

**Neutron Scattering for Condensed Matter Studies**  
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**Week 01**  
**Lecture 01B**

Keywords: Research reactor, Spallation neutron source, Monochromator, Neutron guide

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Sources for thermal neutrons used in neutron scattering

ILL  $10^{15}$  n/cm<sup>2</sup>/s

Nuclear reactors (Presently DHRUVA, future HFRR, In India)  
RHF at ILL Grenoble  $\rightarrow 1.38 \times 10^{14}$  n/cm<sup>2</sup>/s

Proton accelerator based spallation neutron source  
ISIS at RAL, SNS at Oak Ridge



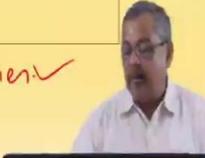
Sources for thermal neutrons used in neutron scattering

FRMII NCNR  
NIST

Nuclear reactors (Presently DHRUVA, future HFRR, In India)  
RHF at ILL Grenoble — Critical assemblies.

Proton accelerator based spallation neutron source  
ISIS at RAL, SNS at Oak Ridge

subcritical assemblies



Sources for thermal neutrons used in neutron scattering

FRM II NCNR  
NIST

Nuclear reactors (Presently DHRUVA, future HFRR, In India)

RHF at ILL Grenoble



Proton accelerator based spallation neutron source

ISIS at RAL, SNS at Oak Ridge

Proton beam  $\approx$  1 GeV



Sources for thermal neutrons used in neutron scattering

2.5 m/fission  
1 MeV FRM II NCNR  
NIST

Nuclear reactors (Presently DHRUVA, future HFRR, In India)

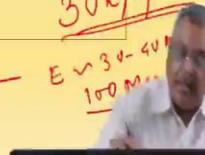
RHF at ILL Grenoble



Proton accelerator based spallation neutron source

ISIS at RAL, SNS at Oak Ridge

Spallation  $30 \mu\text{s/spallation}$   
 $E \approx 30-40$   
 $100 \text{ MeV}$



Sources for thermal neutrons used in neutron scattering

**Nuclear reactors (Presently DHRUVA, future HFRR, In India)  
RHF at ILL Grenoble**

**Proton accelerator based spallation neutron source  
ISIS at RAL, SNS at Oak Ridge**

*Pulsed.      few m A.*




Sources for thermal neutrons used in neutron scattering

**Nuclear reactors (Presently DHRUVA, future HFRR, In India)  
RHF at ILL Grenoble**

**Proton accelerator based spallation neutron source  
ISIS at RAL, SNS at Oak Ridge, J-PARC ✓**

*Time of Flight or TOF*




In this part, I will familiarize you with various sources of thermal neutrons, that are used in neutron scattering. Though neutrons were discovered by using a Radium (alpha) Beryllium source, but these are very weak sources, the radioactive sources. We usually go for either a nuclear reactor or something called a spallation neutron source.

Presently, we have DHRUVA in India, which we have been using since 1985. And we have plans for a future high flux research reactor. The highest flux research reactor is called Reactor High Flux (RHF) at ILL Grenoble, which is a highly enriched core and the flux of ILL reactor is around  $10^{15}$  neutrons  $\text{cm}^{-2} \text{s}^{-1}$ . In case of our reactor DHRUVA, it is  $1.38 \times 10^{14}$  neutrons  $\text{cm}^{-2} \text{s}^{-1}$ .

We usually write the flux in terms of neutrons  $\text{cm}^{-2} \text{s}^{-1}$ . In case of synchrotron, you may be familiar with it that they are writing photons  $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ . One is the brightness and this is the flux. There is a subtle difference because the synchrotron sources are highly collimated and highly convergent beams of very, very small angular width and that is why there we talk about photons  $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$  but as here we up to neutrons it is  $\text{cm}^{-2} \text{s}^{-1}$  and it is difficult to focus neutrons. There are some devices, but usually it is not so easy to focus neutrons. I will discuss these things when the time comes.

The RHF at ILL Grenoble is the highest flux reactor, but there are other reactors like FRMII in Germany, also NCNR, NIST Center for Neutron Research at NIST in USA. These are the most famous reactors that are operating presently.

There is another kind of source which is proton accelerator based, spallation neutron sources. Nuclear reactors are critical assemblies. Critical means that the chain reaction is going on continuously. Unless we stop it, the reactor goes on operating and generating neutrons and number of neutrons from one generation to another generation remains the same. So, it keeps on working indefinitely without any external aid for neutrons.

Accelerator based sources are not critical assemblies, they are subcritical assemblies. A reactor needs to work in a critical mode otherwise we cannot get neutrons continuously. But in case of accelerator-based sources, first an accelerator is used to get a proton beam of nearly 1 GeV.

Why such a large energy required is because, here, the operation is such that, let us consider a nucleus and the proton beam impinges on it, there is a huge coulomb barrier because proton is positively charged and all the nuclei are positively charged so they repel each other. We have to overcome this huge potential barrier of nucleus and once the proton enters the nucleus with such a high energy, then it shares the energy with all the nuclear particles and this phenomenon is called spallation or boiling off.

In the spallation reaction, we get a very large number of neutrons, typically around 30 neutrons per spallation. So, you can compare this with a reactor. In fission, on an average we get 2.5 neutrons per fission. Out of these 2.5 neutrons, we use one neutron to keep the reactor critical or alive and 1.5 neutrons we can use either for our experiments or we can take it out and we can do

some other job with the neutrons. Briefly, typically we have around 2.5 neutrons per fission, and, there are very large number of neutrons in spallation.

Also here, the neutrons come with energy typically in MeV. In spallation, the energy is much higher. It can be 30 or 40 MeV or even hundreds of MeVs when neutrons are knocked off by the proton in the forward direction. So, they can be of very high energy. Such spallation neutron sources are usually pulsed in nature. That means, the neutrons do not come continuously, but the accelerator accelerates a bunch of protons, which are impinging on a target and then there is a gap, then there is a second bunch.

So, they are actually pulsed sources. Accelerator based sources are pulsed sources usually. There is one accelerator-based source (PSI Switzerland), which is an accelerator-based source, but nearly continuous and there is a very large proton current of around few mA and this is almost like a reactor source.

Otherwise, all other major sources, I name a few here, the ISIS spallation neutron source at Rutherford Appleton Laboratory, spallation neutron source at Oak Ridge, then the J-PARC in Japan, spallation neutron sources are pulsed in nature. Because reactors are continuous and spallation sources are pulsed, the kind of spectroscopy, we do use differ, which I will be describing you in my later lectures.

In case of reactors, you have a continuous beam. We use a continuous beam to do all our experiments here. For a pulsed beam, I will be giving details later, but what we use most is Time of Flight or ToF spectroscopy in spallation neutron sources Details we will come to later., The nature is different and I will try to describe the Time-of-Flight spectroscopy or the monochromatic spectroscopy. These are the kind of instruments that you can build. In my lectures, I will explain to you how one is done and how the other is done.

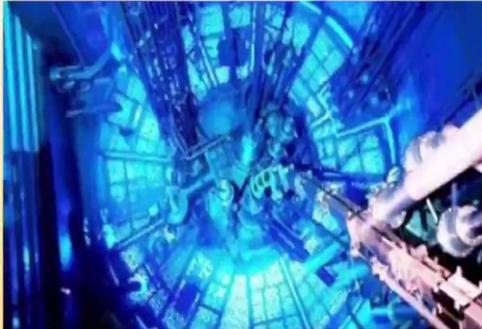
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RHF, ILL,  
Grenoble

UK France  
and  
Germany

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RHF, ILL,  
Grenoble

UK France  
and  
Germany

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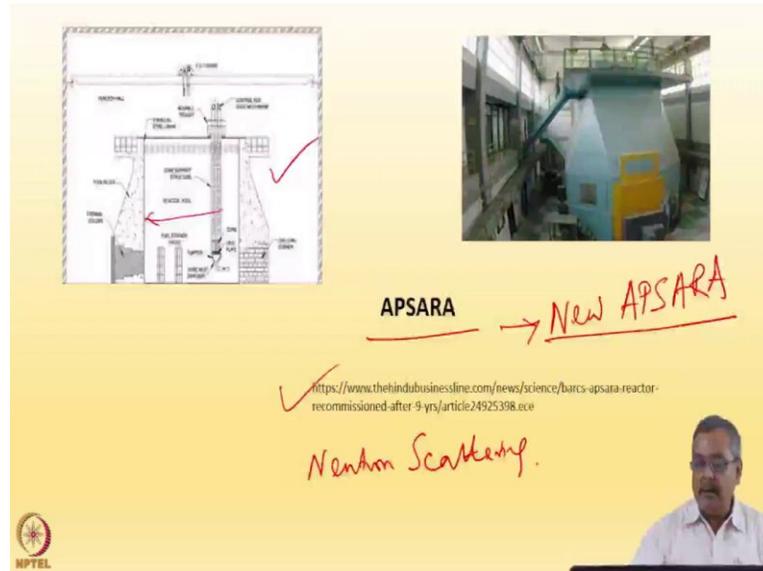


Now, it is a tour for various sources so that you get familiarized with the look and the scale of things. This is the core of the reactor high flux at ILL Grenoble. Source is given, from where I got this photograph. This is a reactor run by UK, France and Germany as a collaborative project, and possibly the most sought-after neutron source where people from all over the world converge to do experiments.

This is just to highlight the issue that one can do neutron scattering and how this is an important technique so that such huge setups are run by multi countries. For example, it is like the CERN setup for particle physicists. These are centralized large facilities.

What you are seeing here, is a photograph of the reactor core from top. The reactor core is very small, if you can look at my hands, it is very small, it is a small enriched core, enriched means it is enriched with uranium by more than 90% and it is surrounded by a large moderator tank and the beam lines I will show you later in various schematics where all beamlines look at this reactor core and receive neutrons from there.

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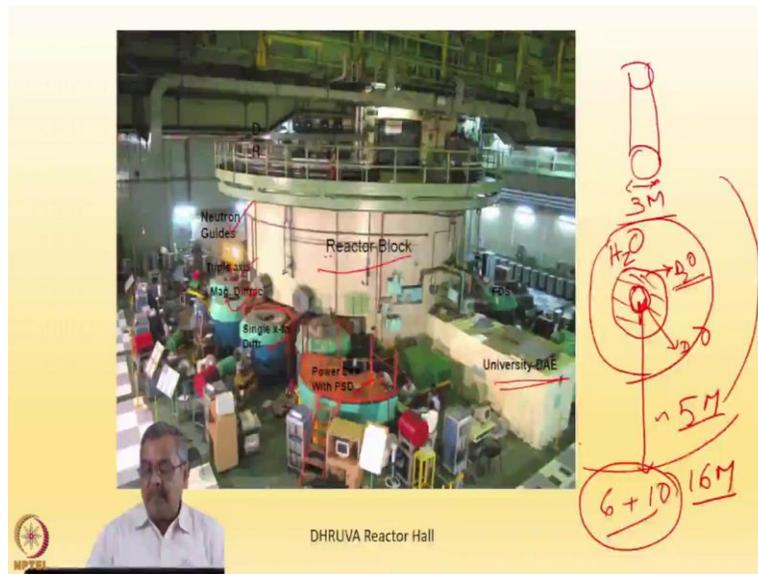


Historically this is the first reactor in Asia, APSARA. This is a pool type reactor. In simple words, pool means the core is sitting inside a water pool and the water pool acts as a coolant, as well as a moderator for this core. Same thing is true for APSARA. This is an external view of the pool; the reactor is inside this. So, you can look at it from top. This is how the pool looks like.

This is the reactor is hanging from top and there was a facility where we could move it from one part of the pool to other to fit to various different experiments., This was a pool type reactor, which is now not operational and new APSARA reactor has come up, that is also pool type in the Bhabha Atomic Research Center, Mumbai campus: that is called New APSARA.

APSARA has given rise to new APSARA. This was the first research reactor in Asia and India happened to be the first country to take up neutron scattering technique to characterize condensed matter using APSARA reactor. I have taken it from the online source and this is how it looked like.

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Now, this is the present reactor what we use is the DHURVA reactor. This just to give you a view, you can see the people doing experiments are here., This gives the scale of the things. One thing you will notice is that there is something which I call reactor block., This reactor actually got a pool, which is typically around, 3 m diameter and 3 m height. These are cylindrical objects, the reactor, and this is the outside the cylindrical block that you are seeing. Because every time we have a spallation reaction or you have fission reaction, lots of unwanted radiation, unwanted means they can be harmful to human beings, also come with fission as well as fast neutron. So, in a reactor you have thermal neutrons, but every time new neutrons are being born and there are fast neutrons.

So, there are fast neutrons, there are thermal neutron, there are a huge intensity of gamma ray flux, because in fission we also have excited nuclear which they de-excite and give out gamma rays., When we plan to do experiments at such places, we need to have a huge shielding, so that the personnel can work safely inside the reactor hall or in the experimental hall of a spallation neutron source.

Here, this reactor core is first surrounded by a  $D_2O$  reflector and the moderator is also  $D_2O$  in this reactor. There is no physical boundary, but there is a region where you have  $D_2O$  reflector when the neutrons leak out to them, sends them back inside the core. So, they are acting as reflector and the  $D_2O$  in the core is acting as moderator so those same  $D_2O$  one is acting as a

moderator to bring the energy of the neutrons down, a part of the thing is acting as reflector to send or to reflect the neutrons back inside the reactor core. So that we do not have any unwanted leakage from the core. This is followed by a light water vault, H<sub>2</sub>O and then it is followed by a huge biological shielding, or it is a concrete shielding, surrounding it. What you are looking at is the outer face of the concrete shielding. And this whole thing, this is approximately 5 m thick. If the reactor core is 3 m radius, so 3 + 3 is 6, plus 10.

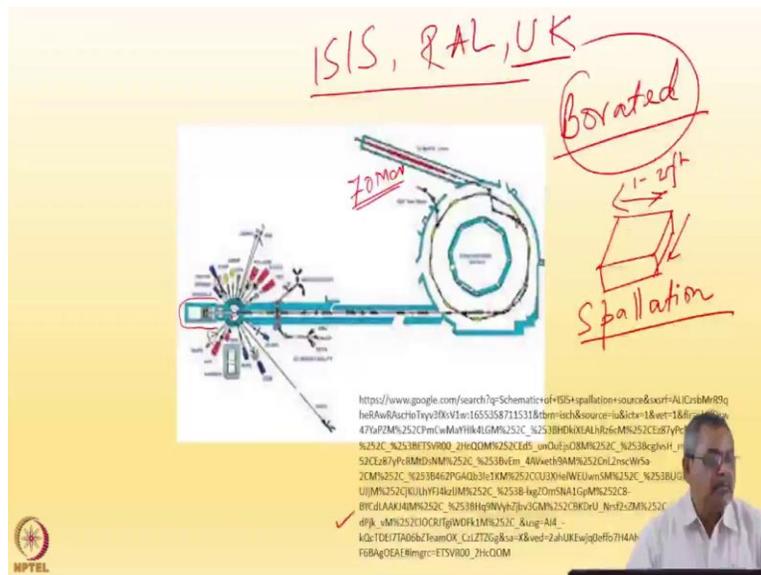
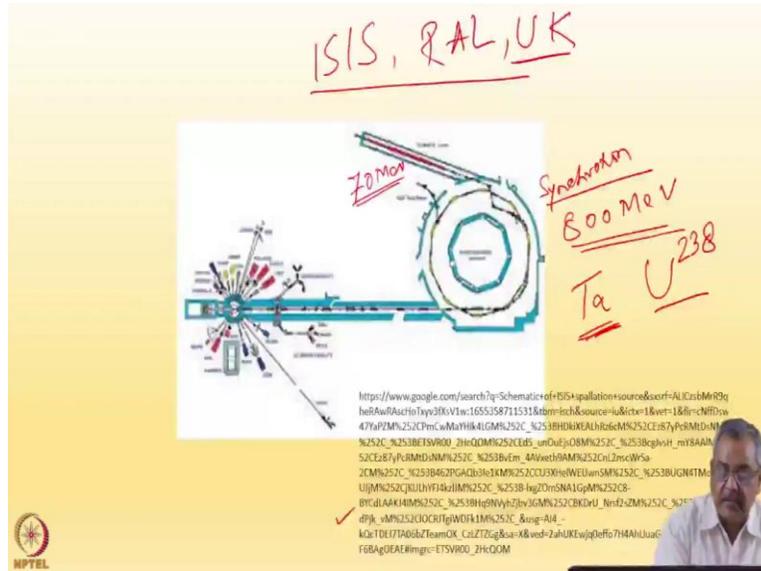
So, what you are looking at is a cylindrical block, which is nearly 16 m in diameter, and outside that we have a large number of instruments. Right now, I can just tell you the names, I will come to each and every instruments later in my talks and explain what kind of experiment, what kind of characterization are done at them, so there is a powder diffractometer using position sensitive detectors, there is a single crystal diffractometer, there is a magnetic diffractometer, there is a triple axis spectrometer and there is something called neutron guides for neutron transport.

And you also have a through tube in this reactor and also, we have instruments run by an organization which is a University Grants Commission, UGC and DAE collaboration, they also run some instruments here.



But there are also experiment which are done in the guide hall. Guide halls at the present day are an integral part of any neutron source whether it is spallation neutron source or reactor, where the neutrons are taken away from the core by using neutron guides. I will explain this to you later.

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This is a typical schematic of a spallation neutron source. I have taken it from internet. This is the ISIS source at Rutherford Appleton Laboratory in UK. This is located in a place called Harwell. So, here you can see first there is a small Linear Accelerator which accelerates a proton way up to 70 MeV.

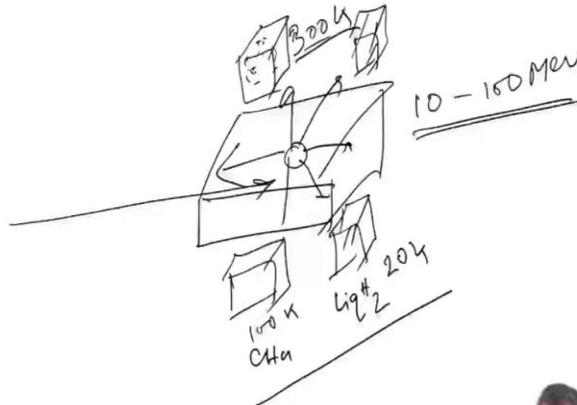
After that, this proton is fed to a synchrotron. This synchrotron boosts the 70 MeV to 800 MeV, 10 times and after that you can see it travels a long path and here, there is the target. This target need not be uranium because this is not a reactor. It is a subcritical assembly, it can be any high Z material like Tantalum, it can also be depleted Uranium like Uranium-238 but usually a heavy target like Tantalum is also used.

Here the target is typically maybe a few feet in dimension and in which the proton beam impinges. As I told you, that is a very high energy proton beam. So, it can knock off neutrons with very high energy in forward direction then the forward direction is a very heavy shielding. Now, for shielding thermal neutrons, it is preferable that to use some hydrogenous material, they can be polymers, they can be wood, they can be borated wood, because Boron is a strong absorber of neutrons and wood is a very good moderator.

We can use the wood to moderate and reflect the neutron beam and we can impregnate wood with Boron to absorb. In this case, when you have a very high energy neutrons going in the forward direction, these will not do because the energy of the neutrons is very high, so use a very high Z material like stainless steel in the front side which can absorb such a high momentum and erase the neutron going in the forward direction.

But apart from that, if this is the target, it is just a schematic I am trying to just give you an idea maybe 1 or 2 feet. So, once proton impinges here, , you have a very large number of neutrons generated in the spallation. I told you, per reaction you have nearly 30 neutrons and now these neutrons are at a very high energy. Let me just try to give you some schematics.

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Basically, this is the target in which the proton beam comes and produce spallation. So, now, these are 10 to 100 MeV neutrons, which cannot be used for the purpose of condensed matter study. So, what is done actually, there are moderators. I am showing the moderator as blocks moderators below and above this target station.

So, ambient temperature means room temperature of around 300 K or moderators at very low temperature like 100 K methane or maybe another moderator liquid hydrogen at 20 K, these are known as cold sources. I will describe to you what are cold sources later.

And there are also several ambient temperature moderators. So, when the neutrons come out in all possible directions from a spallation target, they enter these moderators where they get thermalized. Once thermalized then they are ready for use in our experiments. And then we go for the experiment.

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ISIS,RAL,UK

Target 1  
Target 2

Borated

1-2ft

Spallation

Accelerator

Pulsed

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ISIS,RAL,UK

50 Hz

Borated

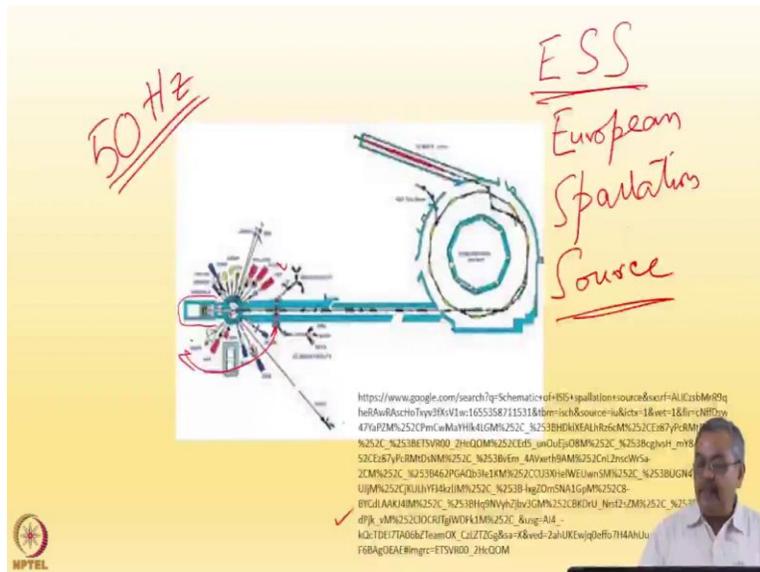
1-2ft

Spallation

Accelerator

Pulsed

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Now, we can see like a reactor is shown to the mono-clonal drum surrounding the core here surrounding the small target and the accompanying moderators, you have large number of instruments sitting on these circles and you can see some beam paths are very large, very long, why I will tell you later. So, this is the part, which is accelerator and this is the part which is experimental hall.

There was a single target till few years back in Rutherford Appleton Laboratory. Now, this beam of protons is diverted to two sources. So, there is target station 1 and target station 2 in Rutherford Appleton Laboratory. And experimental facilities are provided at these two places. This is not to teach you everything about Rutherford Appleton Laboratory, but these to tell typically how an accelerator-based source compares with respect to a reactor source.

Among the reactor source I showed you DHRUVA, because that is what I am quite familiar with. And this is typically how it looks like for a spallation neutron source. In both the places you have moderators, but here, there is an accelerator in a reactor you have the whole assembly, a critical assembly. So, here it is pulsed. And in case of Rutherford Appleton Lab, ISIS we have a source which has got a frequency of 50 Hz which means, every second you have 50 pulses of proton hitting the target.

Source is giving us 50 pulses of neutrons. First these neutrons are arrested in the moderator. They enter the moderators, thermalize and after that they are used for experimental purposes. So, we have about 50 pulses to work with and few of the pulses go to target station 2 and few of the

