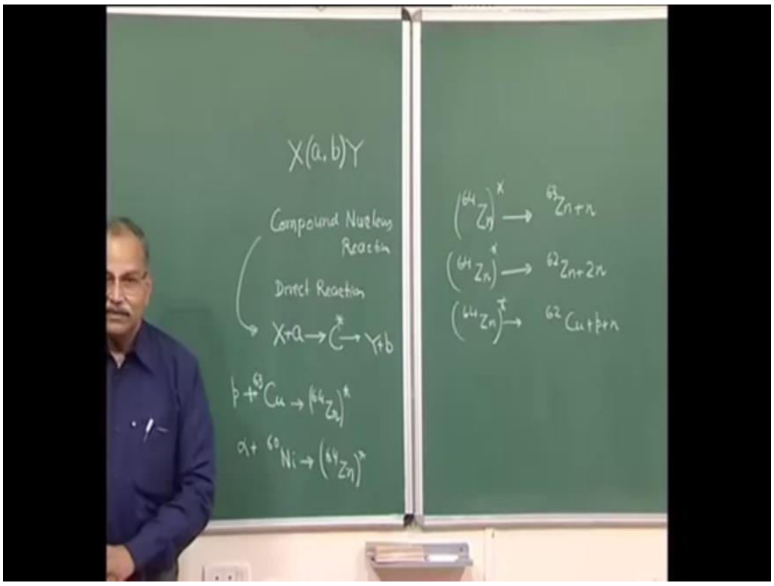
**Physics Nuclear Physics Fundamentals and Application**
**Prof. H. C. Verma**
**Department of Physics**
**Indian Institute of Technology, Kanpur**

**Lecture - 31**
**Nuclear Reactions Contd...**

(Refer Slide Time: 00:23)




So, we talked of varieties of nuclear reactions in general. You write a nuclear reaction as target nucleus X and then projectile particle a, which is either nucleon like proton or neutron or small nucleus neutron alpha particle. So, on and then outgoing particle b which we detect in the detector and the nucleus Y. So, this is the product final product nucleus as we discussed you have varieties of reactions if this a and b is same normally it is known as scattering the same particle which comes out.

Now it could be the same particle which comes out or may be is the similar kind of particle come out that also possible. The proton which you have sent if that same proton comes out then it is surely scattering but, if that protons gets observe in some other proton comes out that also be written like this but, that will be the typical nuclear reactions now scattering can also be elastic scattering or inelastic scattering in elastic scattering you have particles coming in and then going out and the total kinetic energy before the event and after the event are same, and that normally happens when you have low energy charged particle falling on the nucleus because of the coulomb barrier it is not able to penetrate close enough and it is a coulomb scattering which is elastic scattering most of the time then inelastic constants scattering you have this some energy goes into the system excite it is from ground state to some higher energy state.

And finally, kinetic energy is less than what you would expect another thing which we will discuss is the change in the rest mass from there you can get extra energy or you may need energy to pump in to get that final products we will talk that in somewhat more detailed. The kind of reactions that we are discussing at this moment and if a and b are different X and Y are different they are normally known as the reactions typical reaction nuclear reactions and this nuclear reaction we talked of two varieties one is what we call Compound Nucleus Reaction and other we talked of Direct Reactions in this Compound Nucleus Reaction the is a two step process.

So, this a falling on X get's dropped into for some time and that creates nucleus with some higher energy and then after this nucleus decays in Y plus b. In this compound nucleus thing reaction where and this will be more probable when the energies are such that the de Broglie wave length of the incident particle is more like the size of the nucleus. So that the energy is shared by all the nucleons in the nucleus it takes time the energy is first goes into few nucleons or one nucleon and then there are collision among the nucleons and from there the what you called equilibration fine.

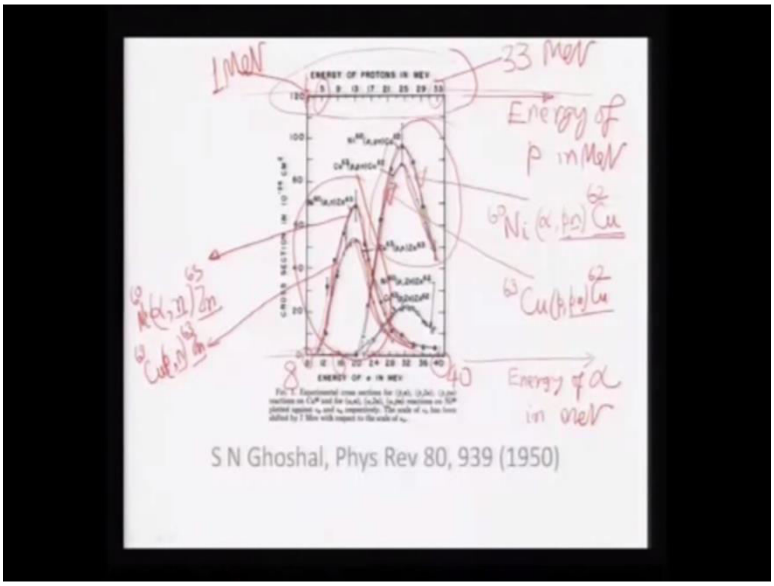
So, the energy is distributed finally in all this nucleus and this compound nucleus is formed and but, this is a in a higher energy state and. So, it can emit the particle and or the excite go to its stable state. So that is this second part whereas, Direct Reaction is when the energy is still higher say twenty M e V and above. So that the de Broglie wave length is of the order of nucleons size not nucleus size in that case it hates interacts with one or two surfers nucleons and some nuclear reaction takes place there itself locally and then something comes out and something gets into the product nucleus.

So that is a direct reaction there are variety of direct reactions also but, come back to this compound nucleus reaction the basic one of the basic assumptions in understanding this kind of mechanism is that once this C star is form once this projectile nuclei are nucleus a is absorbed into the target nucleus it and then the energy is equally rated among all the nucleons and then the energy is equilibrated among all the nucleons. So that the Compound Nucleus is formed then it has lost all the memory of how it was formed?

Now it is this state of this nucleus that decides the future course alright. So, the theory is the detailed theory of Compound Nucleus is developed on this assumption I will show you a slide in which we will have this proton falling on copper 63 and then this will make. So, proton falling on this it will make 64 zinc, and another way in which it can do is this alpha particle can go on 60 nickel and that will also form 64 zinc this is the compound nucleus which will finally, decay to something else the rate can decay in various manners it can be formed in various manners it can decay in various manners. So, after the 64 zinc is formed that can decay to by emitting, let us say neutron if a neutron is emitted it will be 63 zinc plus neutron is one channel it can also go through 2 neutron emission these are the absorbed things in the experiment that is why I am writing this I will show it on the screen.

So, if 2 neutrons are emitted then it is 62 zinc plus 2 n or one neutron one proton can also be emitted in which case it will make copper and 62 copper many other things are possible but, these the work that I am going to show you talks of these three mechanisms. So, is this zinc is formed let us compare that this zinc 64 zinc is formed through is proton reaction. So, proton going into this or it is formed in this alpha particle reaction where alpha particle falls on 60 nickel and then it goes here. So, the later part this zinc going into these channels in these reactions this later part should be independent of how it was formed provided the compound nuclear this formed in the same energy state let me show you slide in which this these reactions are studied and we will see that the assumption is experiment has experimental support.

(Refer Slide Time: 09:06)




So, look at your screen this is prepared by S N Ghoshal Physical Review 8950 and in on the screen you see the x axis horizontal axis here this is an energy, this is Energy here of alpha particle in mega electron volts, and if you can see this is 8 here and this is 16 this is40. So, this is energy scale on top of figure if you see here also you can see here energy scale is written this is also energy but, this is Energy of proton in M e V and here if you look at carefully this is 5 this point is 5 and therefore, this point is 1 this is 1 M e V.

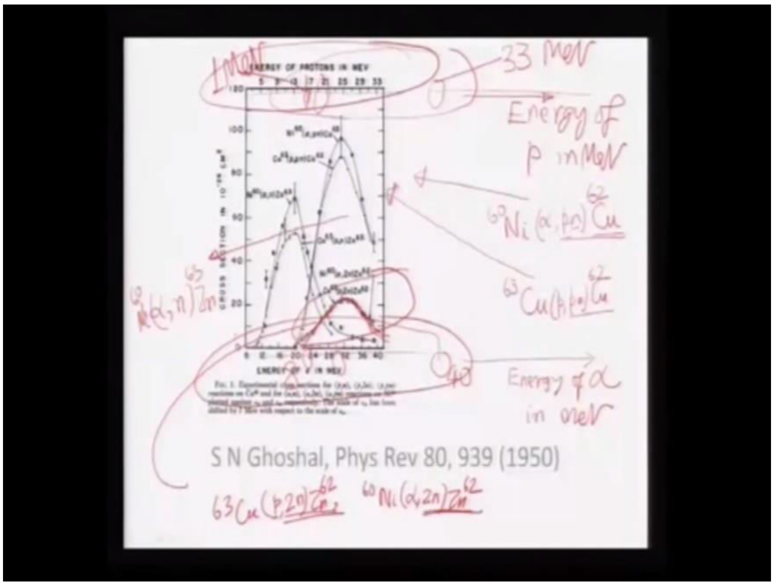
So, here this starts at 8 M e V in on the bottom line here this is 8 M e V and it goes up to here it is 40 M e V. Here on the same graph you see energy scale on the x axis side horizontal side this is 1 M e V and this last point is 33 M e V. So, two different energies scales are used here one for alpha particle that lower horizontal line is energy of alpha particle in M e V and the topmost horizontal line here is energy of protons in M e V and the scales are shifted. So, for alpha the full scale in this diagram is eight M e V up to this 40 M e V the end point here where as in for the case of proton starts from 1 M e V and goes to 33 M e V.

So, this is the same plot in the same graph two horizontal scales are used two different energy scales shifted though the status find 1 centimeter it is equal number of M e V but, it is shifted the values are shifted Y values are shifted that we will talk little later the value are shifted to match the energy available for excitation how much. So that 64 zinc should be formed in the same excited state if you want to compare the two incoming channel therefore, the energy will be shifted. So, we will talk about this when I go to the board now look at the diagrams. So, look at the this diagram here these two curves here alright now the this upper one is written there but, I do not know whether you will be able to see small letters this upper one is for reaction nickel 60 alpha then p n and copper 62 that means these zinc 64 zinc is formed by alpha particle reaction on 60 nickel and lower one this is the lower one, this one for copper 63 p p n and then copper 62.

So, what we are studying we are studying how this zinc 64 decay to copper 62 emitting a proton emitting a neutron. So, the final products are same whereas, the initial constituents forming this 64 zinc they are different and this graph shows how this cross section reaction probability changes with the energy. So, in both cases you see that the pattern is almost the same the two variations this one and this one they are almost same character they are showing similarly, if you look at the other parts here on the left side here you have this these two graphs and here also the variation of cross section as a function of energy is almost same this one and this one is almost same and what are these two this upper one is again alpha particle and falling on that nickel 60.

So, and then neutron coming out zinc 63 and the lower one here is this is copper 63 on which proton is falling and then neutron is coming out and zinc 63 is formed. So, for the same final products we are comparing within the alpha nickel reaction and proton copper reaction. So, the compound nucleus is form in two different ways but, we are comparing the cross section for same final product which is neutron and 63 zinc neutron and 63 zinc and here also you see that the two curves here the cross section as a function of energy here and the cross section as a function of energy here they are almost the same then you are left with two more curves here erasing this.

(Refer Slide Time: 15:51)

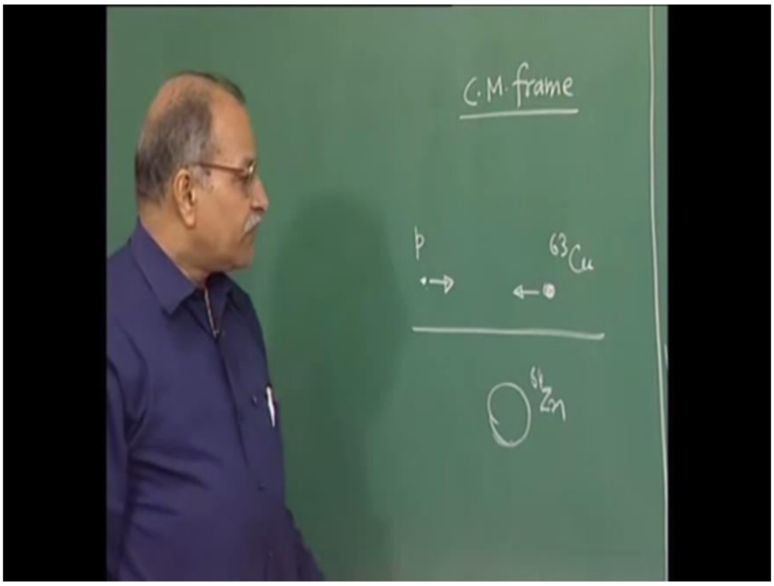



So, the two things left here at this region these two you can see there are two curves here, almost overlapping on each other this one here once again these two correspond to two different reactions but, with the same final product one is copper 63 and then proton and 2 neutrons coming out zinc 62 this is one, and the second one is this nickel alpha. So, 60 nickel and then alpha and 2 neutrons coming out and zinc 62, so for the same final products whether it is formed due to proton reaction on 63 c u or it is formed due to reaction of alpha particle on 60 nickel the cross section as a function of energy is the same.

So that means the final decay is independent of how that compound nucleus is formed. So that basic theories. So, keep this all these thing in mind I am going to the board and I will tell you why these 2 energy scales are two different energy scales are used in this comparison but, the basic assumption of this theory compound nuclear theory that the incident particle gets absorbed into the nucleus forming a compound nucleus in some excited state and then because of that statistical collision and sharing of energy by all the nucleons that intact memory of how it was formed is? Now gone now it is that compound nucleus in that particular excited state which has its own dynamics to emit the outgoing particle and make the product nucleus. So that the underline theory.

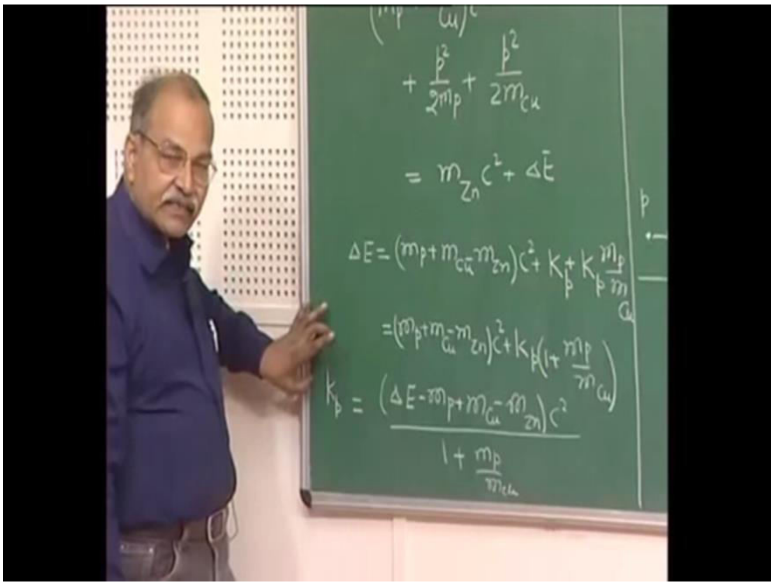
So, let me let me talk of that energy thing if we want to compare if we want to compare this say this reaction and this zinc 64 is formed through this reaction or to this reactions, if we want to quantitatively compare the cross section or the dependence of cross section on energy and so on. What you will need? You have to produce the 64 zinc in the same excited state then only you can compare the two cases. So, what is that energy needed of the incident particle to take it to that particular excited state. So that will be different for proton and alpha and that why the two different scales are used.

(Refer Slide Time: 18:52)




Let me talk in terms of the in center of mass frame easy to do. So, in center of mass frame suppose when you have a proton here and this 63 copper here now in the center of mass frame the total momentum should be 0. So, if it is the going in this direction this will be going in this direction and the magnitude of the momentum will be same. So that total momentum is 0. So that is before the event and once the proton gets absorbed into this copper nucleus making 64 zinc then the whole particle should remain at rest in the center of mass frame alright because the total moment is 0. So, the total momentum must be 0 and since this one single particle. So, it is it has to be at rest.

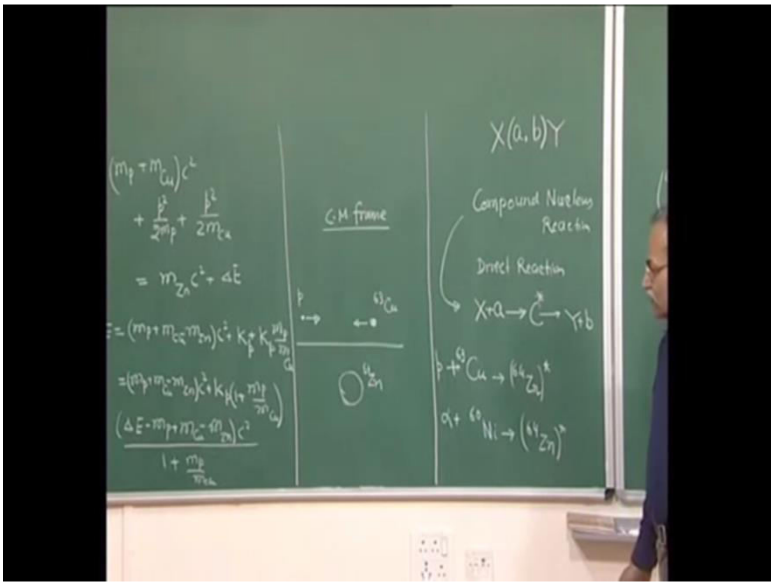
(Refer Slide Time: 20:01)



So, if I look at the energy considerations what I have is before the event it is mass of proton and plus mass of this 63 copper time c square plus kinetic energy of the proton which will be p square by 2 m p this is kinetic energy of the proton p is magnitude of the linear momentum of each of the two particles because they have to be equal and then the kinetic energy of this which will be p square by 2 mass of c u I am writing the same p because in center of mass frame the magnitude of momentum here and magnitude of momentum here should be same. So that the initial kinetic energy before the event and after the event the energy, total energy is mass of this zinc 64. Let us take ground state c square and plus the energy which is taking it is to some excited state alright.

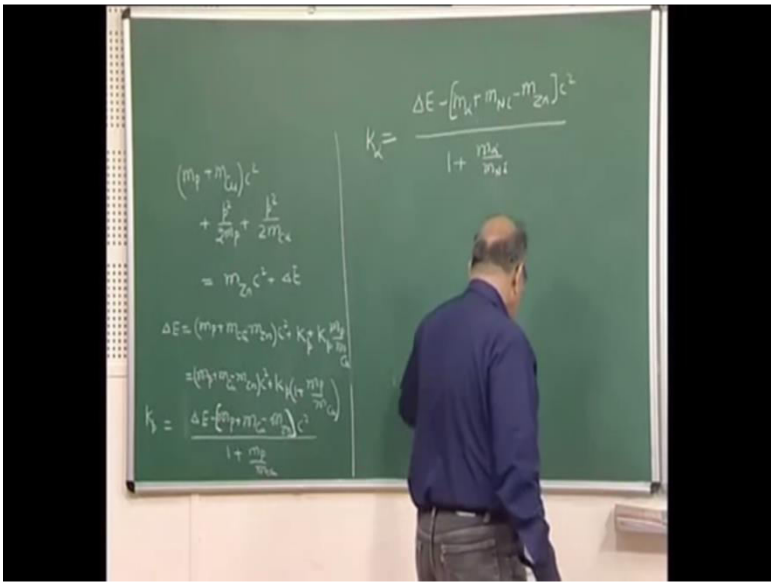
So, this delta E is equal to mass of p proton plus mass of copper and then minus mass of zinc this into c square and plus this p square by 2 m p which is kinetic energy of the proton and plus p square by 2 m c u which you can write kinetic energy of proton again and then mass of proton over mass of copper alright you can write this as p square by 2 m p here E and then m p by m c u. So that m p by m c u is here and p square by 2 m p is kinetic energy of the proton. So, it is m p plus m c u and minus m zinc. So, k p you can write from here and k p will be delta E and minus m p plus m c u minus m zinc c square divided by 1 plus m p m c. So, for a particular excitation energy delta E you need this much of proton energy.

(Refer Slide Time: 23:03)




And similarly, if you work out the same thing or alpha plus 60 nickel and taking 64 zinc to the same excited state. How much alpha particle energy is needed? So, is the identical analysis only the proton and a copper will be replaced by alpha and nickel and therefore, you can straightaway write the energy of alpha particles needed to take this zinc to the same excited state with the same excitation energy delta E.

(Refer Slide Time: 23:40)

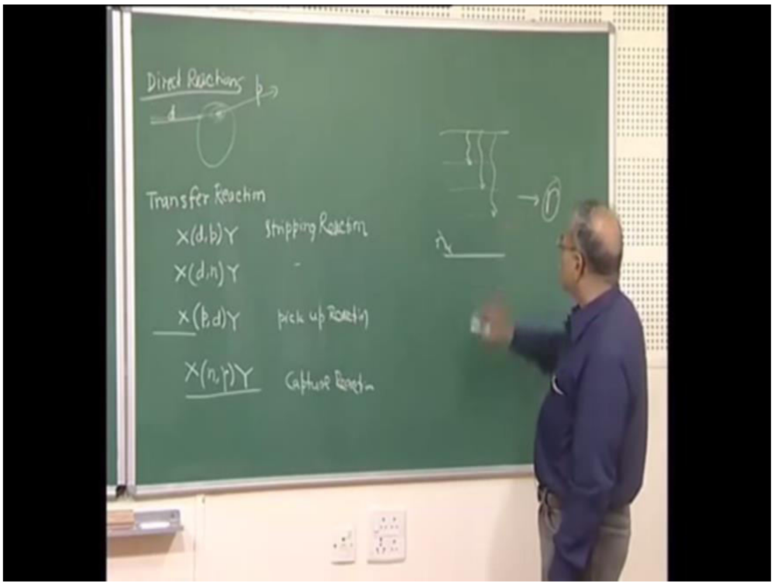


And that will be k alpha equal to the now it is k alpha how much alpha particle energy is needed to take this 64 zinc to the same excited state. So, this delta E is same. So, this will be delta E minus mass of proton is now mass of alpha particle we will write. So, minus mass of alpha particles and then plus wait. So, this is m p this is what did I write it correctly let us check. So, this is m p plus m e minus this is equal to delta E and minus. So, wait let us let me do correction.

So, delta E and minus m p plus m u and minus zinc right alright it is like this now is dimensionally also constant. So, is delta E and then minus put a bracket here and this is m alpha plus m c u in place of that it will be mass of nickel 60 and then minus mass of zinc that will remain there is a minus mass of that zinc 64 times c square and then divided by 1 plus m p here it will m alpha and divided by m c u here it will be m nickel. So, these two are different expressions they are similar but, the numbers when you go to put the numbers mass of protons mass of copper mass of yeah mass of zinc of course. So, if you put the numbers here, and if you put mass of zinc of course.

So, if you put the numbers here mass of alpha particle mass of nickel. So, these two things will come out to be different. So, alpha particle energy needed to put the 64zinc into one excited state and proton energy needed to put the 64 zinc in the same excited state they are different that is why in that plot you have seen that two different scales are used one for alpha particle and one for proton. So that each point on that plot area corresponds to one particular excitation energy. So that is how the compound nucleus reaction goes. Direct reactions can be different types in direct reaction this incident particle interacts with small number of surface nucleons and. So, it comes here and then make the interaction here and then something goes here.

(Refer Slide Time: 26:36)

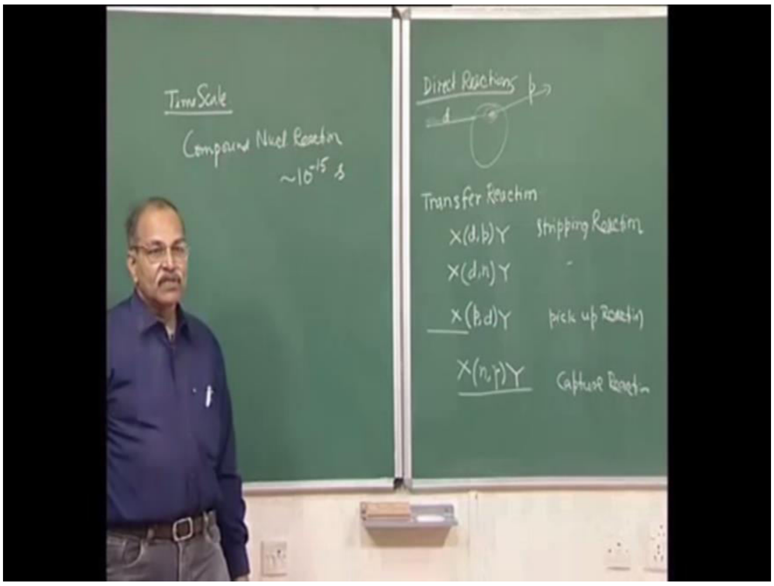



Now one important variety is called transfer reaction is type of direct reactions in transfer reaction there is a transfer of a nucleon or more from the incident particle to the product two this target nucleus or vice versa for example, you can have what you called d p reaction d p Y. So, a deuteron falls on the nucleus X deuteron is a neutron and a proton, and then it transfers neutron to this target X making it Y, and the proton goes out. So that deuteron is coming in and a proton goes out. So, neutron is absorbed here.

So, a transfer of neutron from this d to this p sometimes it is called stripping reaction. You can also have d n this type also you can have that is also stripping reaction reverse is also possible a particle coming in and then picking up something from the target. So, p d reaction this is also this is known as pick up reaction. So, here a neutron is transferred from the target nucleus to these incidents particles.

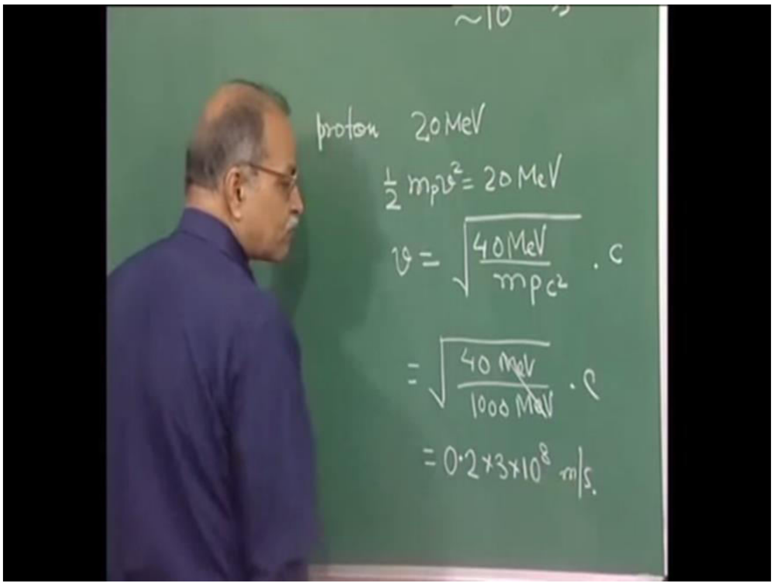
So, you have this p d reaction similarly, you can have many more transfer reactions alright then you can also have capture reactions via a particle comes here and then it gets absorbed in this say gamma particle is emitted. So, in the same nucleus with n of course, one nucleon number more. So, this is capture reaction, so the particle. So, in this in this reaction a this neutron comes here get’s absorbed and then a it goes to some excited state and from there it can come down emitting some gamma rays, it can also emit something else it can also emit a neutron by itself or something else that is also possible but, what we call capture reaction if this gamma ray comes out the outgoing particle is gamma ray in that case that neutron is permanently absorbed into the that nucleus. So, there are verities of these direct reactions now the difference visible difference between a direct reaction and a compound nucleus reaction.

(Refer Slide Time: 30:13)



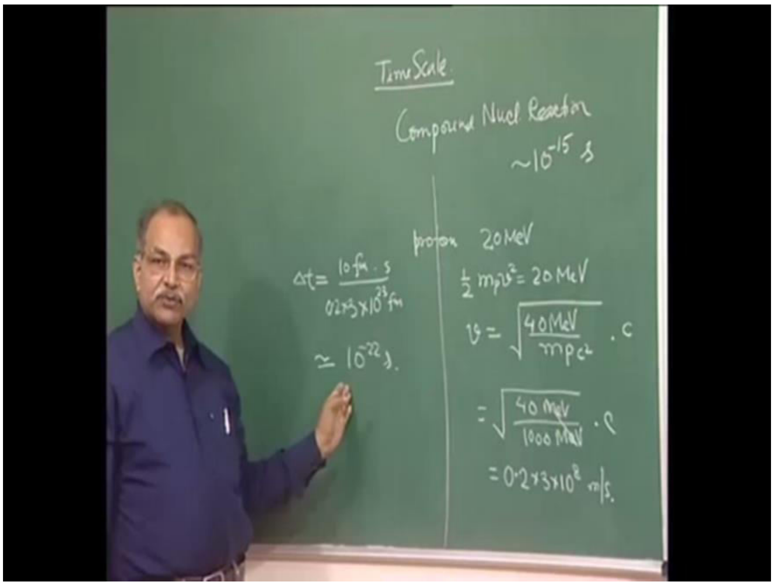

So that there are two differences, mainly one is times scale for compound nucleus reaction the time needed for that reaction to complete is much larger then what it will be for direct reaction why this is because energy has to be equilibrated among all the nucleons and this takes time are the energy deposited at some point in the nucleus and then through collision it is transferred to other nucleons and through many more collisions it is distributed in the whole of the nucleus and then a particle is comes out. So, and it takes time but, even that long time is very small as per as the laboratory is concerned the time scale is something like say ten to the minus fifteen minus 16 seconds and the time for a direct reaction that you can easily work out in the direct reaction the time available for reaction is almost the transit time for this particle to cross this nucleus. So that can be estimated if you know the kinetic energy of this particle and you know distance that is nuclear size nucleus size, that it has to traverse one can calculate this time let us do.

(Refer Slide Time: 31:59)



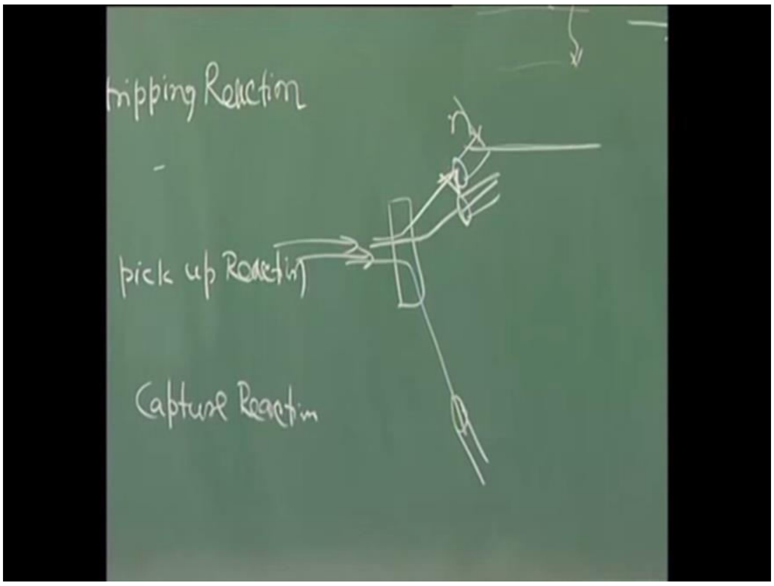

Suppose the particle is proton incident particle is proton and let say the energy is twenty M e V for direct reaction the energy has to be large. So, I am taking somewhat smaller energy here. So, I can calculate the speed of this twenty M e V proton if this is can be the rest mass energy is thousand M e V. So, let me do this non relativistic calculation and anyway we are doing order of magnitude calculations. So, half M e V square this is twenty M e V from here I am trying to estimate this velocity. So, the V will be equal to this is 40 M e V and divided by mass of p square root of that. So, multiply c square here and c here and for rough calculations m p c square put thousand M e V time c here. So, this is four-hundred. So, two-tenth like 0.2 c 8 meter per second, if I take the nucleus phi is to be less of 10 femtometers.

(Refer Slide Time: 33:35)




So, if the nuclear size 10 femtometer the time taken from by this particle to cross that nucleus will be 10 femtometer and then divided by 0.2 into 3 into 10 to the power 8 plus 15 is 23 femtometers and per second. So, this is going to be approximately 10 power minus 22 or. So, there is a huge difference in times scale if this is 10 power minus 15 seconds this is 10 power minus 22 seconds. So, that is one big difference but, a it is still difficult to distinguish between the these two modern equipment can do that but, is still difficult for a typical experimental set the other difference between these two direct reactions and compound nucleus reaction is the angular distribution of the outgoing particle means if you put the detector at different angles this is the target and the beam is coming like this and then you put the detector here.

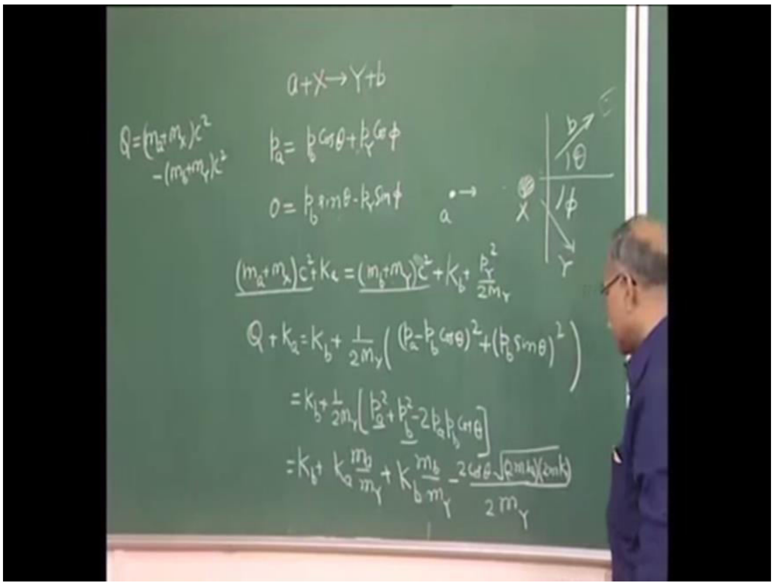
(Refer Slide Time: 34:49)




So, that you look the particles in this direction how many particles are coming here in this direction and you can put the detector at different theta you can put that detector at different theta. So, this is a angular distribution how the number of particles coming in the detector in a given time interval varies with theta. So, that angular distribution will be markedly different in the two cases in compound nucleus reaction if we talk in center of mass frame where the compound nucleus is formed with 0 momentum and then after this all equilibration the this compound nucleus decays I am giving you some outgoing particle. So, there is more likely that the distribution will be symmetric once this compound nucleus is form and it has lost all the memories of the previous direction of that particle coming in and hitting and all that.

So, from here it is now emitting the particles and giving that product nucleus. So, here it is more likely to be symmetric in directions whereas, if you have a direct reaction a it just comes nucleus is coming in the center of mass frame nucleus is coming this way it is coming this way and then some reaction is taking place. So, there that other direction is important and the distribution in different angles will be different and more likely it will it is a forward peaked. So, you will have a larger number of particles in that forward cone a forward directions low theta small theta and less particles of course, there many more things but, not less the angular distribution can be different and from there one can really detect whether it is coming from a compound nucleus reactions are it is coming through a direct reactions one more I would like to talk about in fact two more things if time permits one is energy reconsiderations right.

(Refer Slide Time: 37:21)




So, if you have the reaction a plus X going to Y plus b if I talk in lap frame this is the particle which is going in this direction target is at rest. So that X is at rest this is lap frame and then the this particle a goes in some other direction or some particle b goes in this direction theta where I have put the detector some looking only those particles which are going in this direction and this nucleus will recoil in the some other direction here in at some angle phi. So, in this reaction if you look at the energies conservation of energies initial energy final energy and all those things, then you can write three questions because moment also has to be conserved.

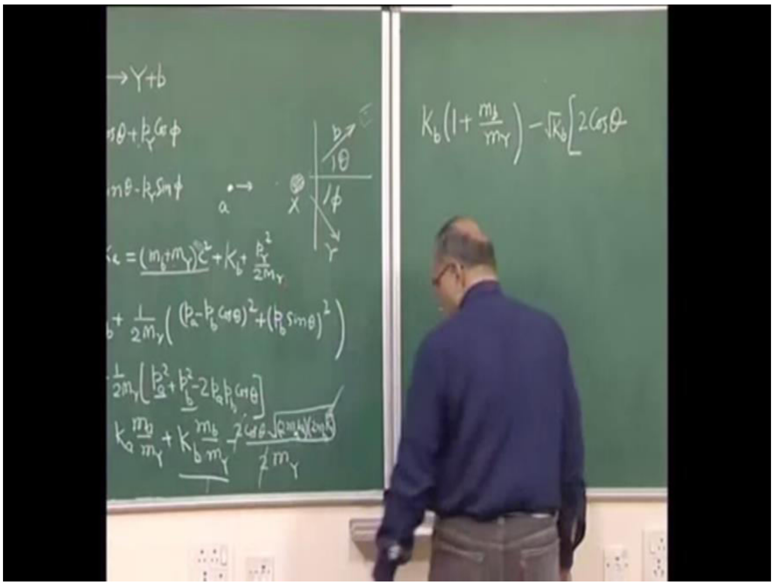
So, in x direction horizontal direction in this diagram your equation will be a equal to the p b cos theta and plus p Y this is the Y particle coming this is not coming out this b particle is coming out this Y particle is still in the target where it will stop in the target normally the target is of some solid material. So, more collision and thermal distribution of those things as per as this nuclear femto meters event is concerned it is requiring in this direction we do not observe this it is remains in that target itself, but it will be p Y and then cos phi whereas, for the perpendicular direction transverse direction the initial momentum is 0 and therefore, that should be equal to the p b sine theta and minus p Y cos phi this has to be taken into account if I am looking for the energy conservations these momenta are to be conserved because they will also be contributing towards kinetic energy now energy is initially you have mass of a plus mass of X time c square plus the rest mass energy and plus kinetic energy of a and that should b equal to finally, you have mass of b and mass of Y c square and plus kinetic energy of the particle b and kinetic energy of this particle Y which we write p Y square by 2 m Y actually initial rest mass energy plus initial kinetic energy the target nucleus is at rest in the target material and then after the events this b particle is going out is going into the detector. So that mass then this Y product nucleus.

So, this the rest mass energy and the kinetic energy of particle b and kinetic energy of the recoiling product nucleus I have written it in this form because this k b we can measure in the detector and k a we have accelerated the particle a. So that k a is also but, the product nucleus momentum product nucleus kinetic energy those things are not known phi is not known inside the target that has gone into some directions. So that we do not know. So, from here we should eliminate this p Y and this cos phi sine phi alright wait this is sine phi here.

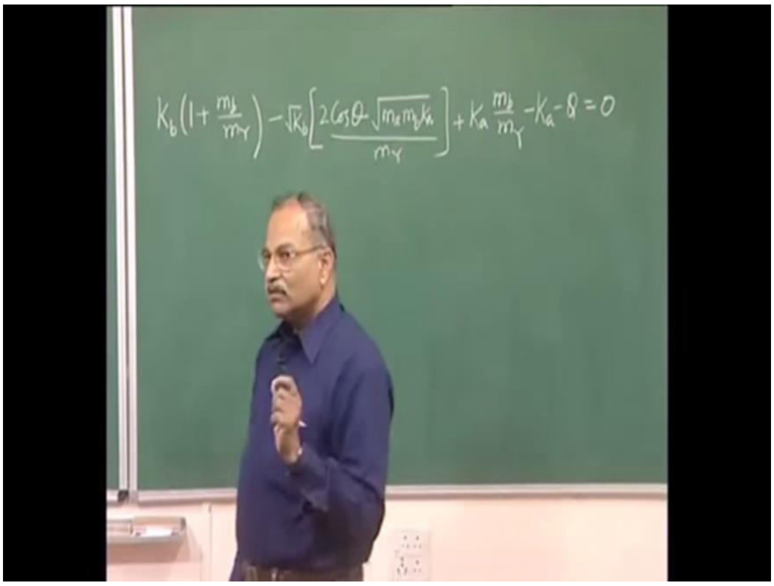
So, you have to eliminate that cos phi sine phi then eliminate phi as well as thus p Y these are unknown quantities then you will get the relation between the energy the kinetic energies and the rest mass energy. So, I can take this to left hand side and right that as q. So, Q is as usual m a plus m X c square and minus m b plus m Y c square. So, Q value we had been talking for quite some time the initial rest mass energy minus final rest must energy that we write as q. So, if I take it to this side and this minus this is Q plus k a k a is equal to k b and plus one over 2 m Y p Y square now p Y square you can write from here p Y cos phi square plus p Y sine phi square. So, from there you can write that p Y square and it is p a minus p b cos theta square.

So that is that is p Y cos phi by square and plus p Y sine phi square which is plus p b sine theta square. So that is p Y square and then 2 m Y I have I have already written. So, this is k b plus one-second m Y and here it is p a square and plus p b square and minus the 2 p a p b cos theta k b one by alright. So, here let us do some arrangement p a square by 2 m Y p a square by 2 m Y you can write this as k a times m a by m y. So, this term I am writing p a square by 2 m Y p a square by 2 m a is the kinetic energy k a and then m a by m Y is this similarly, this p b square you can write p b square divided by 2 m Y this will be k b and then you will have mass of b divided by mass of this capital y. So, it is this and here it is minus and let me write this 2 m y. So that I do not forget and 2 minus 2 times p cos theta and p a p b which you can write as 2 m k a and 2 m k b square root of 2 into mass into kinetic energy is the linear momentum. So, p a p b is square root of 2 m k a 2 m k b cos theta I have written minus 2 I have written 2 m Y I have written now re correct. So, let are as let us write it as an equation in k b. So, let me first see the k b term is here and k b term is here. So, you have and k b term is here.

(Refer Slide Time: 45:36)

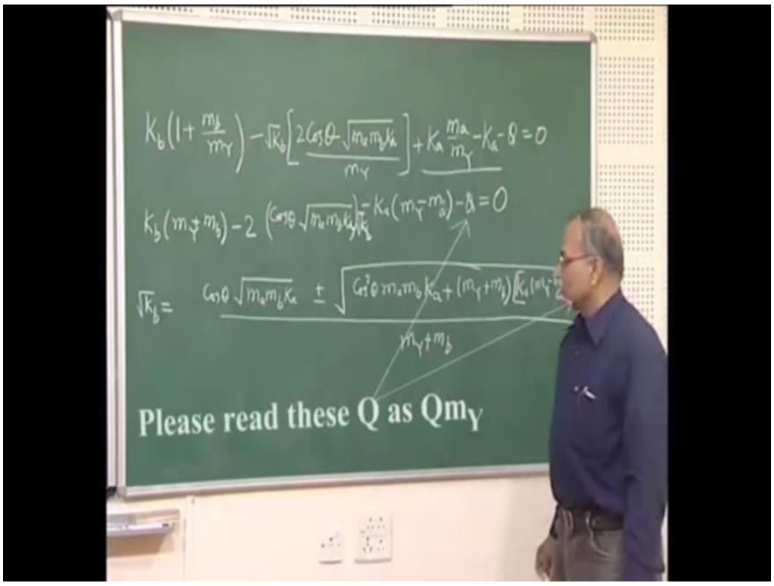



(Refer Slide Time: 46:24)



so you have k b and 1 this is k b and this k b I am writing and this k b I am writing. So, 1 plus m b divided by m Y then square root of k b what you have this 2 you can cancel and this 2 will come out. So, it is minus 2 cos theta. So, put minus here and then it is 2 cos theta and which m is this is m a and this is m b. So, square root of m a m b k a square root of m a m b and k a. So, I have written this 2 m a k a 2 m b all this things I have written and divided by m Y and then what is left. So, we have written this is. So, plus k a times this. So, plus k a times m b by m Y this is that this side and minus Q and minus k a k a and minus Q this is equal to 0 I have not written excitation energy. This nucleus which is formed here this Y nucleus this may be formed in excited state in thay case you have an extra delta E coming in on this right hand side. So, this fine energy when you write here there will be a plus delta E if it goes to the excited state if we you can added here itself or you can keeping in mind.

(Refer Slide Time: 47:39)



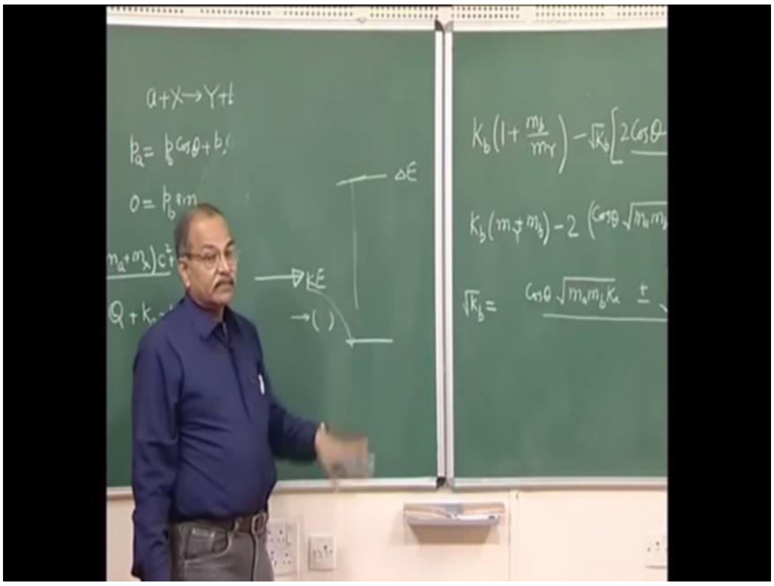

So this is an equation you can let us be simplify m Y plus m b. So, I am multiplying everywhere by this m Y minus 2 times and in this cos theta square root of m a m b and k a this m Y I will already multiplied then plus or minus write it as minus k a taken common from these two terms. So, minus k a taken common it will be 1 minus m b by m Y and I am multiplying by m y. So, it will be m Y minus m b here and then this minus Q is equal to 0 remember this Q can be positive are negative alright it is not alpha decay or beta decay that the final product must have smaller rest mass then the a initial constituents it is a reaction we are sending particle with some kinetic energy. So, Q can be positive or can be negative now this is where is root k b here is root k b this is the quadratic equation in root k b. So, this is root k b square here and this is root k b here and this is that constant term if I take it is an equation in square root of k b. So, from here you can write what this root k b is and what should be the value of k a for this reaction to go in.

So, root k b if you write this will be minus b that is cos theta square root of m a m b times k a plus or minus square root of b square minus four a c. So, it will cos square theta and m a m b and then k a and minus four a c. So, plus and this will be m Y and plus m v and then it will be here k a and then m Y and minus m b you should check all those calculations k a why this k a m b by m Y k a from where I am getting this term am getting this term from this one. So, it is m a with k a it should be m a with k a it should be m a.

So, all these things and then this whole thing divided by m Y plus m b alright plus Q check all the algebra now you should put constraints that this quantity has to be real. So, and then this quantity has to be positive this k b has to be positive. So, put all those constraints and then you can work out that for a particular given reaction and delta is 0 I have taken you can put if you wish to populate one particular excited state that delta E will come there with that Q also, from here you can find what is the minimum value of k a possible. So, if Q is positive then the reaction can go anyway.

So, there is no threshold energy but, if Q is negative then demanding that k b should come out to be real and positive term here you have a threshold energy before below which that reaction will not go and that threshold energy will depend on this cos theta term because that cos theta term is also their where is cos theta here it is cos theta. So that cos theta term is also there. So, depending on which theta you have put the detector there will be a threshold energy after that the reaction will start. So, all these energy consideration those are to be taken into account if you study this nuclear reactions just quick comment on something else and maybe will talk little bit more about that in the next class. And that is if you have from here you can also get what is the energy needed to just excite this final product into the delta E state.

(Refer Slide Time: 53:21)



So, if you have this final product here at this delta E state and then you are sending the particle with certain kinetic energy which allows a certain energy to be deposited here keeping all that momentum conservation into consideration. Then the reaction probability of this excitation that depends on the matching of this energy available and this energy here if the energy available is less this, it will not be excited fine, but in if the energy available is more than this it can be excited, but then the probability will depend on what is the difference in that we will talk about that in the next lecture.