Neutron Scattering for Condensed Matter Studies

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Week 4 Lecture 11B

Keywords: Supermirror polarizers, Transmission Polarizers, Radio Frequency Flippers, DC flippers

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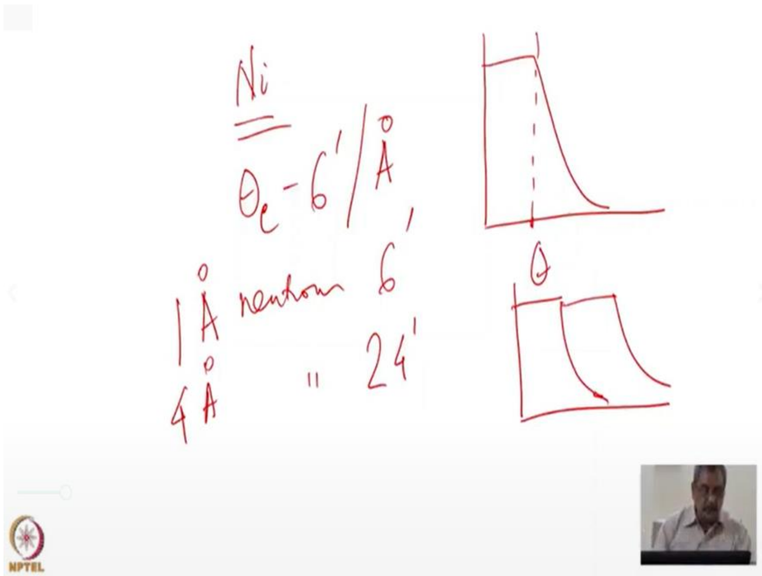

We already discussed that there is a critical angle (for a medium) which linearly depends on the neutron wavelength and nickel is possibly the best element which gives a critical angle of 6′/Å. It means for a 1 Å neutron it (critical angle) will be 6′ and for a 4 Å it will be 24′. Also, as I told you that if I magnetize a nickel medium, usually it is in form of thin films, then for magnetization direction with respect to neutron spin we will have two different critical angles.

I stopped at this point. Now let us discuss neutron supermirrors.

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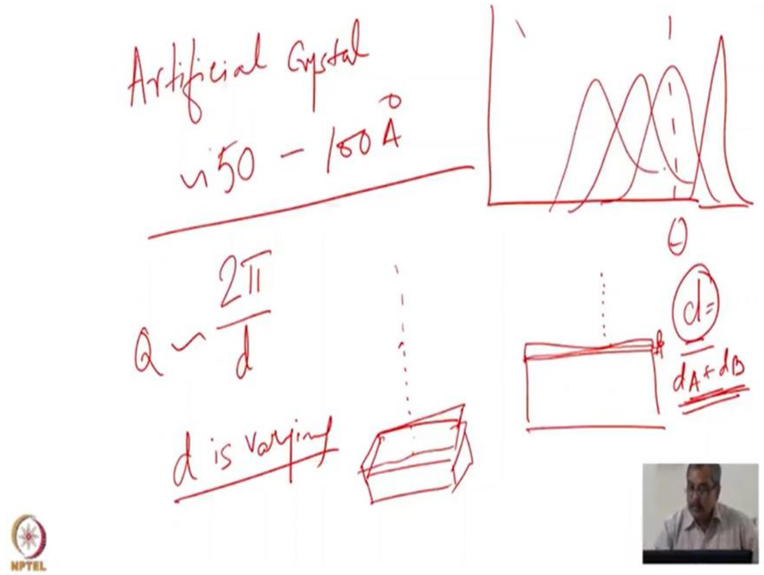

A neutron super mirror is much more than a mirror. Important point is that we need to reflect neutrons up to a large angle or large Q-value. How do we achieve that?

Suppose we have a periodic bilayer thin film which has got coatings of A and B layers on a substrate which d-spacing equal to $d_A + d_B$. Now we know that for a given d spacing in crystallography we have a Bragg peak satisfying the relation $2d \sin\theta = \lambda$. Same thing can be said for an artificial crystal that we can create with the repetition of A and B layers on the substrate with keeping the d-spacing fixed. Typically thickness of each layer is about 50 to 100 Å. Then, for this assembly, apart from the reflectivity curve I should also get a Bragg peak at Q-value given by $\frac{2\pi}{d}$.

This is the case for a single periodicity which means the stacked bilayers are of same thickness. Now as a next step let us keep on stacking the bilayers but we keep on changing the thickness continuously which means 'd' keeps on varying. Then we will have the thin film stack consisting of several d spacings and then it will have broad peaks at all these d values.

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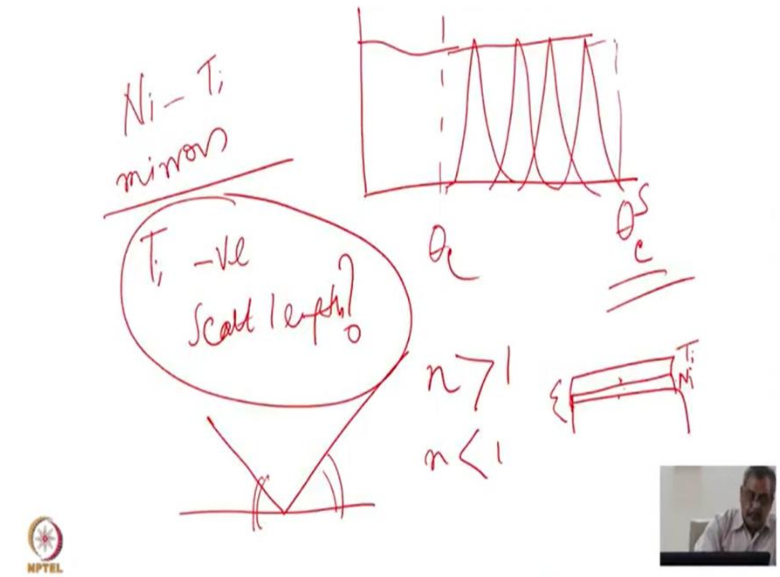

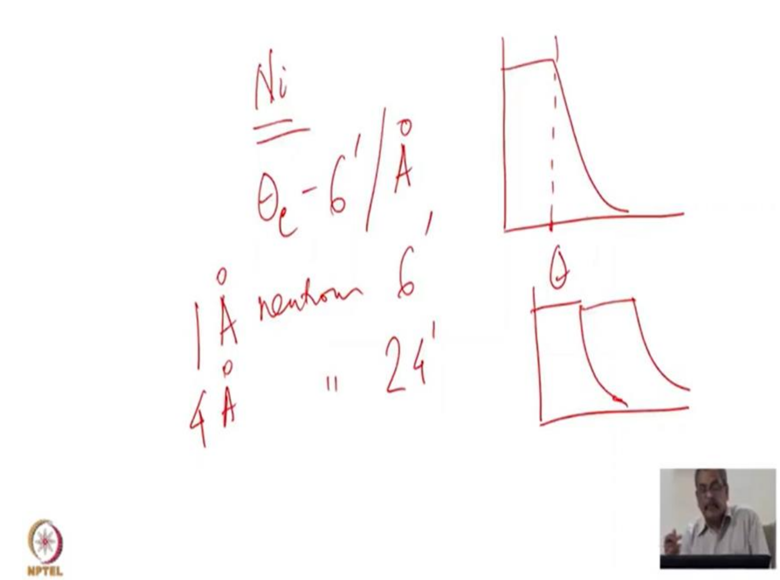

By this technique, we can effectively extend the critical angle due to multiple, overlapped Bragg's peaks at different *Q*-values. This is how the critical angle, θ_c, for supermirror is much higher than that that for a single element. One good example is Ni-Ti mirrors, reason for the choice being that the reflection takes place whenever there is a refractive index contrast. Titanium has a negative scattering length then n is > 1 and nickel has a positive scattering length so n is < 1. Hence, layers of Ni and Ti have excellent contrast because of excellent difference in refractive index between the two media and there will be strong reflection. The next step is to design a super mirror with a variable *d* spacing and I can get a super mirror which can reflect up to a very large angle. That means I can reflect neutrons up to a critical angle which is large compared to a single element. For a single element as I showed you earlier that it is 6′/Å for nickel. In this case this goes much larger and usually comparison is done always with respect to nickel's critical angle. If I say I have got a supermirror which has got $m = 2$ then it will have critical angle of 12′/Å for neutrons. Similarly, for m = 4 it will be 24′/Å for neutrons.

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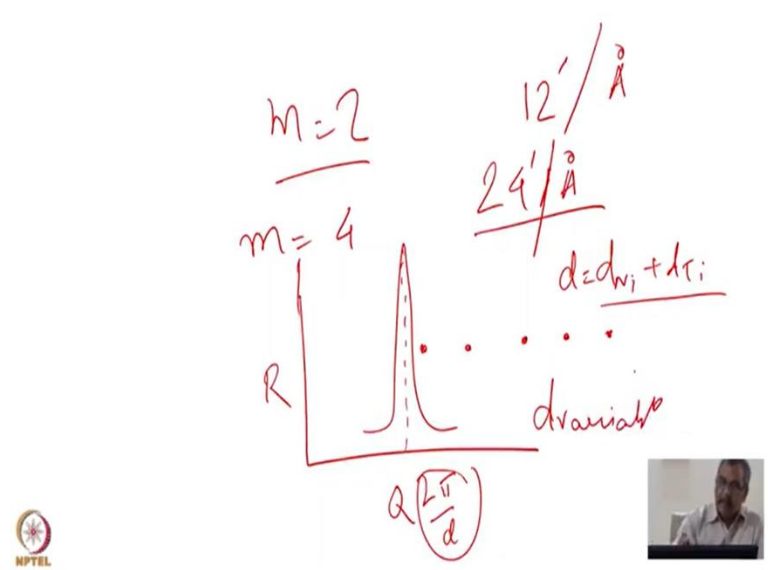

This is not an indefinite game of stacking layers, because you also have to think that neutrons that are penetrating in a medium are getting reflected from each and every interface. And how thick you can make the medium till the absorption starts taking over.

But this is possible and that is how neutron supermirrors are made. We have been talking about neutron supermirrors and supermirrors are actually bilayer stacks. If I have a bilayer stack with a single periodicity then it is like a one-dimensional crystal and periodicity dictates where will be the Bragg peak. Now this Bragg peak is not an atomic Bragg peak but by the same principle it is like a virtual one-dimensional crystal which gives a Bragg peak depending on its *d* spacing. In case of Ni-Ti, it will be $d_{Ni} + d_{Ti}$ and this Bragg peak position is dictated by $\frac{2\pi}{d_{Ni}+ d_{Ti}}$ for this particular single periodicity.

Now the clever manipulation is that in case of neutron supermirror we vary the *d* value in our thin film mirror so this is truly like a mirror. But this of course is at a much lower angle and with a much higher precision (for deposition) this needs to be made with the variable *d*.

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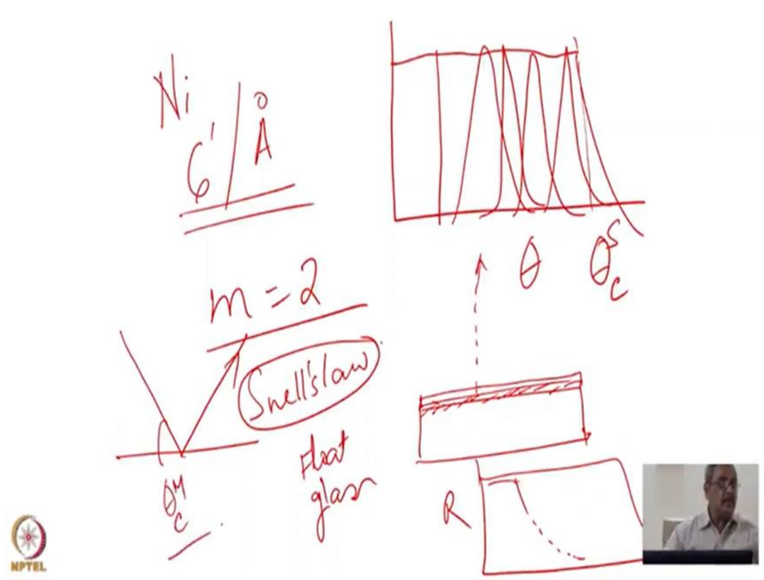

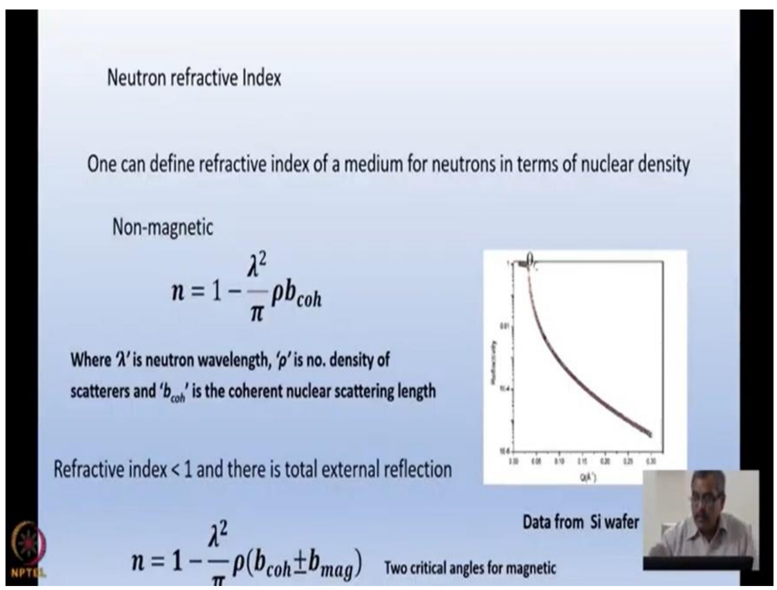

When d is a variable in that case, I can have the Bragg peaks overlapping with each other. This can push the critical angle effectively to higher angles. So, this critical angle is a critical angle for the supermirror. In the field of neutron supermirror, it is compared with nickel.

These are called supermirrors because the critical angle is large. I just showed you the critical angle for a silicon wafer.

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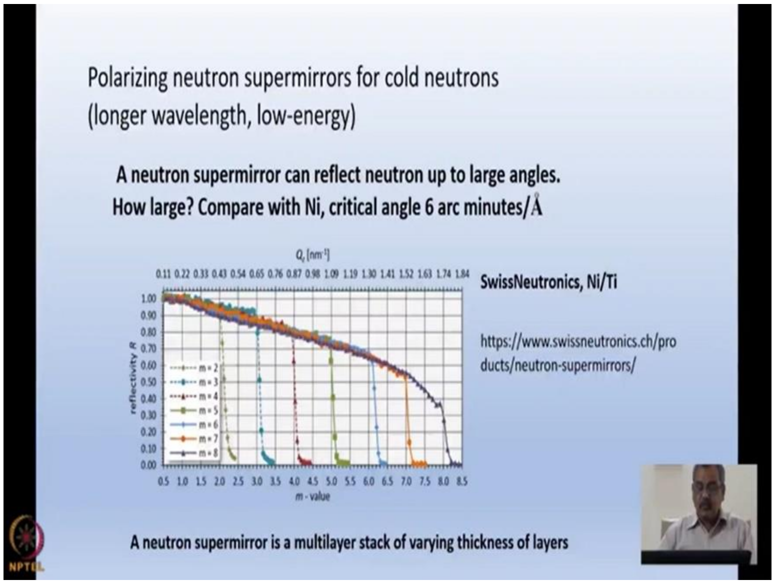

Now I can show you a supermirror from the SwissNeutronics. It has got a critical angle of almost 8 times of nickel that is with m = 8. That means a critical angle of 48′/Å for this super mirror. Of course, the reflectivity is not exactly 1 actually you can see that by the time we have m = 8 the reflectivity has come down to almost 50 %. But if you talk about m = 3 or 4 super mirrors then you have got a very good reflectivity of 80 %.

I have started talking about polarizers and I introduced you to neutron supermirrors. Now let me get back to super mirror polarizers.

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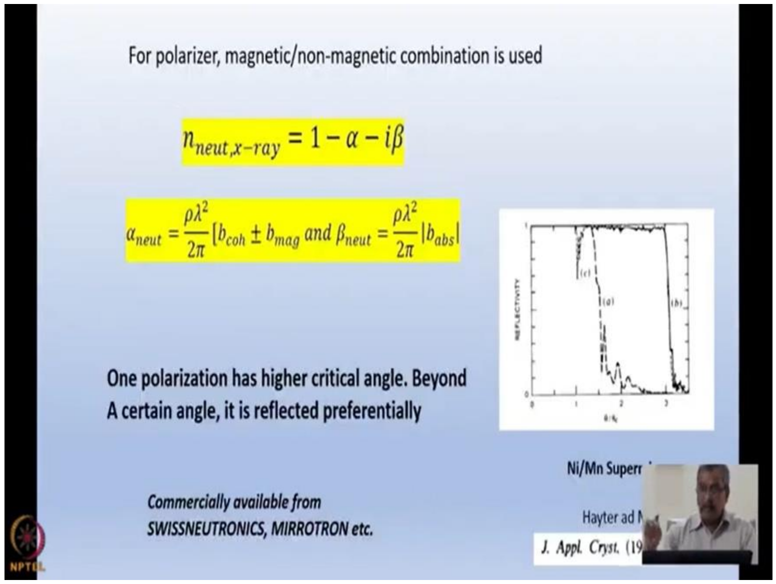

In case of supermirrors also we have got two different critical angles, one is for $b_{coh} + b_{mag}$ and other for $b_{coh} - b_{mag}$. I can design super mirrors with alternating magnetic and non-magnetic layers with variable periodicity and these super mirrors needs to be magnetized. As shown in the figure for Ni-Mn supermirror that the critical angles are quite different for two polarizations. Now, how does it help in polarizing?

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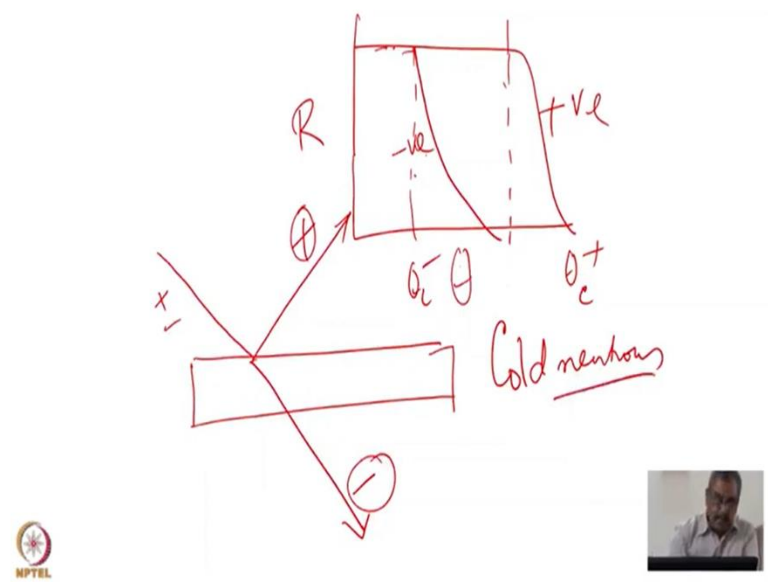

Let us draw a simplified reflectivity versus theta curve where we plot reflectivity curves for positive and negative polarizations. In this plot, you can see that if I reflect unpolarized neutron beam at angles beyond the angle with almost negligible reflectivity for the negative polarization then only one polarization is reflected while the other one gets transmitted. So, I have got a reflected beam which is positively polarized and a transmitted beam which is negatively polarized. This whole exercise is done mostly for cold neutrons.

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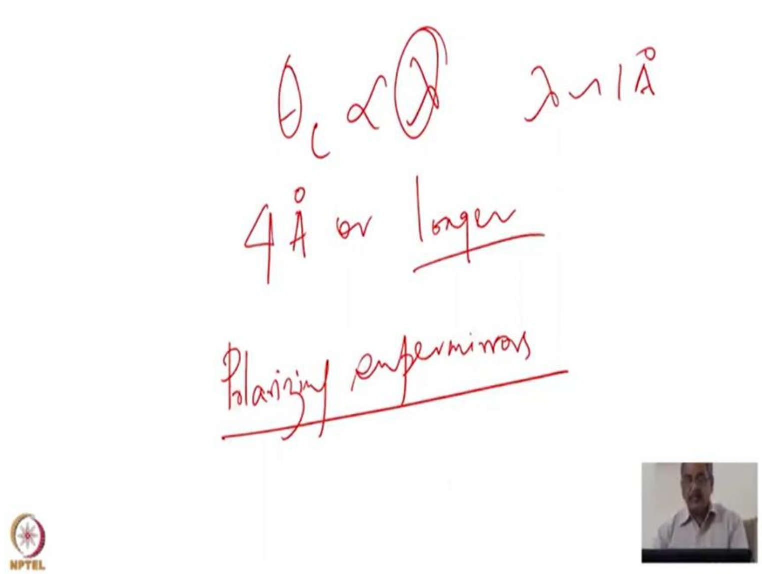

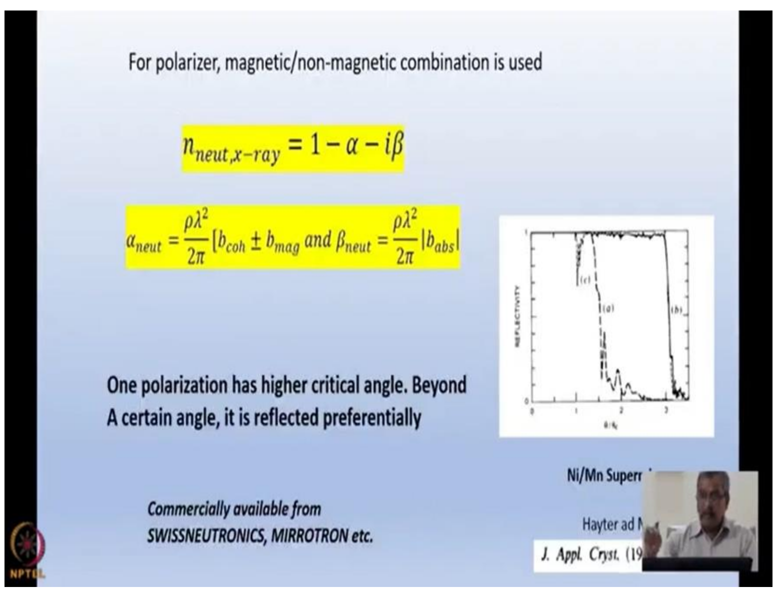

Reason being, the critical angle is dependent on λ. For thermal neutron wavelength is of the order of 1 Å and the critical angles are too small and difficult to control. We talk about cold neutrons when the wavelength is 4 Å or higher. For cold neutrons, nowadays, polarizing super mirrors are used routinely (for polarization) and they are commercially available. In experiments such as neutron reflectometry or small angle neutron scattering, if we have to do with polarized beam, it makes sense to using polarizing supermirror.

I have talked to about single crystal Bragg diffraction from magnetic sample for polarization of thermal neutron beams. Now I have explained to you how neutron polarizing supermirrors are used to polarize cold neutrons in general. Another class of upcoming polarizer is He-3 polarizer. In principle it is simple while in practice it needs very high technology.

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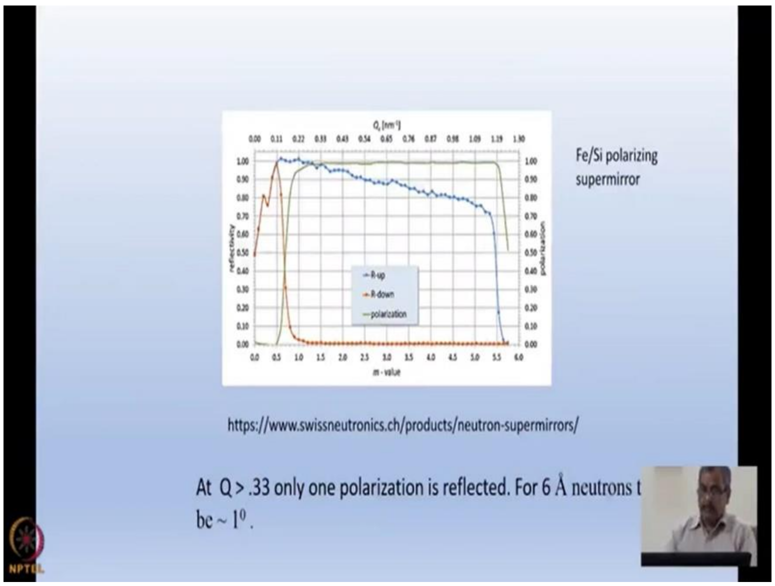

In the figure, neutron reflectivity for Fe/Si polarizing super mirror is shown and as I told you that you can see that the up-neutron reflectivity is very high up to a very large Q-value. This Q-value will dictate what is the lambda or what is the theta because $Q = \frac{4\pi \sin\theta}{\lambda}$, and for the down neutrons it goes down to 0 very quickly. For Q>0.33 already the reflectivity of the down neutrons is 0. Hence, any angle beyond this will give me a polarized reflected beam and also a polarized transmitted beam because the neutron which is not reflected are transmitted through the polarizer. I have taken this data from SwissNeutronics site.

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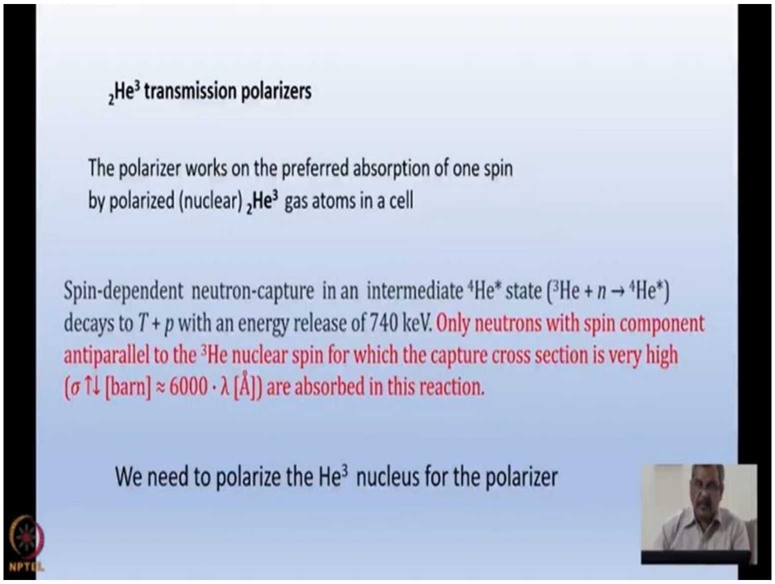

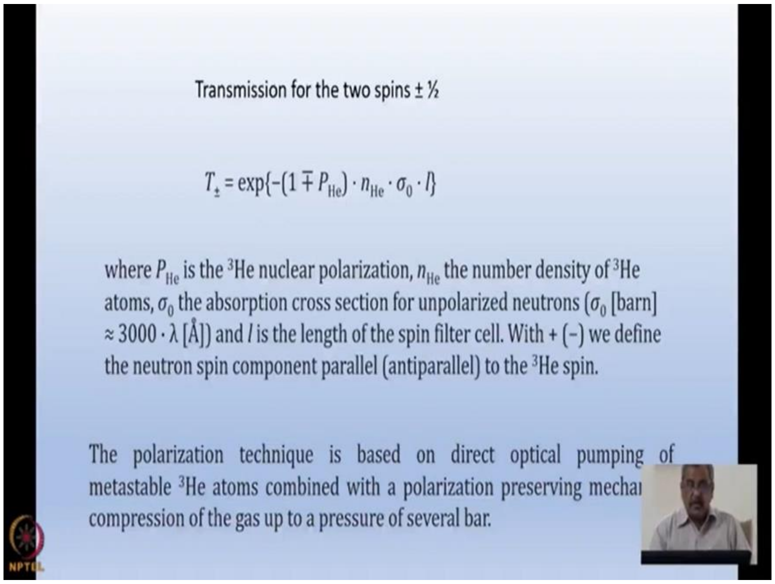

Now we are coming to $_2He^3$ polarizer. These are transmission polarizers. There has been long attempt to use $_2He^3$ nuclear spin dependent absorption for polarizing transmitted beams. This is spin dependent neutron capture in an intermediate state where the $_2He^3$ absorbs a neutron and then decays to a triton and a proton. But interestingly only neutrons with spin component anti-parallel to the $_2He^3$ nuclear spin are absorbed in this reaction. When we talk about $_2He^3$ polarizers it is the nuclear spin which absorbs. So that means this has a very tall order of polarizing He-3 gas by using some techniques.

$_2He^3$ gas polarization is done by interaction of this He-3 in a cell with a laser beam. Transmission of two spins through polarized He-3 can be written as an exponential,

$$T_{\pm} = \exp\{-\{1 \mp P_{He}\} n_{He} \sigma_0 l\}$$

Here, σ_0 is the absorption cross section for the unpolarized neutrons but it gets boosted by $1 \mp P_{He}$ where P_{He} is the polarization of the helium nuclei, it can be as high as 6000 barn for the anti-parallel neutron. That is why only one spin component goes out (transmitted).

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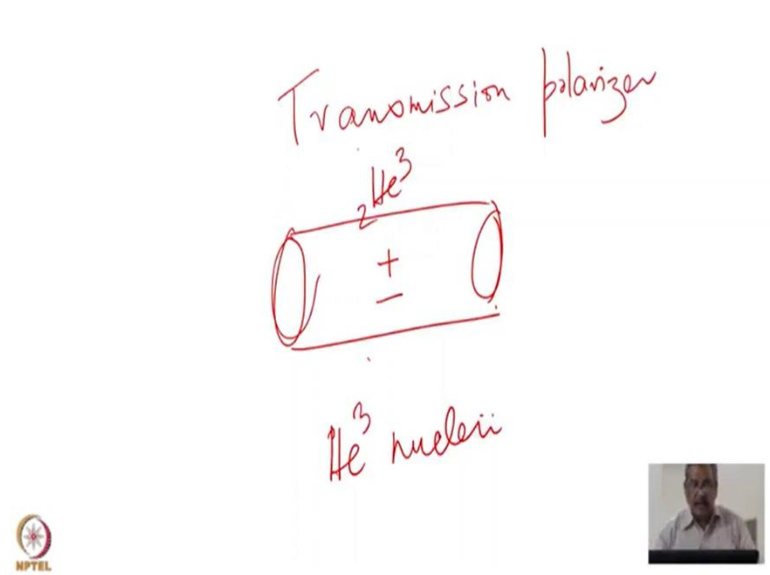

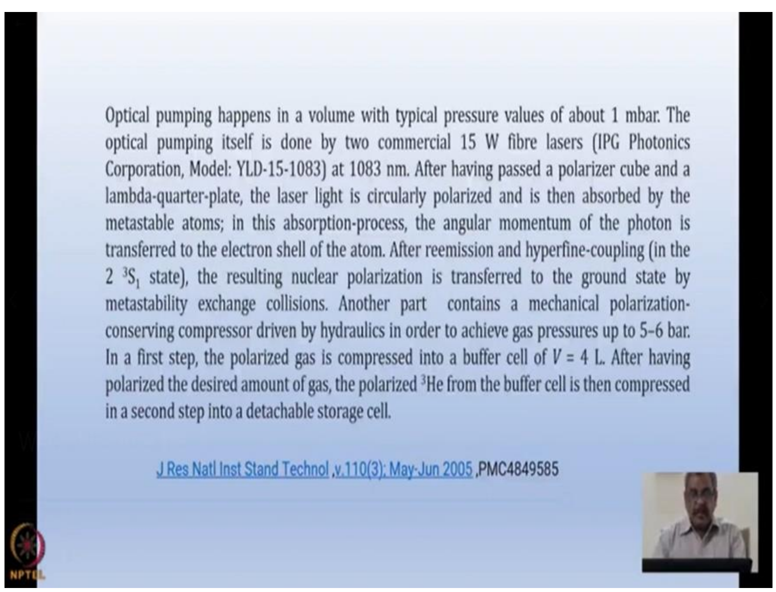

Since it is a transmission polarizer then in a simplistic term you can have very large beam cross sections for one polarization and the beam can be polarized in the transmission mode. From an unpolarized neutron beam, antiparallelly aligned neutron spins get absorbed very strongly if the $_2He^3$ nuclei are polarized. I am just quoting an old paper: it was the status in 2005 at NIST and this tells that it is done through interaction with two laser beams and how the gas is stored in a buffer cell. I am not getting into the details of the theory of the polarization. But the basic fact is that $_2He^3$- gas with nuclear polarization can be used for transmission of one component of neutron spin. There has been advancement in this regard and today at ILL Grenoble and NIST there are helium cells which are put in line with the neutron beams and polarized beams are produced. So, this completes my target of telling you how neutron is polarized for application.

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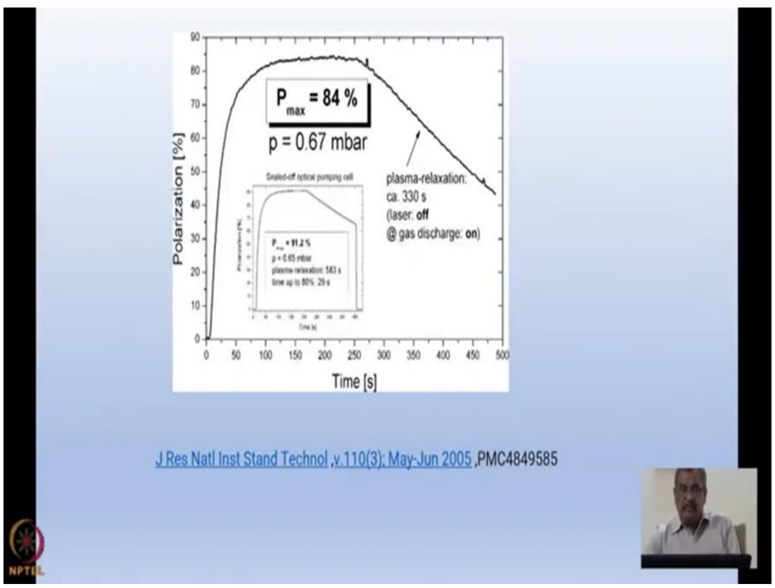

Here it is the data from the same paper and it shows the polarization efficiency of 91.2 % but even at that time (quoted paper) the polarization, say 80%, could be held for 250 to 300 seconds. It has increased a lot at the moment. If the polarization is lost quickly then the transmission polarizer also loses its efficiency. Hence, not only you need to polarize He-3 but you also need to maintain the polarization for sufficiently long time for which the polarizer can be used in the neutron beam. In this paper the time was around 250 seconds for which one can have a good polarized neutron beam. I understand that this has gone much higher today but this is not an often-used technique. Crystal polarizers and multi-layer based super mirror polarizer are used generally.

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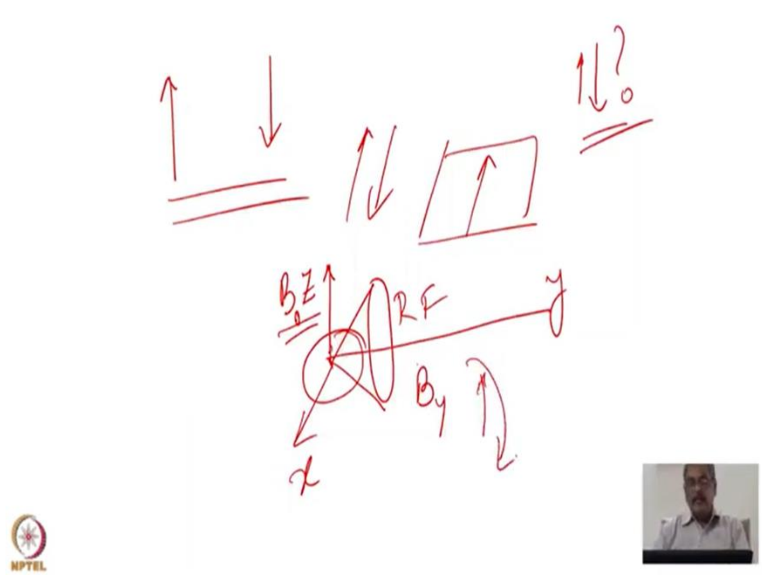

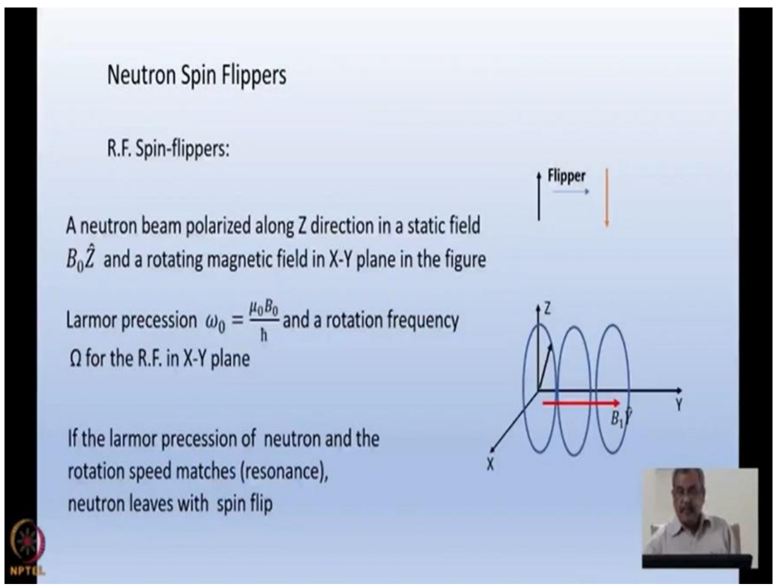

Now the last part of this talk is about flippers.

We not only need to polarize the neutron beam but we may also need to flip the spins. Let us say there is a sample which is magnetized in some direction and we need to have polarization along and sometimes opposite to this direction to get the two different intensities of Bragg-scattered or mirror-scattered beams. Many times, we also need to do a polarization analysis of the reflected beam. Hence, we need to flip the neutron spin depending on the experimental requirement. The flipping is done to change up spin to down spin.

There are several types of flippers. I will just briefly tell you about RF spin flipper. Here the neutron is polarized in the *z* direction in a guide field '*B*'. If *z* is the direction, then I call it B_{0z}. In radio frequency flipper if the particle is moving in *y* direction, then we can apply a radiofrequency RF field which is rotating in this plane. When it is rotating in this plane then you can see that the neutron sees a field which is a cone and experiences a static field of *y* component of the *B* of this rotating RF frequency.

And then in this field the neutron will undergo precision and if the Larmor precision frequency of this neutron I can match with the precision frequency of the field in the *y* direction then depending on the length of the RF cavity the neutron will go out with a flipped spin. This is called RF spin flipper and being used right from the beginning of neutron scattering. Later one more kind of spin flippers were introduced by Ferenc Mezei known as DC flipper.

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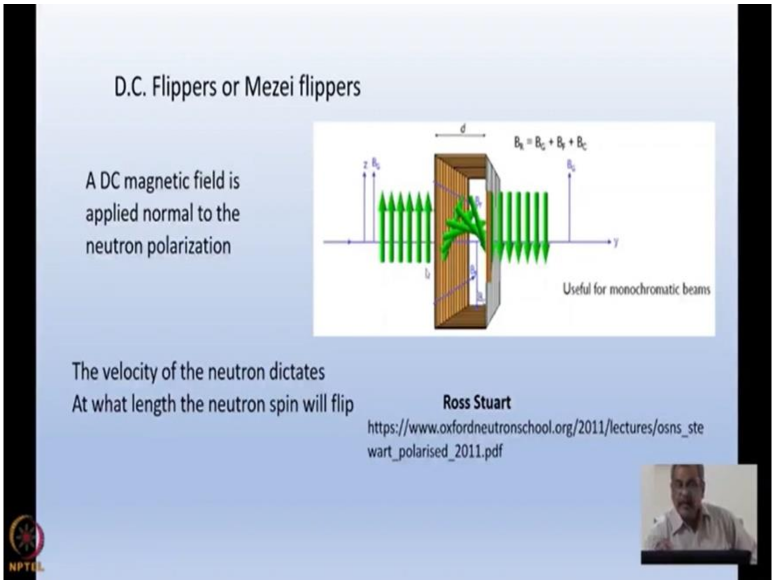

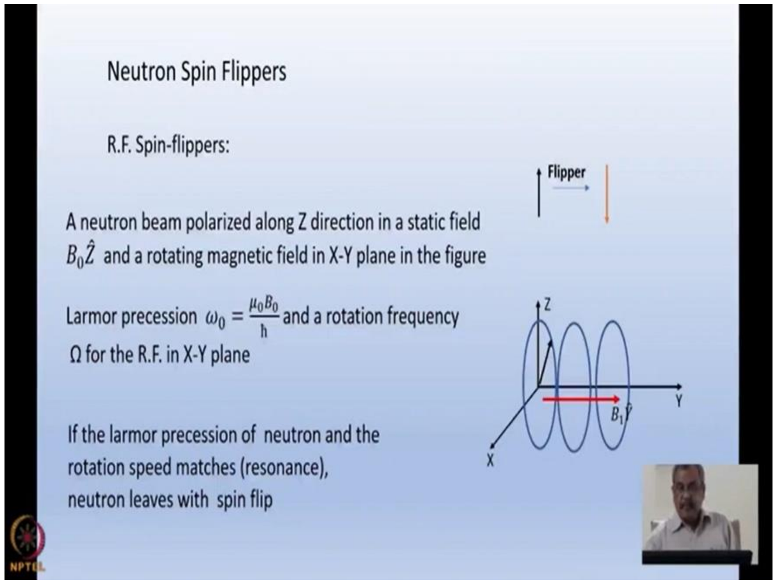

DC flipper is much easier to understand. Here the B_G is the direction of the guide field and neutron spins as you can see, they are up over here. You just take it through a field. There are three components of the field one is that $-B_G$ to cancel the effect of this B_G and the field as you can see it is a solenoid, it is a normal to the spin of the neutron and in this field depending on the velocity of the neutron and the field value the neutron undergoes a precision.

Hence, if you can choose a certain wavelength and accordingly the length of the DC flipper which the neutron has to traverse, then we get flipped neutron spin coming out from the other side of the flipper. You can see the fields written as a guide field plus compensating fields and the field in which the neutron is undergoing precision and flipping.

I have discussed with you two types of flippers, one is a RF neutron spin flipper, other one is a DC flipper or a Mezei flippers. Most of the laboratories use these two kinds of flippers for neutron spin flipping for use in magnetic neutron diffraction or reflection or even analysis of the scattered beam. With this I come to an end for in the discussion regarding neutron polarizers and neutron flippers.