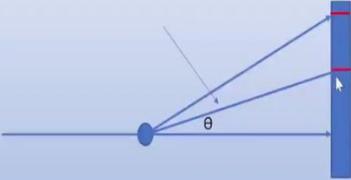**Neutron Scattering for Condensed Matter Studies**
Professor Saibal Basu
Department of Physics
Homi Bhabha National Institute
Lecture – 09B

(Refer Slide Time: 00:13)

This brings us to a new kind of detector, which I will describe to you, known as position sensitive detectors or PSDs. What do you mean by position sensitive? Here I have shown you that this is an incident beam and these are the scattered beams. Now this position sensitive detector not only detects the neutrons, it can also tell us at which position it is detected. That means I can get the information about the momentum transfer from the position information on this detector.

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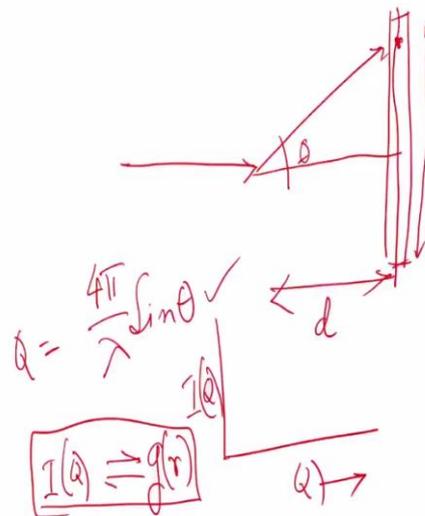
What I mean to say is, I have a detector here and there is a central axial wire and if I can find out where the neutron has entered with some uncertainty then using the direct beam distance, I can calculate out the angle and from the relation, $Q = \frac{4\pi}{\lambda} \sin\theta$,momentum transfer can be determined where lambda is the incident neutron wavelength.

If you remember, my target was to find out intensity as a function of Q in our experiments and this is the experiment where you can find out structure. I know that $I(Q)$ is related to the $g(r)$ - the pair correlation function (of the scatterer). Hence, if I can calculate θ (angle of scattering), then from θ, I can find out Q, so I can get information on a very large range of Q. Later I will show you how we do this in actual experiments. Basically, a large range of Q can be covered in a PSD, so it will save us time.

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Elastic Scattering

Incident beam E, K

Neutron Detector/detectors OR PSD
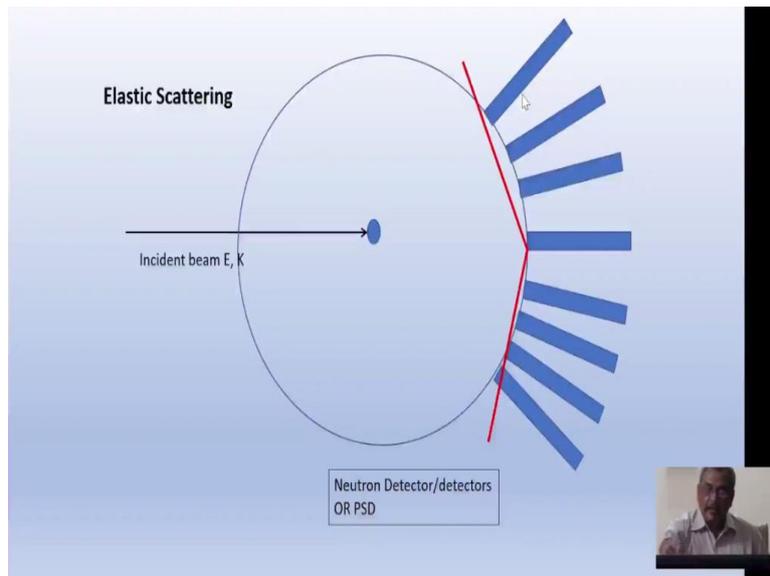
Let me just show you once again which I showed it to you earlier. I am showing you the scattered beam on a circle, but this circle is basically a part of a sphere and it (scattered neutron) is going in all directions, and for every direction I can calculate a Q. In earlier days, we used to move the detector as shown here. But nowadays PSDs are used. I have shown two PSDs which are covering the entire range at the same time. It is something like parallel processing of the signal. Hence, not only I am counting neutrons I am also counting neutrons at certain positions. I will show you the actual counts how they look like and with that, given the incident direction and energy, considering an elastic experiment, I can find out the outgoing direction and then the Q vector and the intensity as a function of Q.

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Position Sensitive Detector (PSD)

PSD gives :

Number of incident neutrons

Position of neutron interaction

Use of resistive anode

Output from both the ends

Processed as potential divider

Output amplitude varies with position
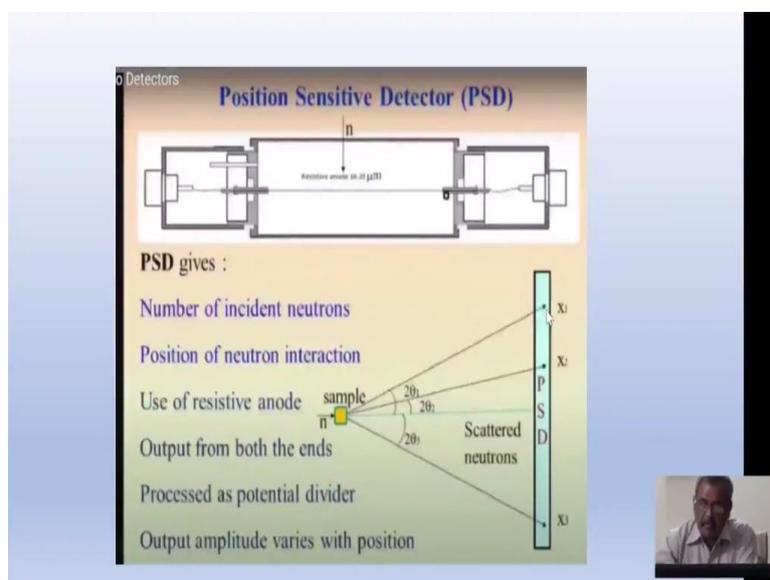
How do we do it? Typically, a position sensitive detector looks like this. It is a gas detector and you can see there is a central anode wire which is a resistive anode typically around 10 to 25 μm diameter. In the figure below a schematic is given which shows that the sample scatters at various angles and the PSD not only count the neutrons also gives me the position which I convert to angles, knowing the sample to detector the distance. How do you find out the position is something interesting? There are several ways, but I will tell you the way it is done in our group in BARC.

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The one shown is called the charge division position encoding.

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There is a resistive anode wire of micron diameter. Now, the neutron got converted into charged particles and with some uncertainty the shower is arrested here say at the position x. Assume that the total length of the anode wire is L, typically these are around 1 m long. Produced charges move in opposite directions (on the anode wire) and they give rise to voltage pulse at the end which is proportional to the distance from the point 'x'. Hence, if the total length is L and from left this is x then it travels a distance of x and $L - x$ when it goes in two directions and then the voltage is proportional to x and L-x at the two ends.

At both the ends we have preamplifiers with impedance Z, then spectroscopic amplifiers, then a circuit which does this algebra. Let us talk about the voltage at both ends. Voltage is proportional to resistance per unit length (ρ) of this wire plus the input impedance of the preamplifier that is $V_a \propto \rho(L\text{-}x) + Z$. Similarly, voltage at the other end is, $V_b \propto \rho x + Z$. With these relations, $V_a + V_b \propto \rho L + 2Z$. Dividing V_b by $V_a + V_b$ we have

$$\frac{V_b}{V_a + V_b} = \frac{x}{L} \; for \; Z \ll \rho L$$

That means the voltage at the two ends are proportional to the distance it (the charge) travelled and then we calculate the ratio $\frac{V_b}{V_a + V_b}$ or $\frac{V_a}{V_a + V_b}$ .using the circuit with which we can find out the position. And then it can be sent to a multichannel analyzer. The ratio output can be obtained from analog or digital ratio circuits. That is how we figure out where the neutron has struck. Of course, there will be certain uncertainty (in position).

Neutron has not struck the anode wire; it reacts with He-3 atom that has produced tritium and proton. These tritium and proton have been collected through a charge multiplication process at the central anode wire, but those lengths in which they are absorbed and the size of charge cloud produced are much smaller compared to the total length and the length resolution we get is of the order of 3 to 4 mm. So, we can consider neutron as a point being detected on the central anode wire.

Once I get this information, I can start recording in the multichannel analyzer position versus intensity. This position versus intensity is nothing, but it is collection of $I(Q)$ data at all Q values at the same time.

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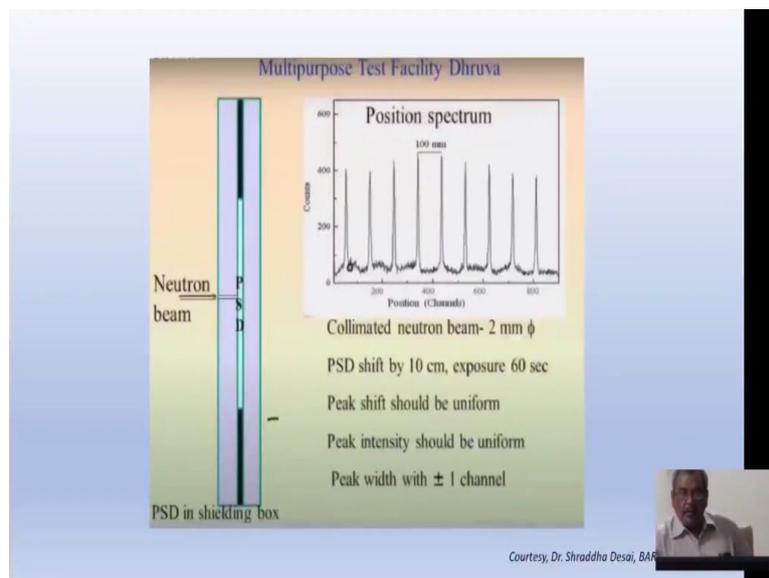
Here, I am showing you a data taken by our detector Group Head Dr. Shraddha Desai of BARC. A PSD is shown in the left. We prepared a very narrow neutron beam going through a slit and either we put the detector across the beam or move the direct neutron beam. Generally, we move the detector across the beam in a shielding box. You can see that as the position is changing the beam counts with changing position as a function of channel are almost same everywhere. This is how a position sensitive detector is calibrated and tested. For one minute the data was collected   and peak width with ±1 channel looks like this. This position sensitive detector can now go for use in a spectrometer. This is how we test the neutron detector for its position sensitivity.

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PSD arrangement at Powder Diffractometer

High efficiency PSDs (10 bar ^{3}He+2 bar Kr)

Angular range $2\theta = 2°$ to $140°$

Courtesy, Dr. Shraddha Desai, BARC
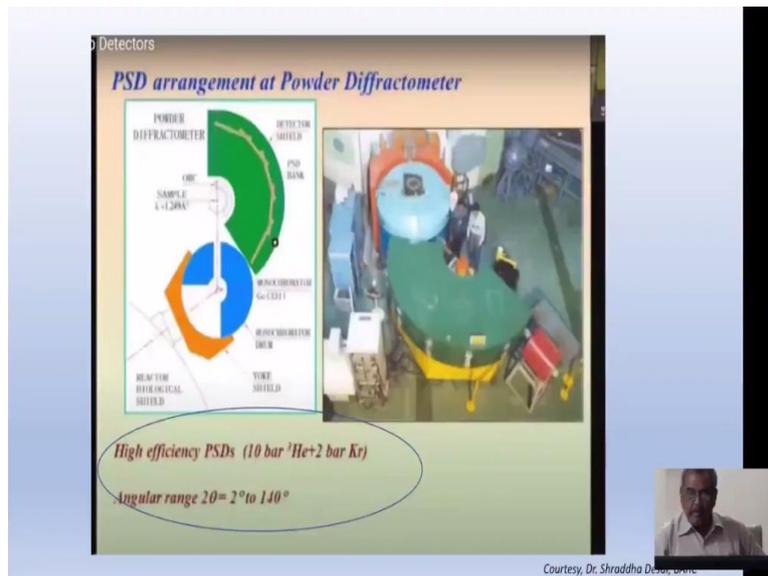
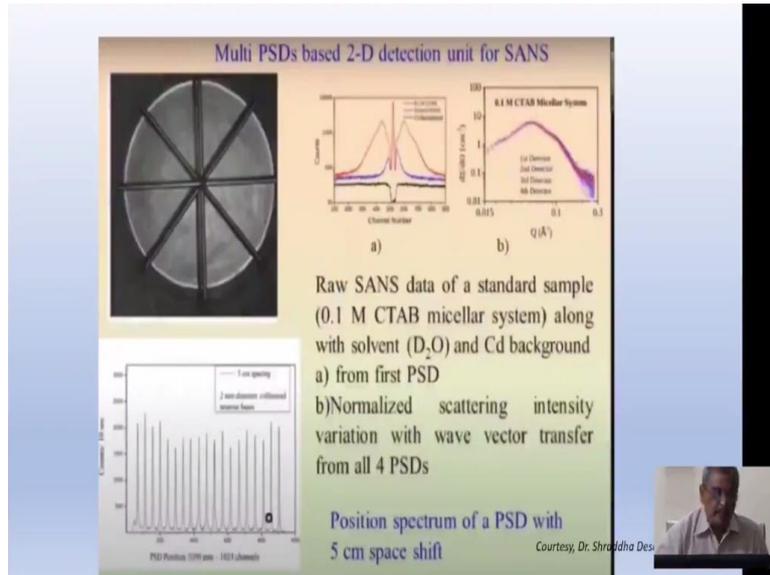Now I will show you a specific example. I will discuss this spectrometer later. This is a liquid and amorphous diffractometer photograph. I just wanted to show you the photograph along with the schematic to give you an idea of the scale of the thing. This is a human size so you can see this is a huge shielding, but inside the shielding box you can see there is a sample where the neutron beam is coming from a monochromator here, goes to the sample and then sample scatters the neutrons. There are 5 position sensitive detectors covering a range of angle which is 2° to 140° and these are He-3 based detectors. We have got 10 atm pressure of He-3 and 2 bars of krypton. Krypton is used as a quenching gas that I will not get into right now, but basically, He-3 detects the neutrons which are kept in this large shielding material.

And this is the monochromator drum at the center of which the monochromator is there and then the monochromator brings neutrons to this sample position and the samples scatters them into the large angle. As the one shown is a liquid and amorphous spectrometer, we need to cover a large Q range to get the pair correlation function in this case.

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Multi PSDs based 2-D detection unit for SANS

a) b)

Raw SANS data of a standard sample (0.1 M CTAB micellar system) along with solvent (D_2O) and Cd background
a) from first PSD
b) Normalized scattering intensity variation with wave vector transfer from all 4 PSDs

Position spectrum of a PSD with 5 cm space shift

Courtesy, Dr. Shraddha Des...

Also let me show you another example of reducing time by using multiple collection at the same time. This is a small angle scattering instrument. This also I will discuss. It is a multiple PSD based system.
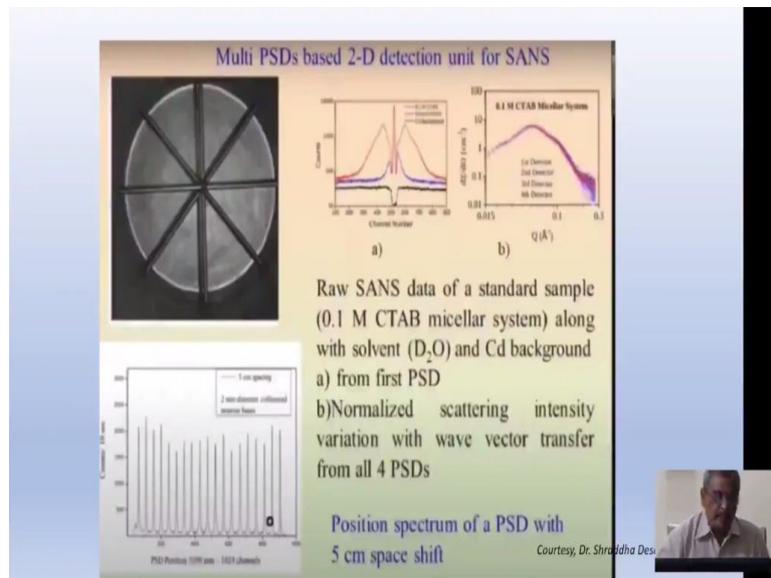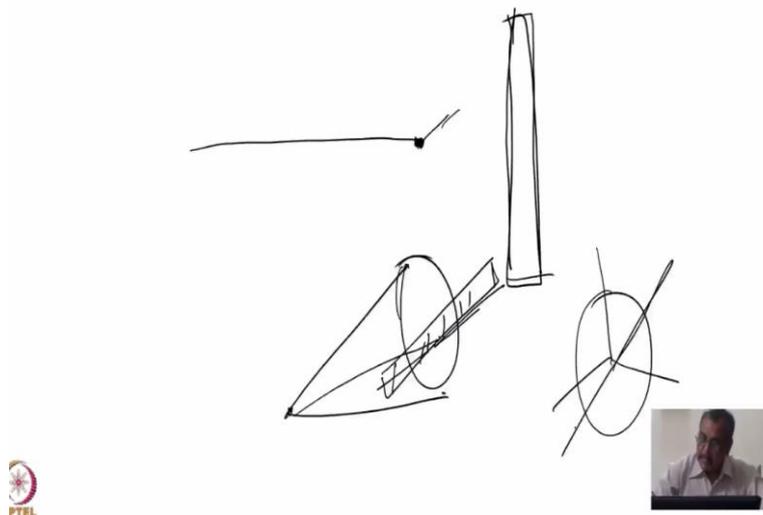
In earlier days we had one detector for the scattered beam. In this case, this scattering is like Debye-Scherrer Cone. So, from a sample a cone goes out, but this detector just cuts one segment of the cone and the rest of the cone is not detected. You do get information about angles as you go from the direct beam to larger angles, but you do not cut the entire Debye-Scherrer cone because we are using a single PSD.

Now it has been improved to the extent as you can see here, we have got 8 (PSDs) over here and hence we can cut the Debye-Scherrer Cone at multiple places.

Multi PSDs based 2-D detection unit for SANS

Raw SANS data of a standard sample (0.1 M CTAB micellar system) along with solvent (D$_2$O) and Cd background
a) from first PSD
b) Normalized scattering intensity variation with wave vector transfer from all 4 PSDs

Position spectrum of a PSD with 5 cm space shift

Courtesy, Dr. Shraddha Desi
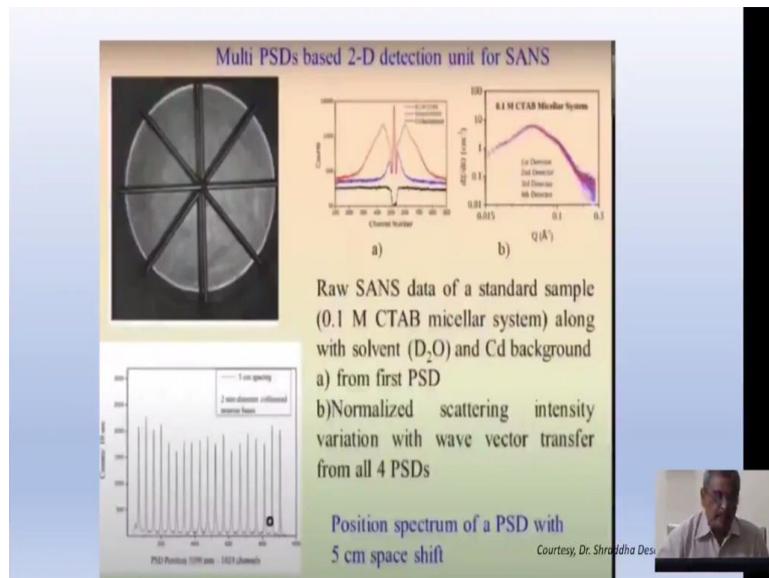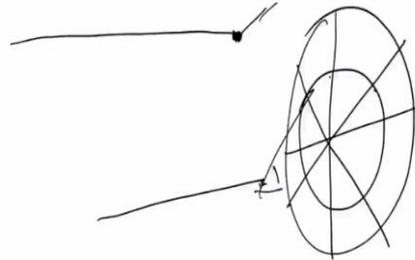
Now instead of one detector if I have multiple detectors then I have got now numbers of detectors counting neutrons at the same time for the same scattered angle. Here, I have got a multiplication of 8 in intensity for the same time of counting. This is what I have shown you here and this is the data collected where the central peak is the incident beam and these are the scattered beam that you can measure on these detectors and similarly the PSD position is shown with respect to SANS data of CTAB micellar systems. All these things I will discuss later. Now, I am just showing you the advantage of using position sensitive detectors. Detectors that use one (angle) after another means not all the angles (are counted) at the same time. Earlier we were using detectors rotating from one position to another.

Now we do not move the detectors, the detectors collect data over the entire Q range at the same instant. In this case the whole data is converted into counts versus channel numbers and data count versus Q which is important for structure determination.

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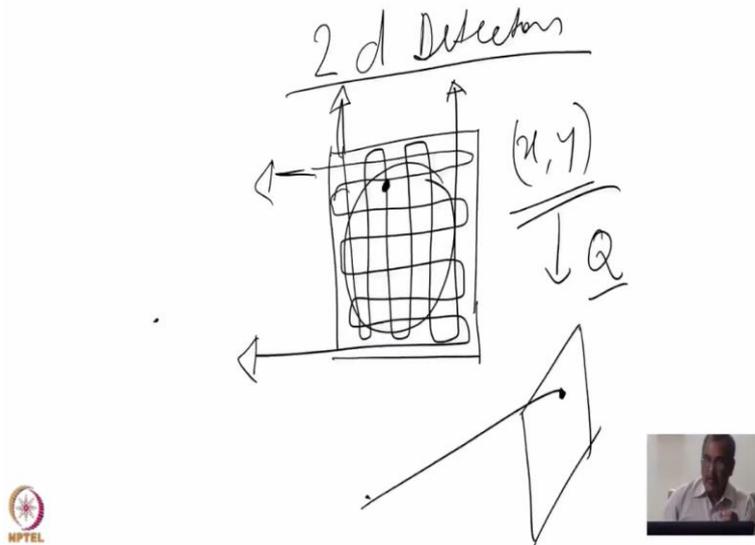
So far, I have been talking about cylindrical detectors, but there are also in the world, nowadays, two-dimensional detectors. There actually you have a square chamber in which you have wires like this. Wire coming out like this can be the anode wire and the cathode wire goes like this, and the electrical signals go out from these points.

With such arrangement, the charge produced in this lattice somewhere can be immediately converted into 'x' and 'y' components and then can be converted from the distance from the sample into Q information. But now not one, not multiple, but you are covering almost the entire Debye-Scherrer circle or the diffraction circle using a single detector.

These are the two-dimensional detectors and this is also used in major neutron sources like PSI and other places. We are working on it right now and we have made the prototype two-dimensional detector in Dhruva where you can collect the entire Q value in one shot. It is a very big advantage with respect to time because neutrons are low intense sources, I am harping again and again, and that is why we need to improve the data collection efficiency. Two-dimensional detectors are one step ahead of one-dimensional detectors where we can collect the entire scattering cone at one go.

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We need low-efficiency monitor detectors for experiments. Especially for serial counting

Neutron experiments take longer time. Hours to even a day!! Different from x-rays

In this time scale reactor power may fluctuate

How long to count for a setting?

Normalization with respect to a monitor count

Now let me get back to what do we mean by monitor detector? Most of us, who have done x-ray scattering might not have experienced this Reason being, neutron experiment takes longer time: hours to even days because neutron intensity is low and we need longer time to count and the reactor is a very big setup so the reactor power may fluctuate. For a particular setting 't' (counting time) suddenly, something may happen then the power might go down and afterwards, operating personal may restore it back to higher power. Technically, the reactor operation is an involved job and they need to keep the reactor operating safely.

If I do a serial counting experiment with one setting of detector then with another setting, and so on with 10 sec at each setting, how do I do it because it may happen that in my first 10 seconds the reactor power may be high and in next 10 second the reactor power may be low. It will cause errors. Hence, instead of time, we normalize with respect to monitor count. So, what is a monitor counter?

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Courtesy, Dr. Shraddha Desai, BAR
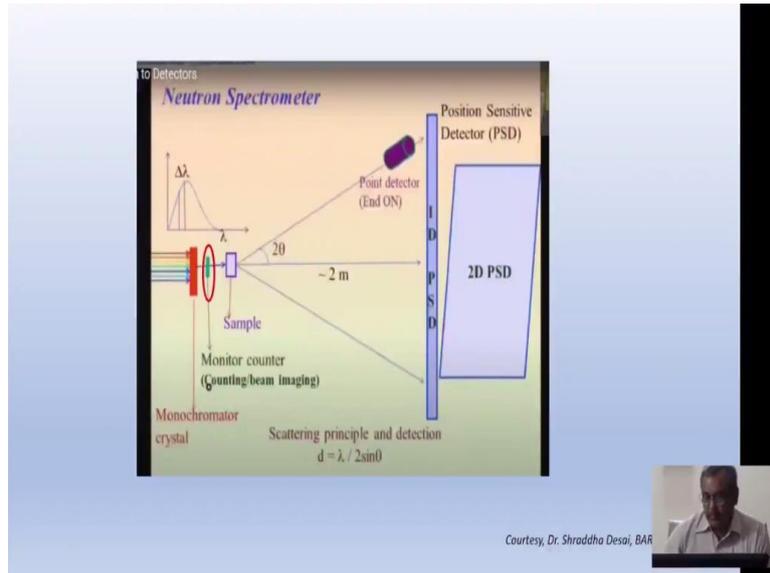
I am just showing you a schematic where you can see that before the sample there is something called a monitor counter and then of course there can be point detector, there can be 1D PSD, there can also be 2D PSD depending on what you have got with you, but there is a monitor counter. Now the monitor counter: what does it do?
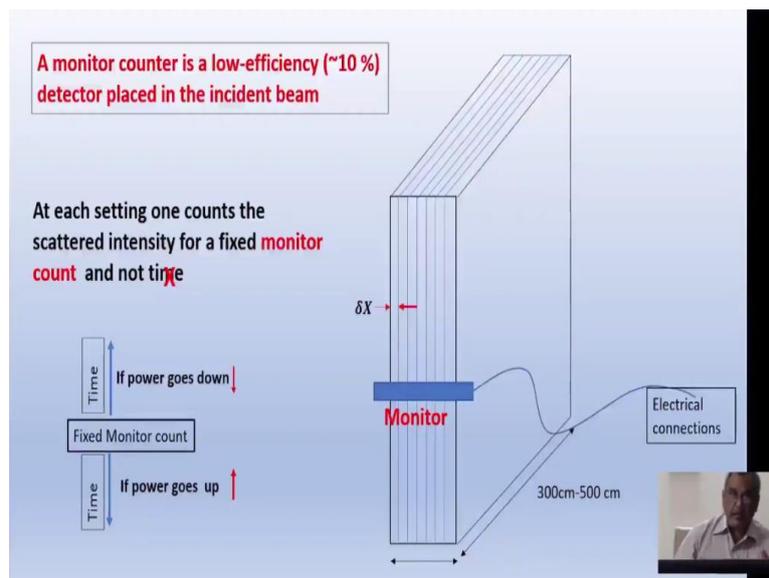
Monitor counter is a low efficiency counter. It is placed in the incident beam before the beam is incident on your sample. Here I show a soller collimators and I put the monitor counter in front of the soller collimators. Now what I do here? I do not count for time, but I count for a fixed monitor count and not with respect to time. How it helps? You can see I have just shown you in a simple diagram.

If I am counting neutrons for a fixed monitor count suppose the reactor power goes down. When the reactor power goes down, less number of neutrons are coming from the source, from my reactor, so it will take longer time. Let us say I have fix monitor counts for 30,000 counts. So, 30,000 counts will take longer time. Again, if the reactor power goes up then the same 30,000 count will take shorter time. So, the monitor will adjust with respect to the reactor power and at every point I am counting for 30,000 monitor count. So, I have beaten the fact that the reactor power can fluctuate. I am doing it for a fixed monitor count so slight fluctuations in reactor power were automatically be nullified by monitor count and because I am counting for fixed monitor counts two points in my data remain equivalent.

But this monitor counter has to be low efficiency because it is put in the incident beam. So, we make low efficiency monitor counters and then put it for the serial counting system. Mostly in inelastic neutron scattering we have put them in the beam path and my counting setup works in a way that I have to set the number of monitor counts for which each point will be counted and then the counting goes on (serially).

Courtesy, Dr. Shraddha Desai, BARC
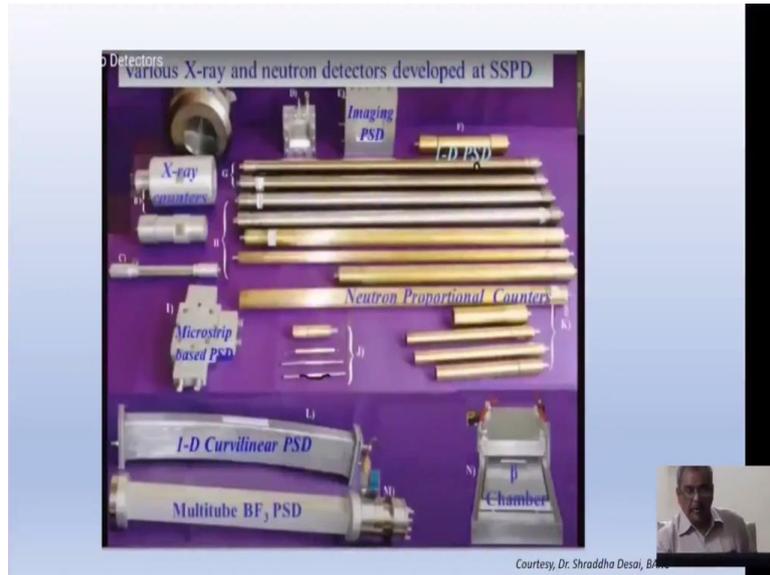
This is the photograph of the various neutron detectors that we have developed at the Solid State Physics Division of BARC and these are the one meter long position sensitive detectors. There are monitor counters and we also make x-ray counters. 1D PSDs are there and also curvilinear PSDs have also been made. These are photographs of various kind of detectors that we make.

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Courtesy, Dr. Shraddha Desai, BARC
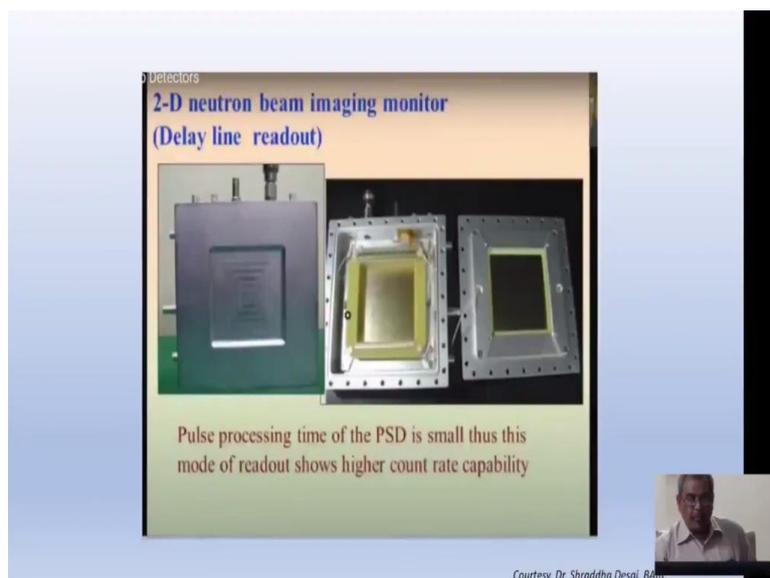
Similarly, there are monitor counters.

Now let me come to the part of scintillation detectors. I have not discussed it so far. These are mostly used in spallation neutron sources and here I will show you a scintillation process, some of you may be familiar with. There is an incident particle inside a medium which causes scintillation. That means it absorbs the incident particles and produces photons. Through a window, these photons get inside a photo multiplier. They first convert into electrons and they multiply it out. These electrodes are called dynodes they are all negative (with respect to the next): this one is negative with respect to this; this one is negative with respect to this. So, the photons come and maybe gives you few electrons.

These few electrons they move to this dynode which further multiplies it, sends them towards this dynode (next) and then this process goes and finally you get an electron shower on the electrode and then we can count the particle. So, here again the neutron has to enter the medium and produce photons. So, how does it do? Neutrons to charged particles to photons the process is like this.
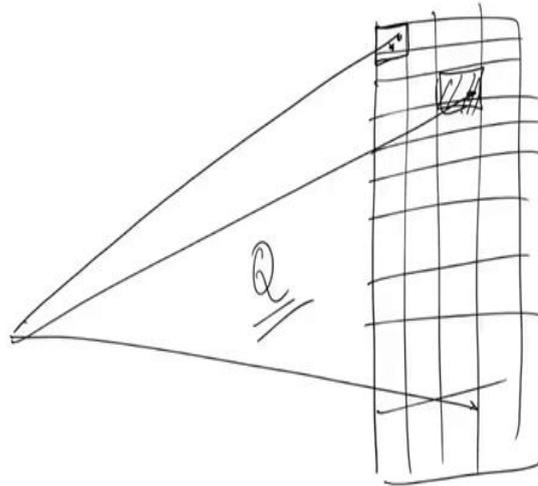
"My name is Nigel Rhodes and I am the ISIS Detector Group Leader. My group looks after all of the detectors for the instruments here at ISIS. This is a prototype detector for the polaris instrument. It is a scintillation detector and the scintillator that we use is a zinc sulphide scintillator. The zinc sulphide is mixed with lithium fluoride. The lithium fluoride is enriched with isotope 6 of the lithium. There are very few elements that are actually sensitive to neutrons. There are only three that generate enough they interact to be useful to us: Lithium- 6, Boron -10 and Helium -3. In this case, the neutron comes in, it interacts with the Lithium-6 particle, its nuclear reaction- an N-alpha reaction- an alpha particle and a triton particle are generated from that reaction. They go through the zinc sulphide lattice causing ionisation. When the electrons decay, they emit light and in that way, we wield up a light flash from each neutron that has interacted with the particle.

https://www.isis.stfc.ac.uk/Pages/How-to-catch-a-neutron.aspx

I am just copying it from ISIS Detector Group. So, you see they are discussing about a prototype detector for Polaris instruments. It is a scintillation detector. Scintillation material is zinc sulphide mixed with lithium chloride. As I told you earlier that it is enriched with Li-6 and reaction with neutrons gives me proton and triton. These are charged particles; they are absorbed by zinc sulphide and produces photon.

There are very few in elements that are sensitive to neutron (absorption). Here, we are using Li-6 and the neutron interacts and generates α-particle and triton particle. They go through the zinc sulphide lattice causing ionization. When they (charged ion and electrons) combine back, they give a light flash. So, each neutron is converted to light flash. And then the light flash goes to these dynodes (produce electron shower) and then finally they are counted.

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$$\begin{aligned} {}^{6}_{3}\text{Li} + {}^{1}_{0}n &= {}^{3}_{1}H + {}^{3}_{1}H \end{aligned}$$

$n \to$ charge $\to$ ionization $\to$ Recombine $\to$ Photon

Hence, the process goes like; neutrons to charge to ionization in the medium and when the ions recombine in the solid medium, they give rise to photons. These photons travel through the zinc sulphide matrix and enter this Photo multiplier tube and are counted. This is an example of a scintillation detector. I have given the reference some of you are interested for more knowledge you can get it from there. So, this as opposed to gas detectors is a scintillation detector and this is used for final detection and not as a monitor. I just wanted to show you the photograph.

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POLARIS Diffractometer, ISIS, RAL, Detector tank

This is the huge detector bank in which these ZnS impregnate with lithium chloride are placed in this Polaris diffractometer. How do I find out Q values for this? This is a diffractometer. This huge detector bank is having a matrix of these detectors and it is a long travel path so you can say for one particular element here the angles are fixed.

Once they are detected then this light signal is taken out to a photomultiplier and converted into electron pulses, electronic signals, voltage pulses and that is how you know the position from the (element) of the detector. Detectors in the matrix provide the information on the Q value.

You collect on a very large Q range and you can see the scale of things (In photo) where this is the detector bank in Polaris diffractometer and this detector bank it is in the spallation neutron source (ISIS) and these scintillating glass detectors, collect the final signal and give you the Q information.

I think I have more or less completed of what I wanted to say regarding the neutron detectors in this talk. We will next go over to the kind of spectroscopies that you can do with neutrons and then we will really enter the actual field of neutron diffraction as well as neutron inelastic scattering. Thank you.