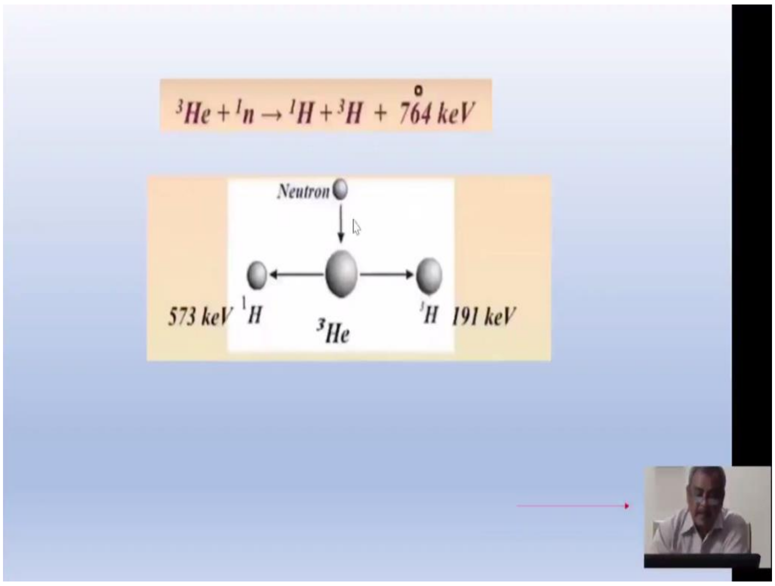

Similarly, the reaction of neutron with He^3 is exothermic. The energy shared by reaction products, the proton and the triton is 764 kilo electron volts (keV) and it shares in the same manner as I told you earlier: the lighter one has higher kinetic energy and the heavier one has lesser kinetic energy and these are the particles which are detected in the gas detector that I showed you. The neutron energy is immaterial here (that is detected). Their (product's) energies are fixed more or less whatever be the neutron energy and we can only detect neutrons in this gas detectors.

This covers the first portion of the topic.