Nuclear Physics Fundamentals and Application

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Lecture - 32
Nuclear Reactions Contd

So, we talked about various kinds of nuclear reactions. We talked about compound nucleus reactions. We talked about direct nuclear reactions in which transfer reactions that is the stripping reactions or pick up reactions, capture reactions, scattering elastic scattering in elastic is scattering. All these things we discussed and little bit of mechanism and physics we discussed. These nuclear reaction had been the tools in the hands of physicists to know about the structure of nucleus inside and many other information. So, typically if we look at what kind of informations one get from these reactions one is to get the energy levels of a nucleus within that nucleus you have nucleons going into different shell module states And then those energies of those things can be obtained from the kinetic energy and the angular distribution of this outgoing particles in a typical nuclear reaction experiments. So, let me work out that energy relation between energy of the outgoing particle and the energy level excited energy levels of the nucleus.

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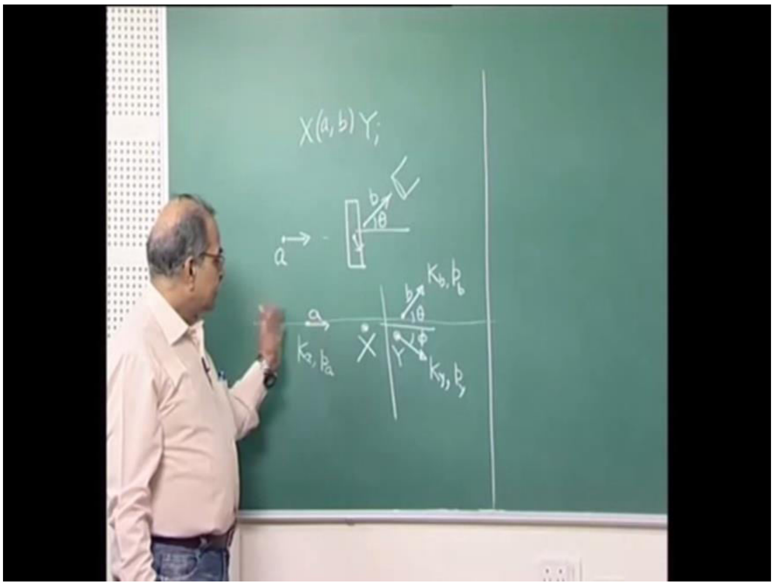

So, typically the nuclear reaction would be something like this we will have a target we have discussed this geometry several times and then some projectile particle a will be bombarded here And it will interact with some nucleus X here and then it will convert this nucleus X to some nucleus Y which will recoil inside and it will generally be stopped here itself but, another particle b can come out at certain angle and it is this b particle that we detect in the experiment. So, we put our detector here and this angle is theta so, we can vary this theta we can put the detector at any angle we wish to get the angular distribution of these particles and the detector also analyzes energies that means the particles b particles which are getting into the detector. So, what is the distribution of kinetic energy? There with what kinetic energy they are coming?

So, all those things are the experimental data that we have now, I show it as as a two-dimensional picture. So, this is that X nucleus initial nucleus and this a particle going here. So, is the initial condition with some kinetic energy k a and some linear momentum p a and then after the reaction this X becomes Y and this Y comes out not comes out it is in the target but, it starts moving in some direction and this b particle is going in some other direction. So, if we call this angle theta and this angle phi the kinetic energy of this particle is K b linear momentum is p b the kinetic energy of this nucleus here the product nucleus Y. So, your reaction is X a b Y that is the reaction. So, this product nucleus Y here is going in this direction the kinetic energy is K y and the linear momentum is p y and this one the kinetic energy K a and the linear momentum is p a the linear momentum will have its own direction. So, if I write the momentum conservation equations and energy conservation equations these equations would be first lets write linear momentum. So, linear momentum in X direction this direction of initial motion of this a particular is taken as the X direction. So, in this direction the linear momentum initial linear momentum is p a remember target is fixed in the laboratory we are using laboratory frame. So, the kinetic energy momentum of this X is 0 in this frame.

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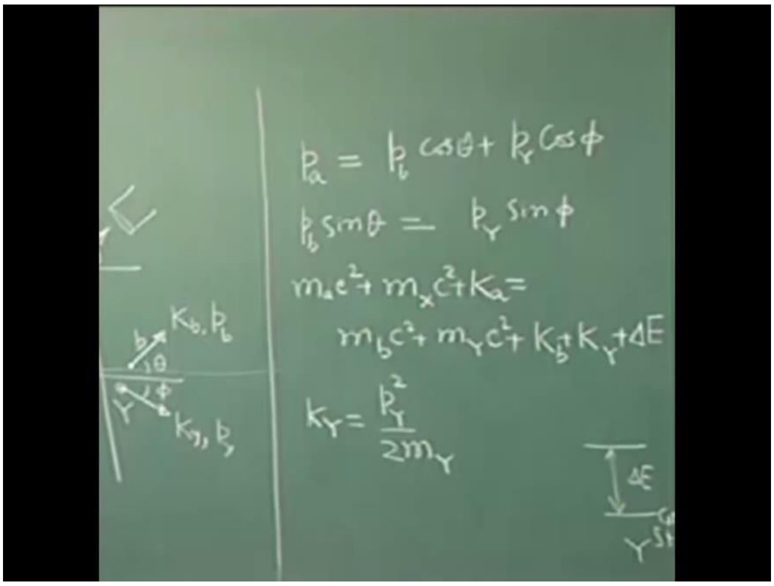

And therefore, the linear momentum is just p a in X direction and that p a should be equal to the final linear momentum in X direction and this will be the linear momentum of b that is p b Cos theta and plus linear momentum of this nucleus Y. So, it will be p y and then Cos phi just start of that nuclear event after that this Y nucleus it is inside the target so, it will collide with other nuclei and then it will stop and all those things will happen but, just after this reaction it is it has started in this direction with this linear momentum so, it is this and in Y direction there is no initial momentum and therefore, the total linear momentum in Y direction should be 0 after the event. So, if I take the Y components we will have p b Sin theta. So, p b Sin theta that should be equal to this p y Sin phi this should be p y Sin phi. So, that in y direction the two momenta cancel each other and the resultant is still 0 which was 0 before the event. So, these are the linear momentum equations now, write the energy conservation equation total energy before the event.

So, total energy is mass energy rest mass energy of a rest mass energy of X and the kinetic energy of a that is m a c square plus m x c square and plus K a . So, that is the initial energy before the event this is the energy the rest mass energy of this a particular rest must energy of this X particle and the kinetic energy of a particular kinetic energy of X particle is 0. So, that is initial energy final again rest mass energies this should be equal to m b times c square plus m y times c square. So, that is the rest mass energy of these two particles and then the kinetic energy of b plus kinetic energy of y. So, K b and

K y and if this y nucleus is produced in an excited state that extra energy also has to be written on the right-hand side if this y nucleus is produced in the ground state then this is all these rest must energy that we are writing that is for the ground state alright. So, if everything is in ground state this is ((Refer Time: 08.03)) but, then if this y nucleus which is produced because of this nuclear reaction and it is produced in its excited state which is some delta E above the ground state. So, that extra energy delta E is also present here.

So, plus delta E this delta E is y nucleus this is the ground state let us say and then when the y nucleus is produced it is produced in this excited state so, this is delta E. So, that is energy conservation equation and from what are the quantities in these equations that are known to the experimentalist? or which are measured in the experiment? or available in the books in the tables in the data? So, if you look at this energy equation mass of a, mass of x, mass of b, mass of y all these things are available in the data tables if you know what are these nuclei? a b x y these things are there then kinetic energy of particle a since we are sending this particle a beam on the target nucleus. So, we are controlling the kinetic energy of a we have set how much with what kinetic energy we are sending this beam. So, K a is also known in the experiment this side K b b particle the kinetic energy of b particle that is measured in this detector. So, the electronics will do the job and will tell that with this kinetic energy of particle b has come.

So, that can be measured that also comes out from the experiment K y this K y is something which is beyond our reach because this y particle is created inside the target and starts in that phi direction with kinetic energy K y and then all those collisions another things it never comes out. So, we do not have any handle on that but, this is not known. So, if we wants to know this excited state energy delta E from this experiment I should eliminate this K y and this K y can be eliminated using these two momentum equations plus K y is p y square divided by 2 mass of y particlt these this is non relativistic expression but, all these kinetic energies are in few m e b 4,5 m e b 10 m e b 1 m e b and the mass of the nucleus is in 1000 m e b. A single proton itself has 938 m e b or so, and therefore, this Nonrelativistic Expression is perfect. So, we use this Nonrelativistic Expression because the kinetic energy is small as compared to the mass of this Y and this p y I can get from these two equations which are the linear momentum conservation equations.

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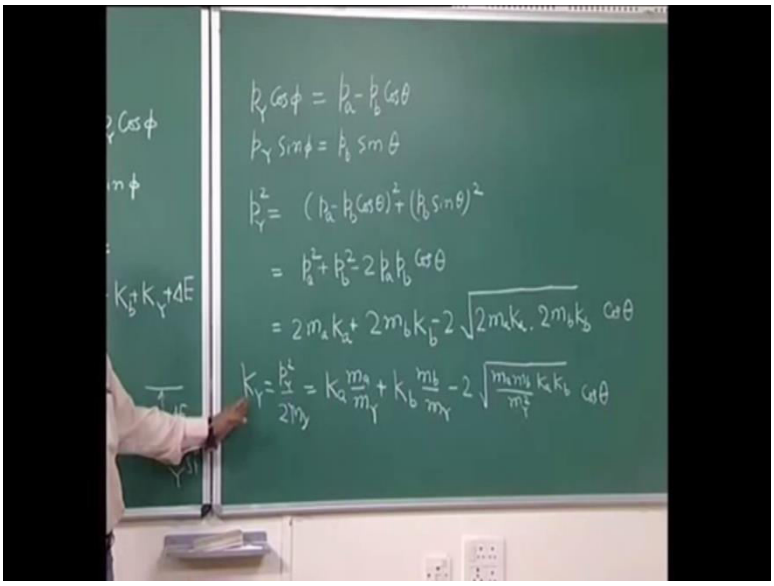

you can write from here p y Cos phi is equal to p a minus p b Cos theta and the second equation is there p y Sin phi is equal to p b Sin theta. So, you square this 2 and add we get p y square is equal to p a minus p b Cos theta square of it and plus p b Sin theta square of it which is p a square plus p b square and minus 2 p a p b and Cos theta. You can write this p a p b in terms of the kinetic energies because that is the quantity that we know that we measure in experiment and. So, this is p a square what is this? 2 of mass a and then kinetic energy of a p square is 2 m K or K p square by 2 m then p b ((Refer Time: 13.16)). Similarly, 2 m b K b and minus 2 times square root of p a into p b. So, p a is the square root of 2 m a K a and p b is square root of this p b here is the square root of 2 times m b K b and then Cos theta.

So, the kinetic energy of Y particle K y which is p y square and divided by 2 M y. So, divide this whole expression by this 2 M y to get the kinetic energy of Y particle and that will be divide by 2 M y. So, K a times m a divided by m y that is the first term then second term is K b multiplied by m b by m y that is here and then minus this 2 will cancel this 2 but, then there will be another 2 from this square root expression. So, you will add 2 here and square root of m a m b and if you write inside that square root it will be m y square then square root of K a and K b is there. So, K a is there K b is there and then Cos theta that is kinetic energy K y.

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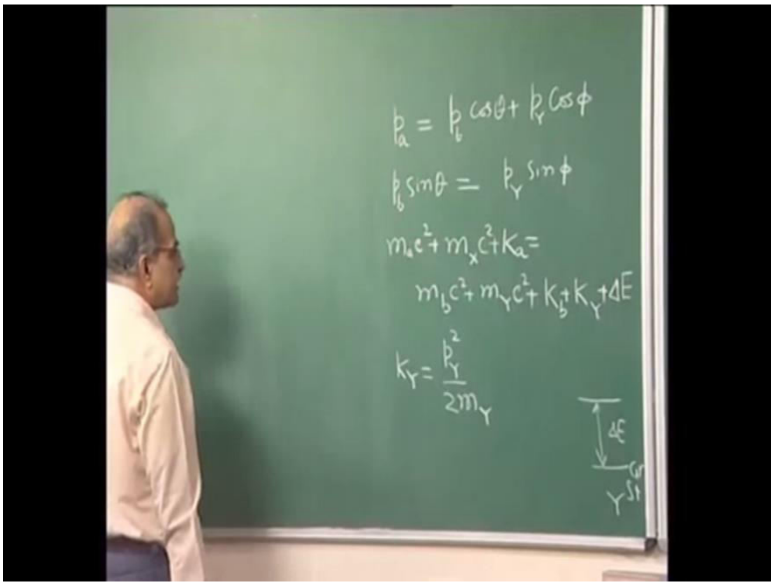

come back to the energy expression which is here m a c square plus m x c square is the initial rest mass energy and m b c square m y c square is the final rest mass energy take it to the left side initial rest mass energy minus final rest mass energy is known as the Q value you know that.

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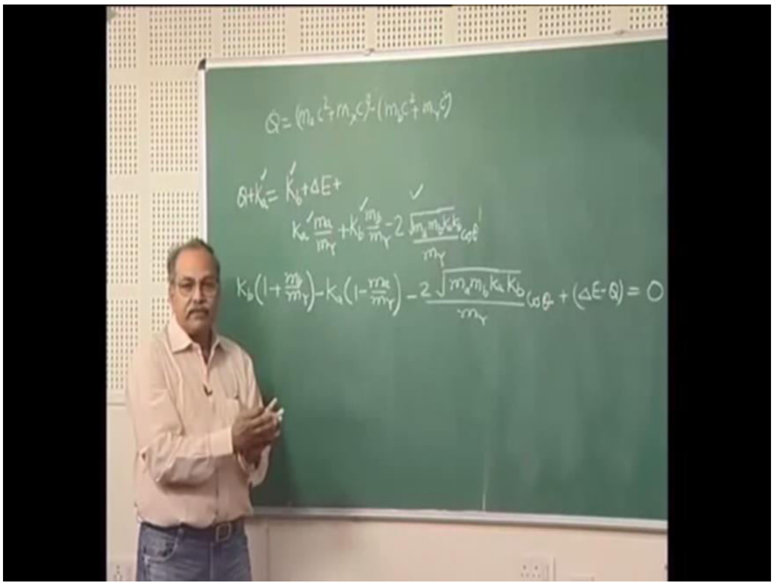

So, Q is the initial rest mass energy m a c square plus m x c square and minus the final rest mass energy that is m b c square and plus m y c square this quantity is known as Q value of the reaction and remember this Q value can be positive can be negative can be 0 because here we are not talking of spontaneous reactions. So, that the final rest mass should be smaller than initial rest mass we are sending the particles with certain kinetic energy few maybe few M e V's of kinetic energy. So, even if Q value is negative even if the rest mass energy of the final product is more than the rest mass energy of the initial product the reaction can still take place we will do the condition for that. So, this is Q value and therefore, I will just write Q here and that will take care of these 4 terms. So, on the left hand side it is Q and plus K a. So, I have taken care of these 4 terms and this K a and then I have on the right-hand side K b plus delta E and plus K y. So, for K y I will be writing all that expression that is plus then K a m a by m y plus K b m b by m y and then minus 2 times minus 2 times square root of m a m b and K a K b divided by m y and then Cos theta.

So, you can collect all those K a terms together K b terms together you can take everything on one side if you. So, wish. So, you have lets take everything to the right-hand side you have K b here K b and then you have 1 plus m b by m y. So, I have taken this term I have taken this term and then let me write minus k a and then 1 and minus m a m y. So, I have taken care of this term and I have taken care of this term remember everything is being taken to the right-hand side. So, this K a comes here minus K a it becomes so, it is minus K a and plus this term. So, this is taken and then this minus 2 times now, let me erase this right-hand part.

So, all these things have been taken and then what is left this term here, minus two times square root of m a m b K a here and K b here divided by m y and Cos theta. So, this term is written and then plus delta E and minus Q. So, plus delta E and minus Q is equal to the 0. So, let me check it once again this is K b and 1 plus this then minus K a that is this so, that and then this minus 2 times m a m b K a K b by m y Cos theta and plus delta E and minus Q and that is equal to 0. So, in this expression if I put all those known quantities I can get this delta E the Q value will be obtained from the masses of those four particles a b x and y. So, those masses are all tabulated.

So, from there we can get that Q value and other things all other kinetic energies are known K a K b then again masses and here also K a K b and theta is measured. So, from this a question I can write what is delta E? So, for a particular kinetic energy observed in the in the detector we can work out what is the excited energy level the where this particle has gone.

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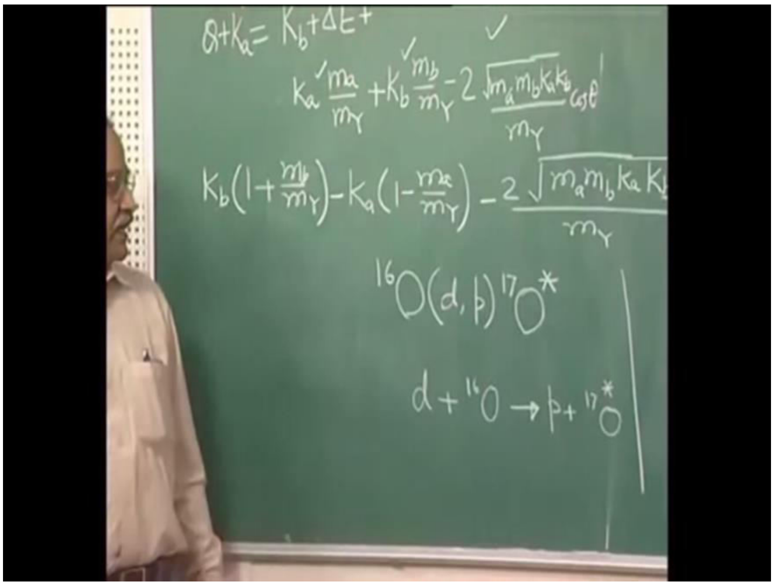

So, I will show you simple calculation for this particular reaction 16 O and then d p going to 17 O of course, it will go to the excited state you can put the star here. So, this is the reaction that means this deuteron is made to incident on the oxygen target and what we are observing is proton and inside the target you are creating that 17. So, this reaction I will do I i will show you an excel calculation and how this comes the this can give you the energy levels of this 17 O.

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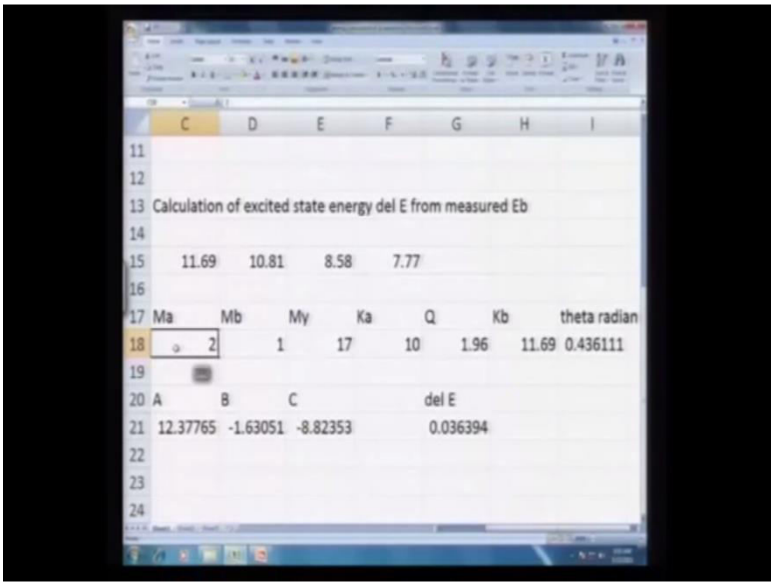

Al right so, look at your screen in the we are calculating excited state energy of for that reaction that is written there and if you look at the quantities that I have written here this is M a A is what is A? A is here the incident particle that is deuteron it is mass in certain units deuteron you have almost 2 M a mu because you will have 1 proton and 1 neutron. So, mass of A.

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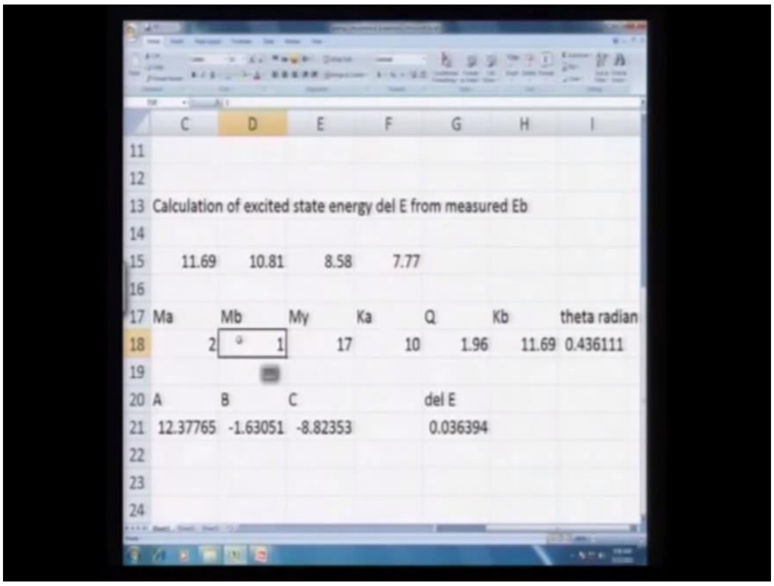

This is mass of B B’s proton. So, that mass is taken as 1. I am doing an approximate calculation to just show that these equations can be utilized and these data can be utilized to get the excited energy levels. So, mass of this b particle that is proton is 1 .

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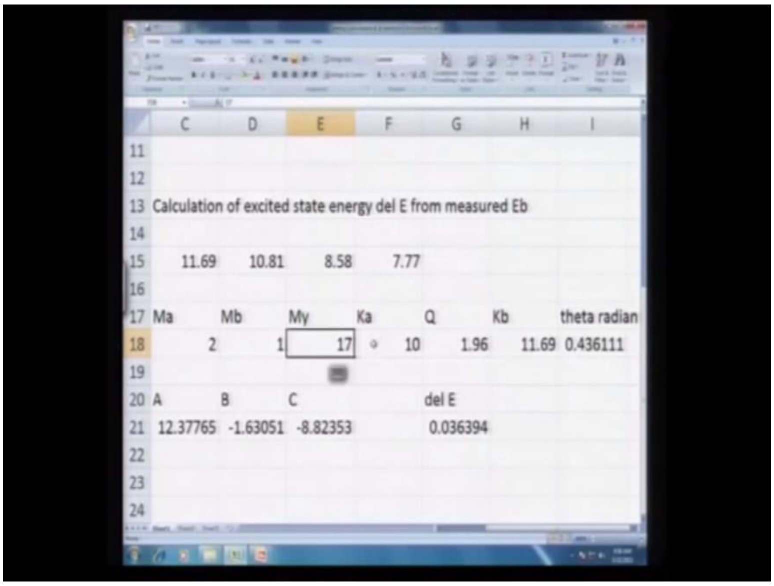

Then y y here is 17 oxygen. So, I am taking mass at 17.

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and then kinetic energy of a. So, let us take this deuterons being sent with a kinetic energy of 10 mega electron volts. So, 10 M e V. So, all these energies are in M e V 's. So, kinetic energy of this is a particle that means kinetic energy of the deuteron is 10 M e V .

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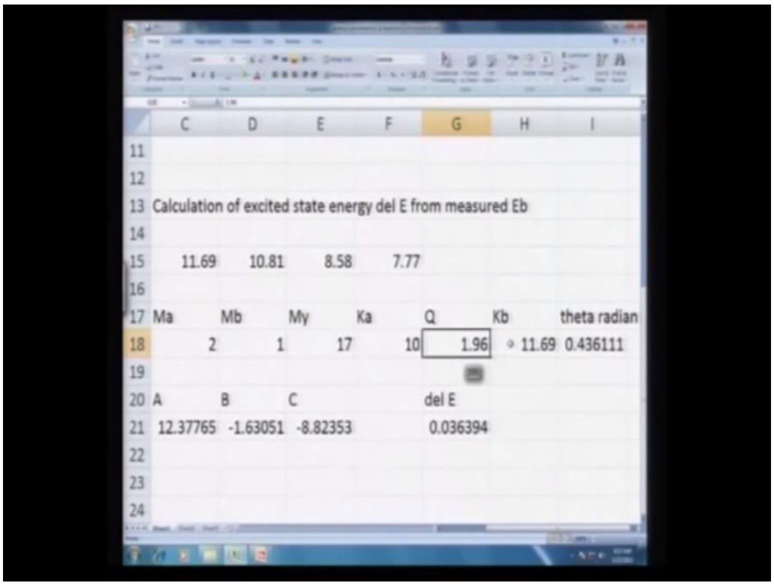

Now, Q value for this particular reaction which you can just calculate using the known masses of oxygen 16 oxygen 17 deuteron and proton that Q value turns out to be about 1.96 M e V. So, this is 1.96 M e V now, this b kinectic energy of b particles some value you have to take.

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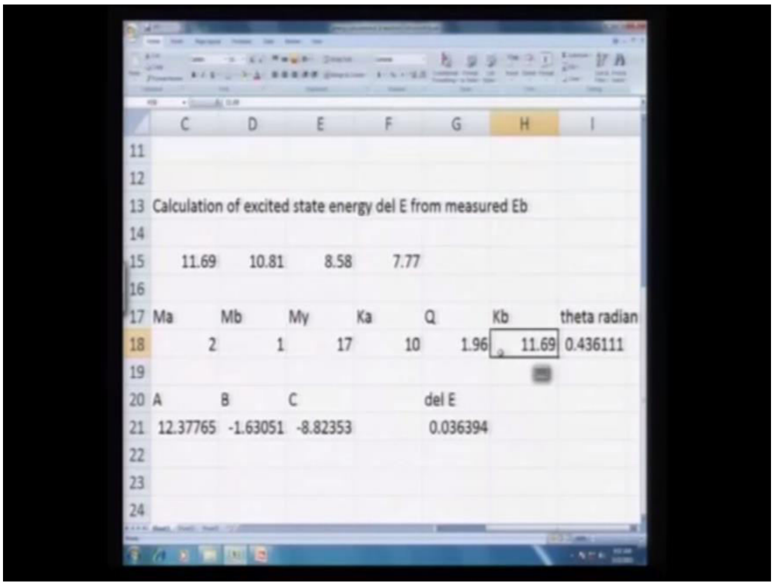

So, I am taking some value 11.69 close to what a particular experiment has measured it.

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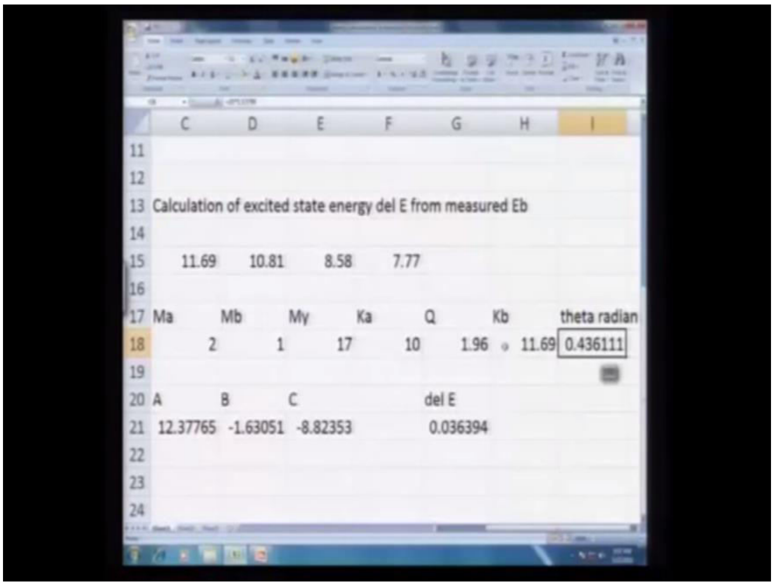

And then theta this theta that I am using here correspond it is written here 0.436 triple 1 as you can see here this is an radian it corresponds to 25 degrees. So, what situation I have taken? I have taken a situation in which the detector is placed at 25 degrees from that incident direction and then it is picking up the outgoing protons.

And suppose the proton kinetic energy it has measured is 11.69. So, for the particles which for which the kinetic energy is measured, this much what is the corresponding state of this Y particle. So, that calculation is shown here all that expression that you have on your board. So, that is also all these values you can put there and then calculate the value for delta E and that delta E turns out to be for this particular number it is 0.3 in fact it is the ground state 0 excitation energy is 0. So, if corresponding to the ground state of 17 O the kinetic energy of these protons which are detected in the detector is something kinetic energy 11.69 but, the the detector not only detects these can these particles of kinetic energy 11.69 it detects other particles of other energies to. So, what other energies are there they are discrete in fact if you plot the cross section as a function of kinetic energy detected in the detector kinetic energy of protons you find that there are certain peaks. So, eleven 0.69 was 1.

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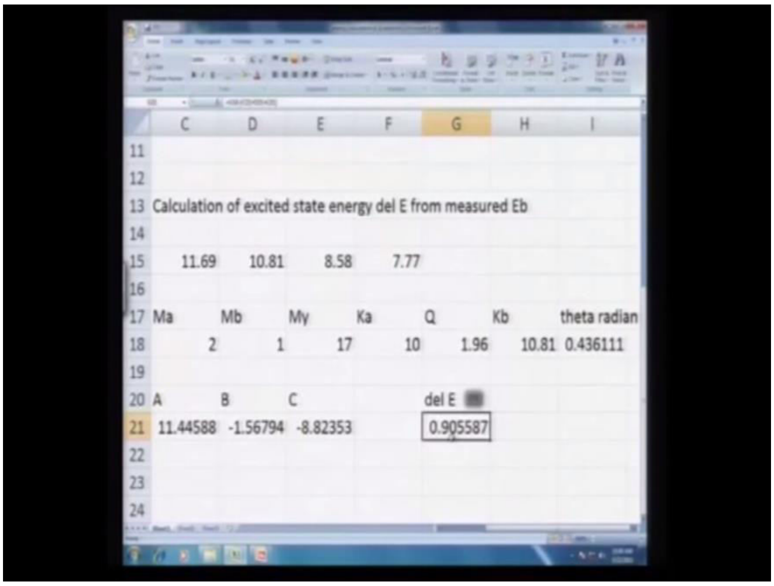

The other one is about 10.81 that is written here. So, one gets kinetic energy somewhere around 11.69 M e V and then the other next peak comes out to be about 10.81. So, if I write 10.81 here if I use 10.81 here what happens? So, place of this 11.69 let me replace it 10.81 now, I write this and we see that the energy this delta E has changed right which was almost 0 now it has 0.91 or so, if I get the kinetic energy of 10.81 M e V in the detector from there I come to know that 17 oxygen which I never observe in this particular experiment. The oxygen 16 was our target and deuteron was our projectile and what we observe in our detector was proton 17 oxygen was formed inside the target nucleus and we had no to look at that but, then from this data we know that 17 oxygen has an excited state at 0.91 M e V. So, the first excited state is 0.91 M e V.

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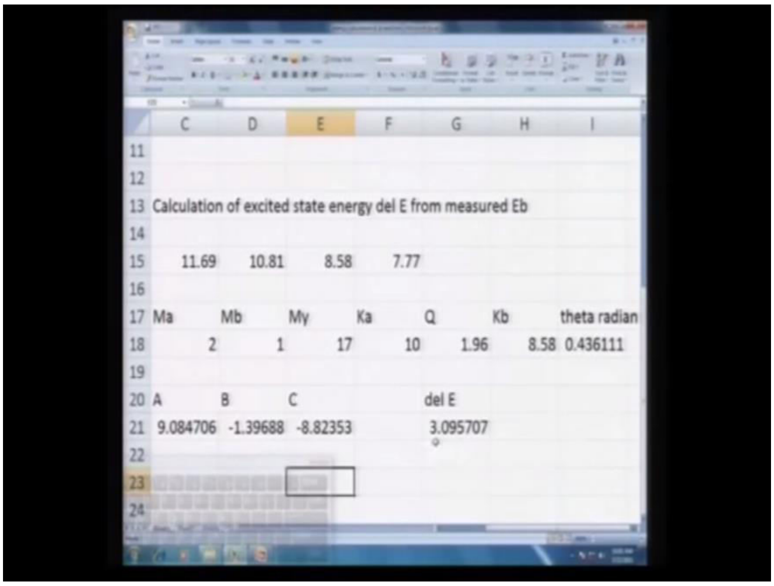

The next lower kinetic energy that one observes, is approximately around this 8.58 M e V and corresponding to this energy you again calculate. What is the energy of that 17 oxygen above ground state? So, what I have to do? I have to write here 8.58 in place of this kinetic energy of b particle. So, you can do that and 8.58. So, what you see energy of 3.1something like 3.1 M e V. So, you have gotten you are getting the energy level diagram of 17 O the ground state was there then the first excited was at 0.91 and in the second excited state is here about 3.1 M e V.

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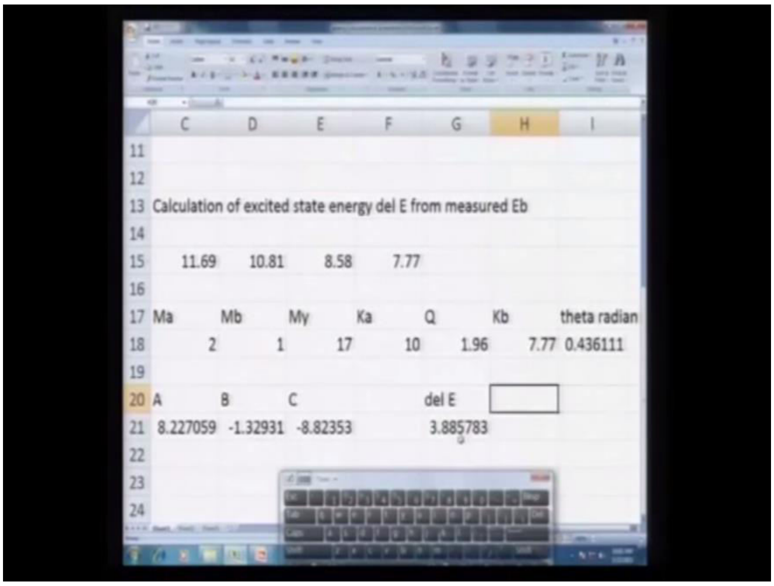

Similarly, you can go for the this fourth one 7.77 so, you can write that 7.77 here. So, 7.77 this is the kinetic energy of the proton and if you do that it is somewhere else 3.88 these numbers are only to show you how you get delta E from the measured quantities these are not the very accurate number of for that 17 oxygen but, this is how you make the calculations. So, I am coming to the board.

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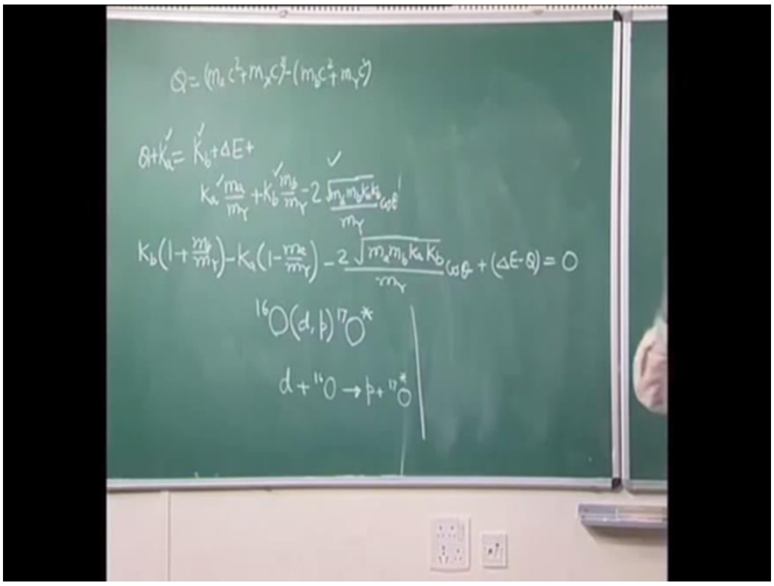

Now, from this equation that is here this equation you can do some more things for example you can think of threshold energy what minimum kinetic energy of this projectile particle is necessary for this particular reaction. So, if you look at this equation and focus on this kinetic energy of b particle you see that it is a quadratic equation in square root K b. So, squire root K b square is there and then there is a term of square root K b and then these are the so-called constant terms. So, if you think in terms of quadratic equation a x square plus b x plus c equal to 0 and for X you think of that square root of Kb I can write it little bit in that form.

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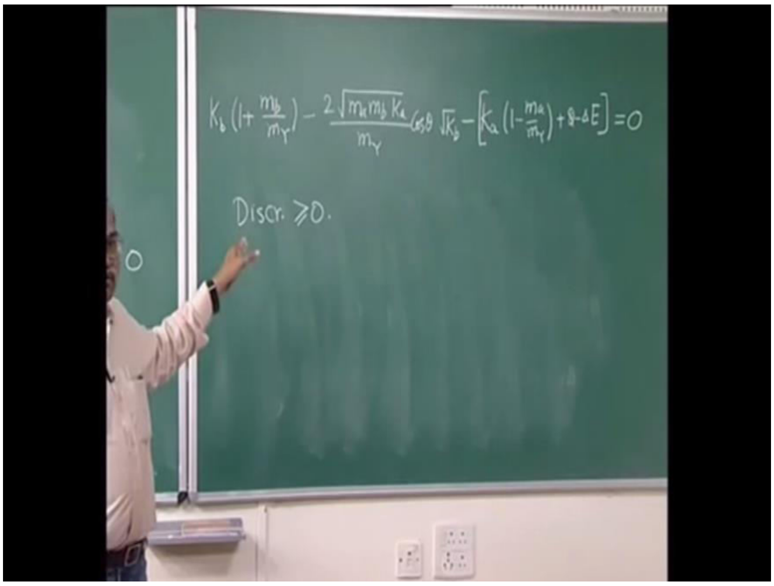

So, it will be K b times 1 plus m b by m y and then let me write this one. So, it is minus 2 times square root of m a m b and K a here divided by m y and Cos theta also and then square root of K b and everything else I will right here. So, it is minus K a I can ((Refer Time: 29.23)) put bracket here remember this minus. So, K a into 1 minus m a by m y that is and then plus Q minus delta E this is equal to 0. So, that it is standard quadratic equation format. So, square root K b square is the so, a x this is a a x square and then plus b x so, this is in place of b and then x and then see the rest of it. So, minus taken outside K a 1 minus m a by m y and then since I have taken minus outside it is plus Q minus delta E equal to 0. Now, the condition on K b would be that this discriminant should be first it should be greater than or equal to 0.

So, that you get a real value of K b so, that is one and also square root of K b should be positive because square root of K b I am taking from linear momentum p b p b I had written as a square root of 2 m b K b p. So, if that be the case linear momentum p b is positive I have already taken Cos theta Sin theta Sin phi. So, directions are taken care. So, that p b is positive. So, root K b is positive. So, from this equation you can put conditions first is that the discriminant should be greater than equal to 0 that is one otherwise the roots will be imaginary. So, that will put certain condition on K a that K a should be at least this much and then even if they are real the quadratic equation has two roots they are real. So, if one root is positive one root is negative reject that negative root and pick up only the positive root the certain range in which you have both roots positive. So, they are two kinds of kinetic energies of b particles are possible but, normally if the target is heavy and this incident particle and outgoing particle they are quite light which is generally the case in these nuclear reactions in that case that range is very small and you have almost one to one correspondence between the kinetic energy of K b and the kinetic energy K a.

So, we can work out all the things any can put up conditions what you will find? Is if this Q value happens to be positive that means the rest mass energy of final products is small and rest mass energy of the initial products is larger than there is no threshold there is no minimum limit on K a any K a will do but, if this Q value is negative natural if Q value is negative if the final products masses are larger than the initial one then you have to provide certain minimum K a how much that k should be? That will come out from these condition discriminant greater than or equal to 0 and of course, it will also depend on delta E which state you are taking that final nucleus in and also the Cos theta. So, it not just the difference in the rest mass energies because the linear momentum has to be conserved. So, certain kinetic energy will be present to conserve the linear momentum. So, that initial kinetic energy of K a particle should provide the increase in the rest mass energy as well as together with that it also has to provide them with the kinetic energy needed to conserve the momentum and that kinetic energy will also depend on theta. So, depending on theta depending on delta E you can find how much would be that threshold K a from here. So, all these energetics all these energy considerations one can work out and that will be useful for analyzing the data obtained from the scattering data.

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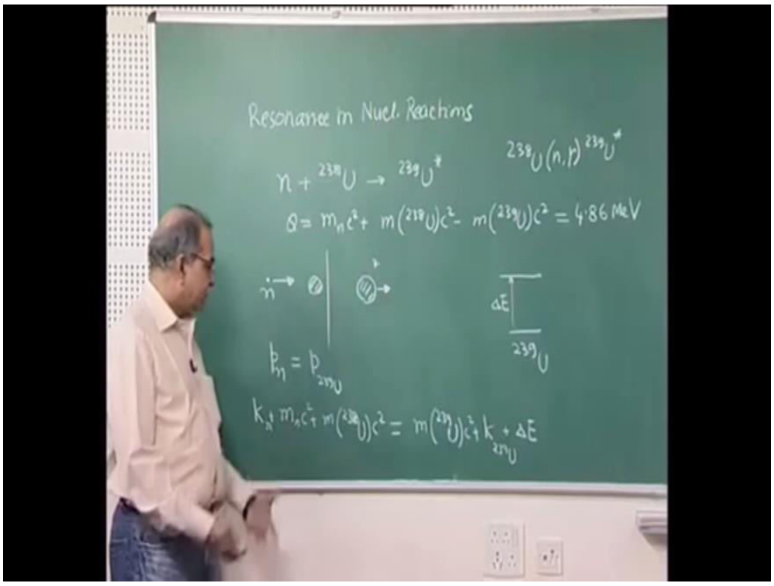

So, there is one more important phenomena related to this nuclear reactions and that is known as resonance in nuclear reactions or nuclear resonances sometimes it is called what is this phenomena? So, let me take a specific example which we will be dealing in more detail in the next chapter and that say a neutron going to uranium 238 and getting captured there. So, it makes 239 uranium normally in excited state and then it will decay through gamma emission. So, you can write this reaction is 238 uranium and then your incident particle is neutron and the outgoing particle is gamma and you are producing uranium 239 and maybe in excited state.

So, if we look at this equation we can work out what is its Q value? The masses of neutron and uranium 238 and 239 in ground state they are all tabulated and from there you can calculate the Q value. Q value will be mass of this neutron time c square plus mass of this uranium 238 times c square and minus mass of this 239 uranium in ground state time c square that is Q value and that turns out to be positive 4.86 M e V. So, let us work out its energetics so, if this neutron going this way with certain linear momentum and then getting into this uranium 238 in the target fixed that is before the event and after the event this becomes uranium 239 and lets just take it excited state formation of this uranium 239 later it will decay throw gamma.

So, the nuclear reaction event is this nucleus just gets absorbed here and it takes its to certain excited state of 239 uranium alright it takes it here this is delta E and this is the excited state it takes later on we will decay throw this gamma emission and all that but, as far as the nuclear reaction is concerned it is just this. So, it will move in this direction because linear momentum has to be conserved and this is a simple story no theta another things phi. So, it is linear momentum of this neutron that is the initial momentum and that should be equal to linear momentum of this uranium 239.

So, that is linear momentum conservation is single particle. So, it cannot go anywhere else it has to move in this original direction only inside the target remember we are not accessing this nucleus, we are not reaching this nucleus, it is inside the target but, it has to start in that direction. So, this is one and then we can write the kinetic energy which will be kinetic energy of this neutron plus rest mass energy of these neutron and plus rest mass energy of this uranium 238 c square. So, this is the initial energy kinetic energy of the neutron plus the rest mass energy of the neutron and plus rest mass energy of this uranium two thirty eight. So, this is the initial energy and that should be equal to the final energy and that should be the rest mass energy of 239 u that is 1 c square and then kinetic energy of this uranium 239 and then delta E that is the final energy final you have only one particle uranium 239.

So, it is a rest mass energy its kinetic energy and also it is in excited states. So, that extra energy is there it is in a higher energy state. So, this is the energy business once again we can eliminate kinetic energy of this 239 uranium because that is something which we have no control and then and all these rest mass energies I can put on one side and right it as capital Q.

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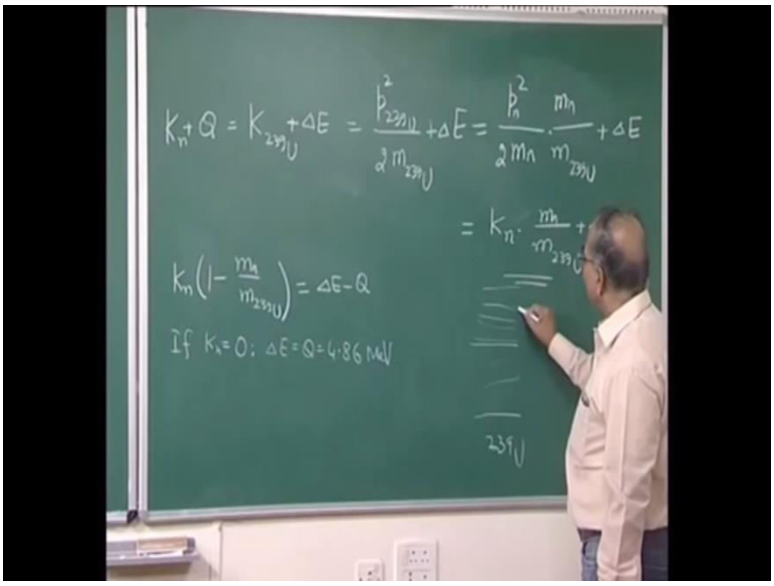

So, it will be K n plus Q. So, this is K n that I have taken and this Q I have taken and this is equal to K of kinetic energy of that 239 uranium and plus delta E this kinetic energy of uranium 239. Once again I can eliminate and by ((Refer Time: 39.52)) as put it this linear momentum of 239 uranium square divided by 2 times mass of 239 uranium that is this k 239 uranium and plus delta E. Now, this is equal to linear momentum of this 239 uranium its same as linear momentum of the incident neutron that you can see on this board this p n its same as p 239 uranium. So, I can write this as p n square p 239 uranium is same as p n n is the neutron incident neutron linear momentum of that divided by this quantity and this I can write as 2 times m n here and then divided by mass of 239 uranium and plus. So, take this and this is kinetic energy of the neutron this kinetic energy of the neutron and the m n divided by mass of 239 uranium and plus delta E.

So, what you have? K n common 1 minus m n by m 239 uranium. So, I am taking this to the left this I have taken to the left here and Q I will take to the right this is equal to delta E and minus q. So, if you send a neutron which almost negligible energy K n close to zero. So, if K n close to 0 then delta E is equal to Q alright. So, if you just send a neutron with almost zero energy then delta E will be equal to Q and that will be 4.86 M e V whatever Q I am writing here in 2 decimal places 3 significant digits whatever is the value of Q for this reaction this almost 0 energy neutron if it is absorbed it will excite this uranium 239 the nucleus final nucleus that is formed by capturing this neutron to the energy level close to four point eight six M e V. Now, where is that energy is there an energy there because the nucleus will have discrete energy levels. So, I just cannot demand that X height and this particular energy. So, if the nucleus here this uranium 239 nucleus uranium 239 nucleus it got its own energy levels. So, at 4.86 there may be a level they may not be a level. So, but, this energetics says that if this reaction is to take place this should be delta E and then depending on what kind of kinetic energy I am supplying neutron if neutron kinetic energy 0 it is this.

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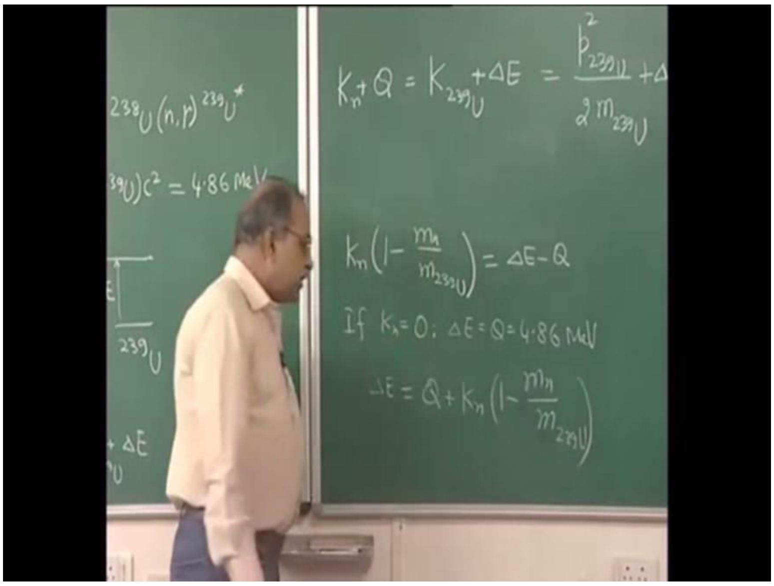

but, otherwise this delta E will be Q that is 4.86 plus K n times 1 minus m n by mass of 239 uranium on what kind of K n I am applying? What kind of kinetic energy I am giving to the incident neutron? That particular level is to be populated but, then if there is a level there then its perfect and then this neutron will get absorbed there the probability of its getting absorbed there will be high and if there is not the level at that particular delta E then this reaction will have a low probability because all this energetics have to be satisfied. So, if you look at the variation of cross section of this reaction which is related to the probability of this reaction which is which means the probability of this neutron getting captured by this uranium 238 that will have large values for certain kinetic energies which will match these energy levels that exist and if they do not match the probability will be low.

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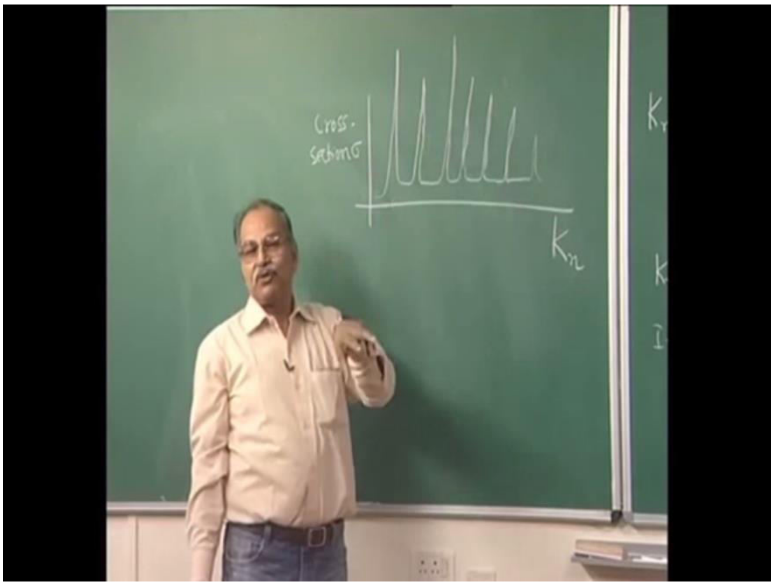

So, if you do a plot where this is the incident kinetic energy of neutron and here you are looking at the cross section sigma of this reaction then at certain energies the reaction will be very high the reaction probability will be very high and the it will drop like this what this peaks correspond to? These peaks corresponds to energy levels of uranium 239 beyond 4.86 M e V. There may be levels below that that will not be populated by these neutrons because even if the neutron kinetic energy is 0 the delta is 4.86 M e V.

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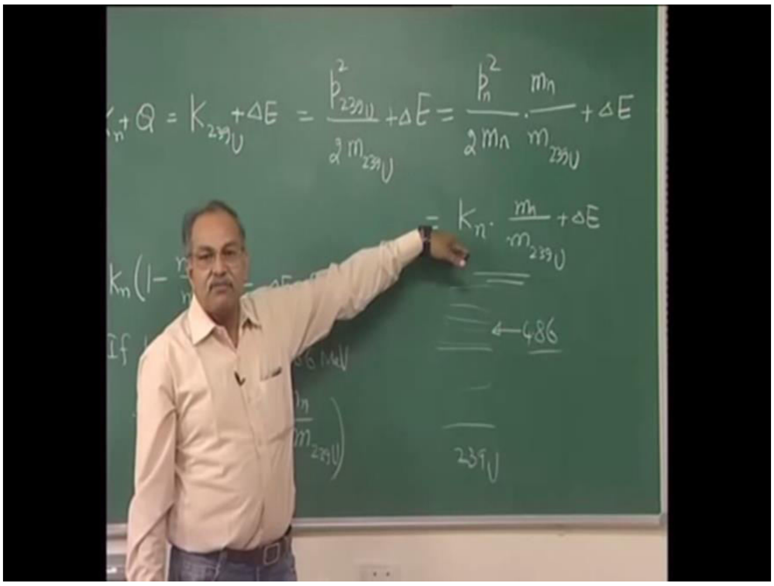

So, depending on where are those levels beyond that 4.86 mark and they are discreet. So, there are certain values discrete values, where you have the values of delta E coming from this energy level scheme of uranium 239.

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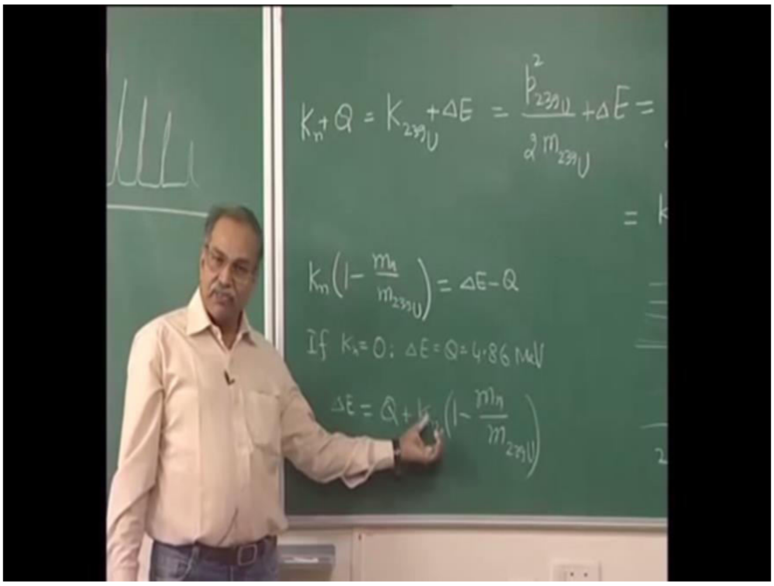

So, for those particular levels delta E, you will have corresponding K n corresponding kinetic energy of the neutrons, where the probability of its getting captured probability of this particular reaction to take place will be very high. And then if you send the neutron with little more energy or little less energy the probability will be low there will be other reaction scattering and all those other reactions can be there but, this particular capture this particular reaction where neutron is going into uranium 238 making it to uranium 239 that probability will be low.

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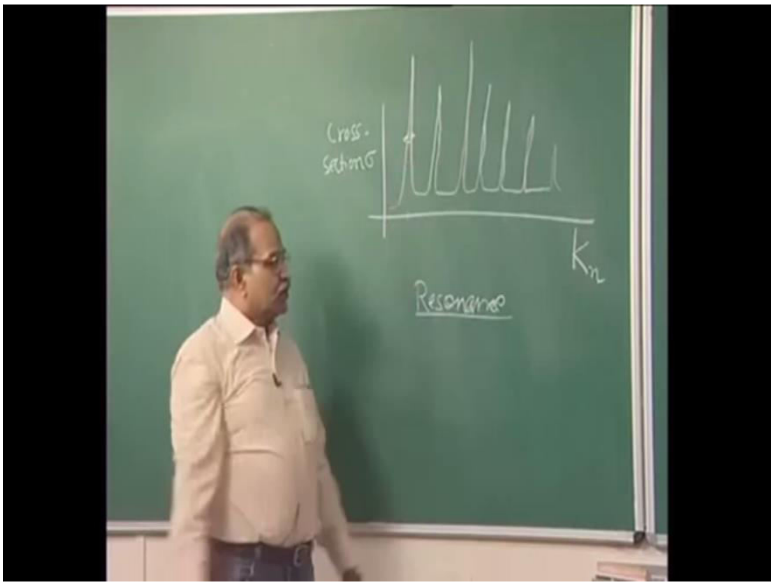

So, this phenomena where the cross section suddenly increases at certain kinetic energy of the projectile particles and drops this is known as resonance. And it plays very important role in our fission reactors and some of the astrophysics nuclear reactions and. So, on the shape of this line has been worked out theoretically known as Breit-Wigner formula its kind of lagrangian and this width here is related to the the lifetime of that particular state in in that uranium.

So, larger the lifetime more stable is that state and narrow will be the with, so this is resonance reactions these are examples this is an example of nuclear resonance reactions in which the cross section resonantly increases at certain the energies, where the energy available for excitation matches with the actual energy level difference in that particular nucleus. So, if it exactly matches it goes up that is all about nuclear reactions and next lecture I will going another topic and that will be nuclear fission reactions.