

Neutrons as Probe of Condensed Matter
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Lecture – 01A
A Brief Introduction to Neutron

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Hello,

This is the beginning of the course, titled “Neutrons as Probe of Condensed Matter”. This course will cover various aspects of the technique known as neutron scattering, for understanding the structure and dynamics in condensed matter. This course will deal with the basics of neutron scattering and will also familiarize you with the various techniques and various experimental facilities that are available in the country and outside the country for use in neutron scattering techniques. Before I start the topic, it will be interesting to give you a very brief introduction to neutron, which is a nuclear particle.

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**NATURE: LETTER TO EDITOR, 27
FEB. 1932**

Discovery of neutron

„matter should resemble those of a quantum of high energy.....up to the present all the evidence is in favour of the neutron, while the quantum hypothesis can only be upheld, if the conservation of energy and momentum be relinquished at some point

**J. Chadwick,
Cavendish Laboratory, Cambridge, Feb. 17**

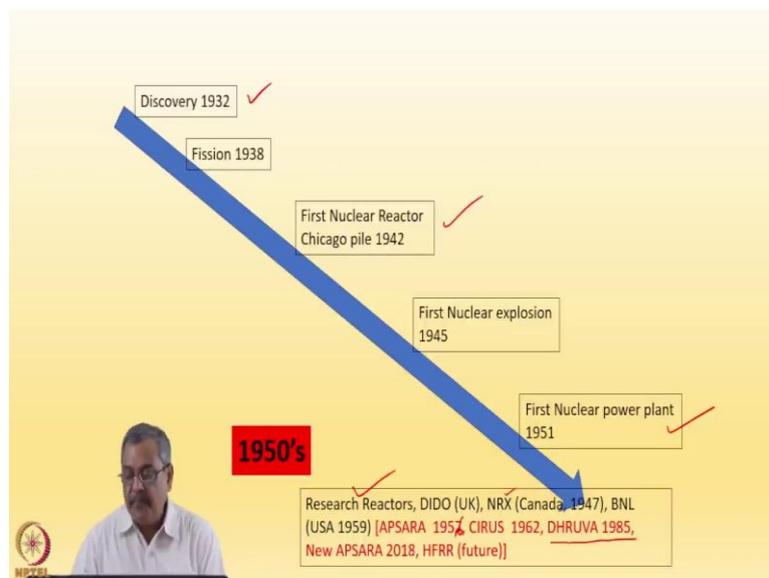
Neutron was predicted or rather discovered in a short letter to the editor of Nature by Chadwick, where he stated that this particle should resemble matter that have a quantum of high energy. Because, these experiments were done earlier where, one tried to understand a

radiation coming from radium(alpha) beryllium sources. They found that they knock out or give very large momentum to hydrogenous materials.

Earlier, great scientists like Joliot Curie thought that this is possibly a gamma ray. But, for the gamma rays to knock off hydrogenous materials very efficiently, they had to include very large energies to the radiation. It was Chadwick, who very clearly stated that the present evidence is in favour of the neutron and if the conservation of energy and momentum is there then it is a mass which is close to the mass of proton and this is the elusive neutron.

And if the conservation of energy and momentum can be relinquished, then possibly you can talk about quantum hypothesis, which means, it is a gamma radiation. But we know that his assumption or his understanding was correct and neutron was discovered in 1932 by Chadwick. This is a spin half particle with a magnetic moment of -1.91 nuclear magneton and it is a nuclear particle, existing in almost every nucleus.

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After that, many things happened very rapidly. After the discovery in 1932, in quick succession, people tried to bombard things with neutron and in the process, fission was discovered. We know Liza Meitner, Otto Frisch, Otto Hahn, who got the Nobel prize for discovery of fission, were the scientists behind fission. They worked a lot. It was discovered that, when you bombard uranium with neutron, along with transuranic elements you also get elements which are of much lower atomic number. They called the process as fission because, the uranium nucleus undergoing fission giving rise to much lower Z value materials.

And then, very quickly the first nuclear reactor was built under a basketball court at Chicago university known as Chicago pile.

All of us are familiar or we know the history of first nuclear explosion atom bomb and the drop of atom bombs at Hiroshima and Nagasaki. But, we will also point out that after the discovery, very quickly, nuclear power plants and research reactors came into existence. People realize quite early that neutrons can be an excellent probe for matter, which I will be discussing.

In 1956, research reactors like DIDO in UK, NRX in Brookhaven National Laboratory, Canada, started coming up. We had APSARA reactor in 1956, which was a highly enriched uranium core reactor. We had a CIRUS reactor in 1962, which was similar to the NRX reactor at Canada. Presently, we have a completely indigenously built reactor, built by the scientists in India, known as DHRUVA.

There is a new reactor, called new APSARA which has come up in 2018. And we also have plans for a high flux research reactor or HFRR in future for use in research. Now, condensed matter research is mostly done using thermal neutrons.

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Thermal neutrons

Neutrons are produced in a fission in a reactor with energy in the range of MeV

To sustain chain reaction, the energy needs to be brought down to meV or milli electron volt

This is done by colliding with a moderator with low 'Z' material like 'H' 'D' 'C' through ping pong ball collision

Moderators used are H_2O , D_2O , graphite (C) etc

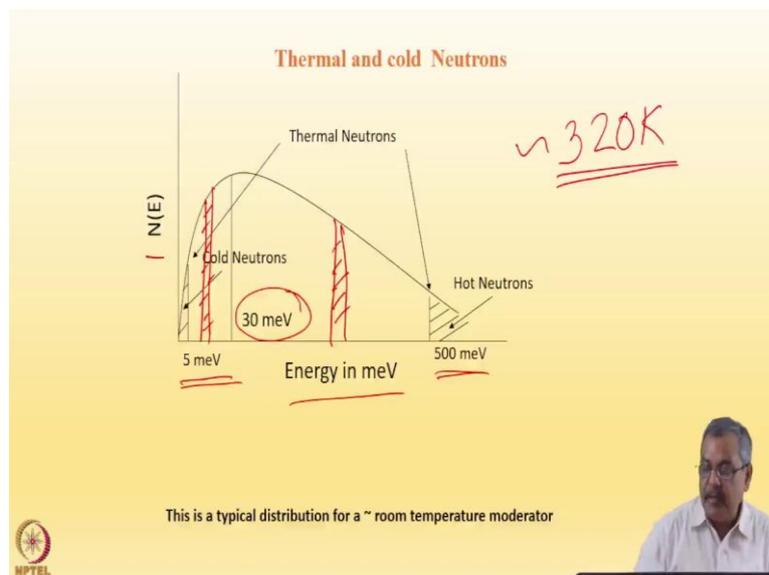
Neutrons thermalize at the moderator temperature and are called **thermal neutrons**

Handwritten notes: few MeV ↓ thermal energy meV

Thermal neutrons are neutrons which are available in the core of a reactor. Neutrons produced during fission in a reactor possess energy of few million electron volts. But, to keep a reactor critical, meaning, the reactor will keep operating using neutrons generated in it. It is called the critical reactor, and the reaction is called a chain reaction, which keeps the reactor operating without any external aid.

But, this chain reaction is so controlled that from generation-to-generation, the number of neutrons remain exactly same. Neither they decrease nor they increase. This is known as a critical reactor. To maintain this criticality, the neutron energy has to be brought down to the thermal energy range. This is done by using a moderator and the thermal energy is in the range of milli electron volts. The moderators are nothing but low Z materials, mostly, H₂O, D₂O, or carbon which, through ping pong ball collision with neutron of high energy, brings the neutron energy down in an inelastic collision. Neutron gives its energy to the moderator nucleus and its own energy comes down. This process goes on till the neutron temperature thermalizes at the moderator temperature. And at that time, we can call the neutrons as thermal neutrons. Usually, moderators used are H₂O, D₂O or graphite as this is a ping pong ball collision, and we are familiar that when the mass of the projectile and the nucleus are same, then we can have maximum momentum and energy transfer. So, the neutrons thermalize at the moderator temperature are known as thermal neutrons.

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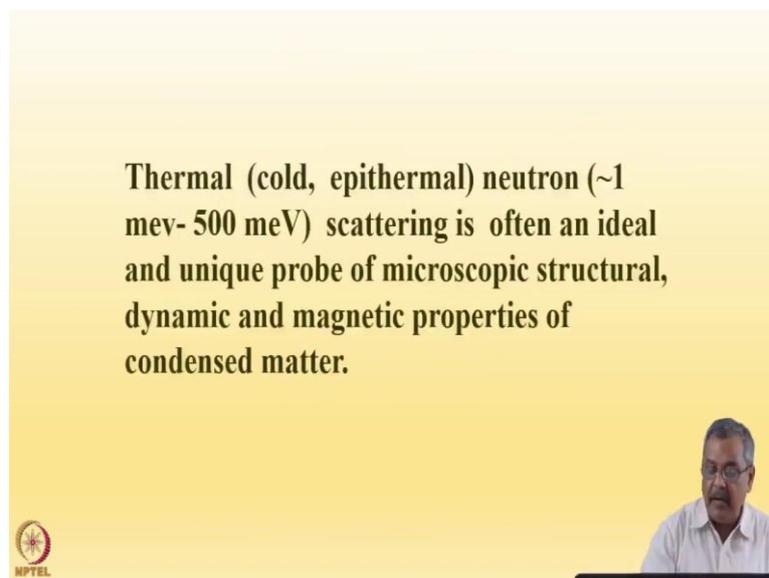
To show you the energy distribution, this is typical Maxwellian distribution of the neutrons at a moderator temperature of typically, say, 320 K, i.e, around 50°C. Typically, 40 to 50°C is the temperature of the moderator, which is present in the reactor. Once thermalizes, it is not that you have neutrons of one energy but you have an energy distribution, which is Maxwellian.

This is the Maxwellian distribution. In this, you can see there is a peak which is typically around 30 meV and we have also low energy neutrons in this spectrum which are called cold

neutrons broadly below 5 meV energy. We also have hot neutrons where typically energies are more than half an electron volt or 500 meV.

There is a typical distribution of thermal neutrons and we can choose the energy of an incident neutron beam from this Maxwellian spectrum by choosing a particular energy band with the use of something called monochromators. I will be describing these things later. You can take out a slice of energy from this Maxwellian for the experimental purposes and how we do it that I will be describing later.

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So, thermal and epithermal neutrons are having energy typically around 1 meV to 500 meV. And neutron scattering is an ideal tool and possibly unique probe of microscopic structural, dynamic and magnetic properties of condensed matter.

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Why Thermal NEUTRONS for condensed matter ?

- Wave-length close to inter-atomic distances (0.1– 10 nm) *1 Å ~ 12 KeV*
- Just as energetic as atoms and molecules in condensed matter *meV*
- Gets deep into the samples *~ 10 cm*
- Contrast between isotopes and neighboring atoms in periodic table *~ 10-100 meV*
~ 500 meV
~ 100 meV
- Magnetic (spin) to probe magnetism *C-d, Gd*
- Non-destructive characterization.

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- Magnetic (spin) to probe magnetism *1H -ve*
1D +ve
- Non-destructive characterization. *1.91 Å*

Another very interesting aspect apart from all other radiations

There are many reasons for choosing thermal neutrons for the study of condensed matter. One is that the wavelength is very commensurate with the inter-atomic distances which is typically around 0.1 to 10 nm i.e., 1 Å to 100 Å. There are various kinds of structures we can find at this length scale.

Crystallographic arrangement in a crystal are typically around 1 Å level and also various inhomogeneities in a bulk medium like, pores in a rock or a chemical precipitate inside another medium or a colloidal sample have structures around 10 nm or 100 Å.

Interestingly, in this aspect, they are quite similar to x-rays and we have to accept that x-rays are by far the most used tool for understanding the structure in condensed matter. But, one

advantage of neutron is that they are just as energetic as atoms and molecules in condensed matter. Their energy is in meV range and this is commensurate with various dynamical processes in condensed matter, not only in solids but also in liquids. That's why I used the term condensed matter because like phonons, they are typically around 10 to 100 meV energy range. There are inelastic processes like vibrations, they are typically around 500 meV.

There are also very slow dynamics like diffusion, there, the energy is typically around hundreds of micro electron volts, one or two orders of magnitude lower. For all these kinds of dynamics, and their study, neutrons are preferred. Generally, X-rays are not used for dynamics because, typically 1 Å X-ray will have an energy of ~12 keV. This energy is much above the energy range in the condensed matter and x-rays are the basic tool for structural analysis. Another big advantage of neutrons is that they get very deep into the sample. Neutron is a neutral particle and it can get very deep in to the sample of the order of tens of centimetres or even more. This is a property which is much better than most of the tools that we can use. X-rays can go to 10 to 100 microns. If you talk about electrons, they are absorbed by 30 to 40 Å depth. If you talk about protons, it will be even less. And light, it will enter a medium provided the medium is transparent to light otherwise it cannot enter a medium.

In these respects, neutron can get deep into most of the samples except a few strong absorbers like cadmium, gadolinium. There are some strong neutron absorbers but apart from them in most of the materials, neutrons can penetrate very deep. That is the reason we can get bulk information from the use of neutrons in our experiments.

Another very interesting property is that there is an extremely good contrast between isotopes and neighbouring atoms in periodic table. We know that, in the case of X-rays, the cross section increases in a power law called Moseley's law, i.e., $(Z-\mu)^3$. So, neighbouring atoms in the periodic table do not have much contrast with respect to X-rays, because, their charge cloud is almost the same size and X-rays are scattered by the charge cloud around the atom. Nickel and copper as an example, are the neighbouring atoms in the periodic table, and there will be poor contrast. Whereas, in the case of neutron, the scattering takes place from the nucleus., Neutron-nuclear interaction is a strong interaction and it depends on the isotopes like hydrogen or deuterium.

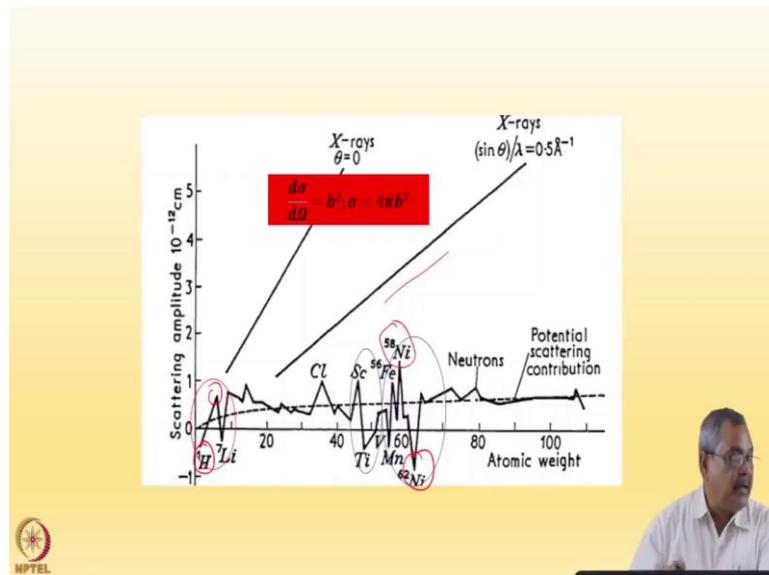
Hydrogen has a negative coherent cross-section; deuterium has a cross section which is positive. There is a huge contrast between hydrogen and deuterium and there are many such

examples. Also, they do not vary systematically across the periodic table because, the nuclear interactions dictate what should be the scattering cross section for that particular element.

So, there is very good contrast between isotopes. In that respect, the physics or chemistry remains the same if we change one isotope with another. But, with respect to neutron, they provide a completely different kind of contrast factors. Also, neutron is magnetic because, it has a spin of -1.91 nuclear magneton. That is why, for understanding the magnetic structure and dynamics, possibly neutron is the only tool to get the microscopic view of the magnetic material.

Also, it is a non-destructive characterization. Unlike, sample preparation in the case of transmission electron microscope, this probe is non-destructive in nature. Thus, all these things make neutron a very desirable tool for understanding the structure and dynamics in condensed matter and countries build nuclear reactors and accelerator-based spallation neutron sources for such studies.

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Briefly, this is how X-ray scattering cross section changes with atomic weight. Here I show the same for neutrons and you can see that this is a zigzag line where first one is hydrogen and deuterium, they have different values, and actually hydrogen has negative scattering amplitude whereas deuterium has positive scattering amplitude.

The use of hydrogen-deuterium contrast is wide because, we know that most of our organic and biological systems have hydrogen as the large component and that is why we can use the contrast between hydrogen and deuterium to highlight the contrast between various parts of a protein, or a polymer molecule etc. This can be used to understand not only the whole material but also the part of the molecule or part of the protein. Similarly, there is also negative scattering cross section for nickel, which is ^{62}Ni which is different from ^{58}Ni . This is typically nature of scattering cross section or scattering amplitude for neutrons as a function of atomic weight. This is for thermal neutrons and one is for X-rays. So, in comparison to X-rays, this is also a desirable property for neutrons.

I will stop and then I will take you for the neutron sources in the next part.