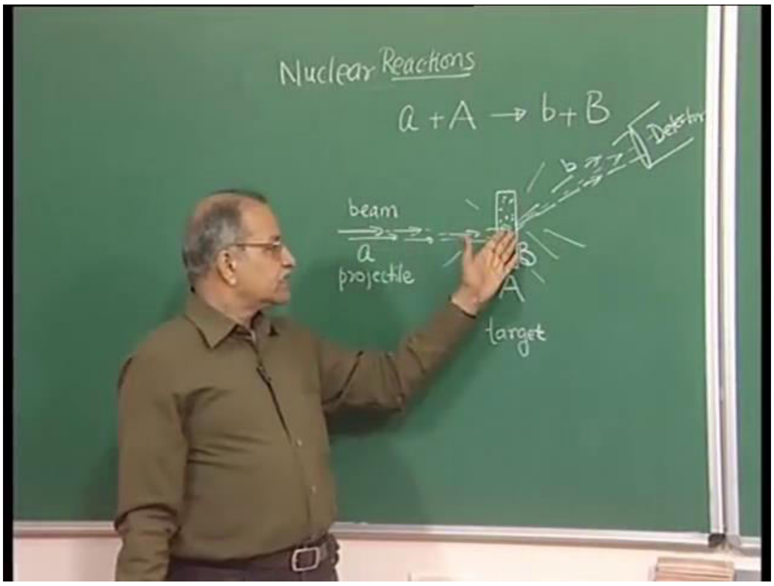
Nuclear Physics Fundamentals and Application
Prof. H. C. Verma
Department of Physics
Indian Institute of Technology, Kanpur

Lecture - 30
Nuclear Reactions

We discussed nuclear decays, alpha decay, beta decay and gamma decay. In these alpha and beta decays the nucleus changes, the parent nucleus is different than daughter nucleus. In alpha decay just two neutrons and two protons form an alpha particle and come out of the parent nucleus. In beta decay a proton is converted into neutron or a neutron is converted into proton, that is how the nucleus changes. In gamma decay nothing changes the nucleus remains the same is only d excites from an upper energy level to lower energy level, that we briefly talked about.

(Refer Slide Time: 01:13)



Now, the next topic or the next chapter is on what we call nuclear reactions. Reactions you are familiar from your chemistry terminology, in chemistry there are lots of reactions where you have some constituent molecules and then they interact and there are re distribution of atoms from one compound to other compound and so on. So, you get some product compounds, so some a plus b become c plus d or c plus d plus e and so on. So, the chemical changes take place the molecules change, but the elements remain the same it is only a redistribution of those ions or atoms and rearrangement that gives new compounds.

Similarly here nuclear reactions, in nuclear reactions we generally have redistribution of free or rearrangement of nucleons. So, protons and neutrons are same just like chemical reaction you can have generally you have two constituents to start with there is one nucleus and another nucleus is sent towards it, so that it can interact using nuclear interactions and from that some kind of a final product is formed maybe two particles or three particles and so on.

Typically your nuclear reaction will be something like a particle a and another particle capital A and going to some b plus capital B typically you can have more than two particles on this side, this side generally you have two particles. So, in a in an experiment or in a real situations this A is nucleus which is part of material generally heavy nucleus middle weight or heavyweight nucleus part of some material plate or some film or some solid block or something.

So, that is here and then so this is those A or these are the nuclei in this material normally known as target fixed in the lab in whatever experimental arrangement, these reactions are done in some kind of a chamber evacuated chamber. So, that they do not get scattered by those air molecules and so on; so a low-pressure chamber in. So, this material this target is clamped or is fixed they are in that chamber and that contain those nuclei of interest. So, if you want to bombard something on gold, you can have a cold plate here or a gold film here.

Similarly if you want to do something on magnesium, you can have a magnesium film here or a layer here and this is this small a, this is a another nucleus another nucleus it can be one nucleon or it can be a nucleus of more nucleons. So, you can have for example, protons coming and hitting the target. So, this small a is proton or neutrons coming and hitting the target, small a is neutron or deuteron coming and hitting the target or alpha particle coming and hitting the target or lithium three coming and hitting the target, so this small a is this.

You can also have heavy ions coming, so that is heavy ion reactions, so they are the physics is somewhat different. What we will be discussing briefly here in this topic in this chapter is low mass projectiles, so this a this are known as projectiles these particles are sent and they come and fall on this target. So, this is called projectile this a is called projectile in the terminology and this is a beam, so one after. So, these a particles are produced somewhere and then they are accelerated and they are given certain kinetic energy and then that beam of particle that falls on this target.

Then the nucleus a and nucleus capital A they interact here in this target volume and then there is a the varieties of possibilities of this reactions and so this a nucleus may get converted into a nucleus capital B and this particles a may get converted into a particular small b. And then this nucleus where some changes have taken place perhaps one neutron is added or one proton has gone out some. So, capital A becomes capital B, but it is inside the target material. So, it remains there normally it does not come out it can come out in several cases also, but normally what we study here.

So, this capital B will still remain inside the target material and this is small b, which is again a light particle close to small a perhaps one nucleon less or one nucleon more or maybe this small a itself without any change, that will come out of this material this side or this side in whatever side. And then this b which is this small b which is coming out, so it is coming out in all kinds of directions, but then in an experiment they have to be captured and they are captured by what we called detectors depending on what kind of particles you are detecting you have specific detectors.

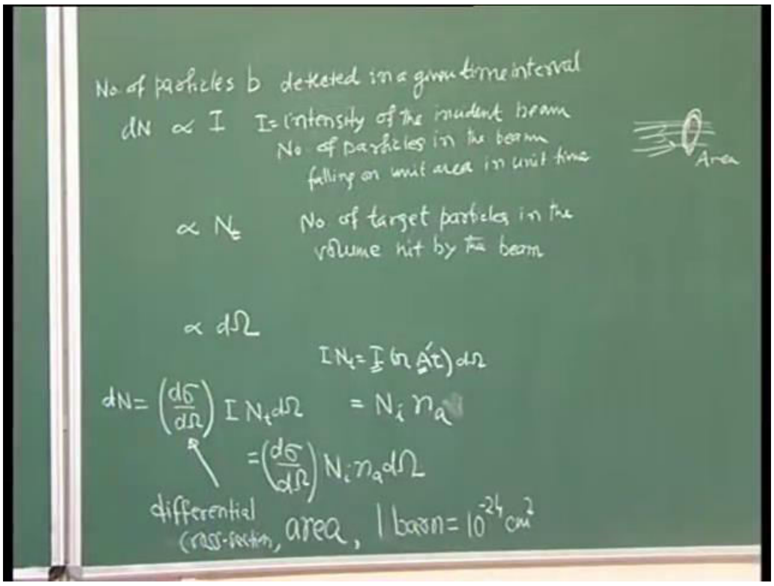
So, you have that detector the detector is placed at certain distance and the detector has some kind of window, which can capture all these particles which are going here. So, if you put the detector here then only the particles, which are going in this direction these are those b particles they are going in all directions, but depending on where you have placed the detector you will be detecting only those particles, which are able to enter this window of the detector. Now, the detector will measure, will count the particles that are coming in any given time interval.

So, how many particles have come that is one parameter and what is the energy of that particle kinetic energy of that particle whether it is coming with 100 kilo electron volts or 1 mega electron volt or 1.2 mega electron volt or 4 mega electron volt. So, it can count the detects that is one and then it can also detect the energy, so you have number of particles as a function of energy that you get from this detector, so this is the typical arrangement.

Now, the there are various types of reactions depending on what is this how this a changes to b or this capital A changes to capital B here, so those thing we will talk, but then there are a there is a very important parameter cross-section, which is the central keyword in making any study out of these reaction experiments. So, essentially it is related to the probability of that reaction and giving the final particle in a particular direction.

So, what is that cross-section if I look at this geometry and see how many particles we are detecting here per unit time whatever unit of time we select maybe the whole duration of the experiment. Suppose the experiment is done for 5 minutes, say for 5 minutes this beam is on and the particles are hitting this target and then these particles are getting detected here. So, in that 5 minutes how many particles I have detected here.

(Refer Slide Time: 11:00)



So, that number if I call it d N, that is number of particles, which particles, particles b detected, detected means in this detector in a given time interval, so that is this d N. Now, there are some obvious dependences, obvious dependences means if you have this incident beam, if this incident beam has larger intensity; that means, per unit time more number of particles are incident here then this d n the number b here or number of reactions taking place will be proportional to that beam intensity.

If you are sending less number of a particles per unit time naturally you will expect less number of b particles in this detector. If you are sending more number of particles per unit time then you will expect more number of b particles here in that same time interval. So, it has to be proportional to I what is I, I is intensity or flux of the incident beam and that is number of particles in the beam falling on unit area in unit time. So, this is the measurement of how strong the incident beam is, so if you have this beam here particles are coming, so take any cross-section and then if this is a the cross-section area here.

So, how many particles are hitting this area or going through this area or falling on this area per unit time and per unit area. So, number of particles falling here, per unit area per unit time that is known as the intensity of the beam or flux of the beam capital I. So, it has to be proportional to this, that is. Then secondly, it will be proportional to how many this capital A particles it is encountering, because reactions are taking place in this target material, where this small a particles are hitting.

So, if you have more number of target nuclei, because these atoms are distributed in this target material and each one of that at atom has that nucleus and there is a possibility of making an a reaction there. So, larger the number of target particles in that volume, larger will be the number of reactions taking place and therefore, larger will be the small b particles counted in the detector. So, this is also proportional to the number of target particles. So, let me write it N t this t is for target, so number of target particles were in the volume hit by the beam that is it.

So, all these dependence that I am writing they are obvious dependences nothing is said about the mechanism of reaction here, what kind of interaction is taking place, what kind of potentials are seen, what kind or how it is the how that small a is entering capital A or going in the vicinity of capital A and how it is converting to small b capital B. So, those things a part whatever it is it has to be proportional to these quantities, so that is why these are obvious dependences.

Then another obvious dependence is on this solid angle d omega normally the beams have a small cross-sections, the these beams that you take from your accelerator and then on the target you make it fall that has small area, say millimeter square nowadays we have focused beams. So, it can be very, very small it can be micrometers square and so on. But, typically less let us say millimeter square, so this width here or this radius here is around say millimeter or less and the detector is placed at say 10 centimeters; that means, 100 millimeters and so on.

So, this is quite small just like a point for this distance, so from here the particles are entering in this and the solid angle id d omega. So, it is the solid angle made by the detector window on the point or on the place on the target where the beam is hitting. So, although the beam is hitting in an extended area of say millimeter square or so but for this distance it is like a point. Suppose I put this detector still far away double the distance, so what will happen the meaning of these particles which are entering.

Now, they will miss the detector, solid angle is reduced and the number of particles detected will be reduced. So, as long as this d omega is small, this number detected in that time interval is proportional to d omega. So, these are say you can say geometrical dependences, irrespective of the nuclear interactions and when you write this d N as a product of I N t and d omega then you have some of proportionality constant. And that proportionality constant contains the information about the actual nuclear interaction taking place during the reaction.

So, you write this d N as that proportionally constant this I write d sigma by d omega that is the proportional constant. Then I than N t and then d omega and this quantity is known as the differential cross-section, I will talk about it further, but let us write this in a slightly different mode, this I is the intensity of number of particles. So, it is number of particles coming per unit area, per unit time N t is the number of this target material target nuclei.

So, N t this is equal to I into N t you can write as say density of this target atoms per unit volume and multiplied by volume and volume is area A do not confuse with that capital A nucleus area a and into thickness t, there are two many simple problems this capital A is the area of the beam area of cross-section of the beam. So, on the target it is hitting this area. So, let me write a prime A I have already written for that nucleus. So, A prime is this beam area, beam cross-sectional area this is A prime.

So, on the target also it is hitting that area A prime and this t that I have written here this t is the thickness is the normally small, thickness does not mean that 1 centimeter normally small. So, that the beam can penetrate up to that point, so that is the volume. So, A prime into t is the volume of this target material where the beam is interacting with those target nuclei and small n, this small n here this is the number density number of target nuclei per unit volume in the target.

So, this A prime into t is the volume and this is number per unit volume, so that is the number of target atoms here. Now, if you combine this A I and this A prime, what is that I and A prime, I is the number of particles per unit area per unit time and then this A prime is the area. So, this becomes the number of incident particles per unit time this I and A prime. So, this all this is per unit time, so this you can write as number of incident particle.

So, this is now number of incident particles falling on the target per unit area and this is N into t and N into t the number density number per unit volume and multiplied by thickness that is that becomes areal density, areal means area wise it is per number of particles per unit volume and multiply it by thickness. So, if I just look at this area and then how many particles are here in this volume divide by this area.

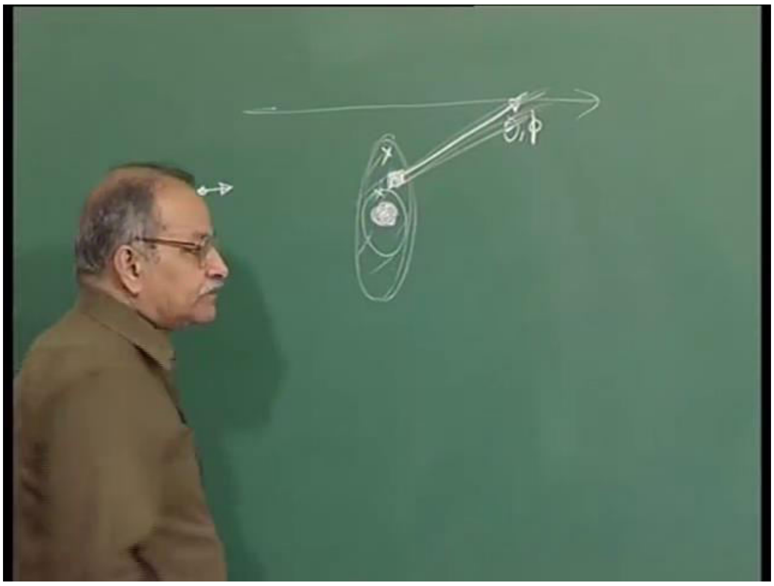
So, number of particles divided by this area that is areal density, area density, density not with respect to volume, but with respect to area per unit area on the target surface and then you make this whole target here, this volume how many total number of target particles are here, that is this areal density that will be N into t and that is written as small n a, so this is small n a and then. So, this is d sigma d omega and then you have I into N t is N i into n a and d omega.

So, you can write it in terms of number of target particles or you can write it in terms of number of incident projectile particles falling per unit time. So, both ways it can be, look at the dimensions the number of particles being detected d N per unit time. So, it is a number and here what it is this is or take this one for example, this is N i number of incident particles per unit time. So, that is number d omega is dimensionless solid angle. So, it is n a and d sigma d omega that is again dimensionless and what in this n a, this n a is the area density number of particles in that that volume of interactions divided by area.

So, this is 1 by area, this n a is one by area or you can take it from here also it is 1 by area it is the incident I is the number of particles going point unit area per unit time. So, this is 1 by area and since this left hand side is dimension less this has to have a dimensions of area. So, this proportionality constant which is related to the mechanism of that nuclear reaction is having the units of area. So, that is why it is called cross section, so this is in terms of area it is meter square and typically the cross sections will be much smaller than meter square.

And therefore, another unit is widely used barn, 1 barn 10 to the power minus 24 centimeter square, so that is the unit of area typically used for these cross sections. So, all this reaction probabilities depending on the mechanism apart from the geometrical factor will be in terms of this cross section, in terms of areas, what is the significance of this area, the significance of this area we can talk qualitatively.

(Refer Slide Time: 25:48)



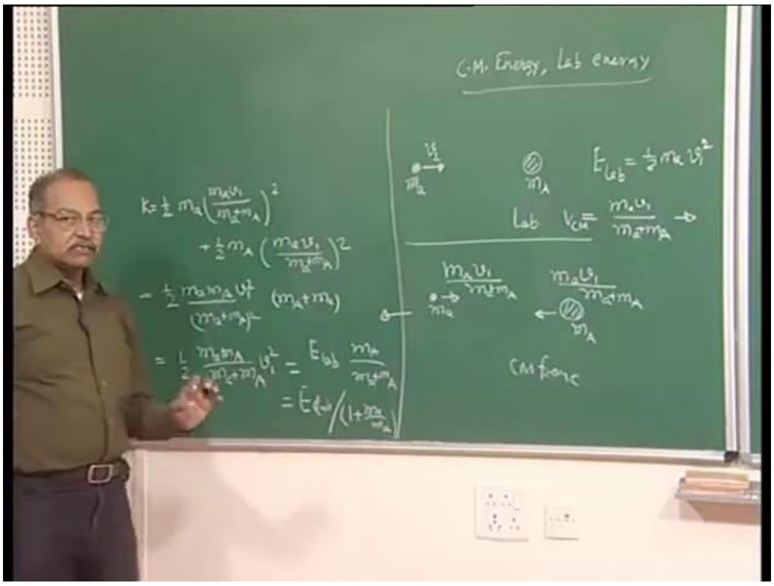
Suppose you have a target nucleus here and then the projectile nucleus is coming, let me make it slightly bigger, so that is look like target nucleus and this is the projectile nucleus with this coming. So, that joule of interaction if it is too far away from this nucleus, then the nuclear interactions will not take place. So, as it moves towards this target this distance is decreasing, but then there will be a minimum distance and then again the distance will increase.

So, there will be a joule of influence you can say on joule of interaction you can say, that if it falls in this particular area; that means, if it is closer than this, suppose the interactions can take place if the distance is this much or this much or this much or this much; and after that the probability of interaction is too small because the distances have gone up, so there is an area of interactions. So, if incident particle hits somewhere in this area in this joule then the reaction will take place.

So, it is this area, which is represented by the cross section a, but this is the total cross section in the sense, that in this area if the particle is hitting close to the nucleus it can go in some other direction. If it is hitting away from the nucleus it can go in some other direction, if it is just outside this it will just go straight. So, different distances in this area correspond to different directions in which that reaction particle will finally, be emitted. And similarly at the same distance it can be here or here or here or here or here or here.

So, accordingly it can go in one direction or it can go in other direction with the same theta, but different pi. So, each small part here correspond to a particular direction defined by theta phi each small part here corresponds to a small direction theta phi, if this incident particle hits here it will go in theta phi direction. A qualitative discussion this to give a geometrical physical visualization what cross sectional area can be related, but not very quantitative and not very realistic explanations at such. So, it is this area this particular area, which says that if you hit this area, then it will go in this direction of this area is that cross sectional area, so that is one thing.

(Refer Slide Time: 29:00)



Another thing is which is important in these discussion is that, center of mass energy or; that means, energy in the center of mass frame and the lab energy what is this many of the theories that are needed to understand these nuclear reactions and those equations and related formula they are easy to derive easy to work in the center of mass frame center of mass of what of the incident particle and the target particle. So, in this center of mass frame, where the incident particle is also moving and the target particles is also moving in opposite direction, because in the center of mass frame the total linear momentum has to be 0; and therefore, the two particles must move in opposite directions.

So, in that frame although in the laboratory the target is fixed and the incident particle only is moving, but then in the center of mass frame if I move then this target is also moving the incident particle is also moving and with some speeds and there is some energy kinetic energy involves. So, that is known center of mass frame energy or energy in the center of mass frame. So, in an experiment we control the kinetic energy of this incident particle, so that is the lab energy in the laboratory where the target is fixed and we are sending those projectile particles of...

So, what kind of acceleration we have given, what kind of kinetic energy we have given that is the control parameter, so that we know, so that is the energy of the lab. So, when we do the experiments and collect the data we use lab frame the parameters used in lab frame, similar to the theta the direction in which that reaction particle is coming that is measured in the lab frame, but then the analysis, the theories the equations, which is which is developed these are developed in center of mass frame.

So, energy in that center of mass frame or deflections in the center of mass frame those are important and these two are to be related. So, lab parameters are to be converted into that center of mass frame parameters and then compared with theory. So, if I compare this energy, so suppose in the lab frame I have this target which has some mass m A in the and then we have this projectile with mass of small a and this is going with certain momentum or certain velocity say v 1 and this is text velocity 0, so that is the lab frame situation.

If this same and therefore, the energy in lab frame is m A and v 1 square talking non relativistically, even if you have a proton has the incident particle the rest mass energy is some 938 mega electron volts and most of the typical reaction that we have in mind are say few M E V's. So, non relativistic expressions are, a o that is the energy in the lab frame. And in the center of mass frame what will happen the center of mass velocity, velocity of the center of mass frame had seen in the lab will be m A into v 1 and divided by m A plus m capital A.

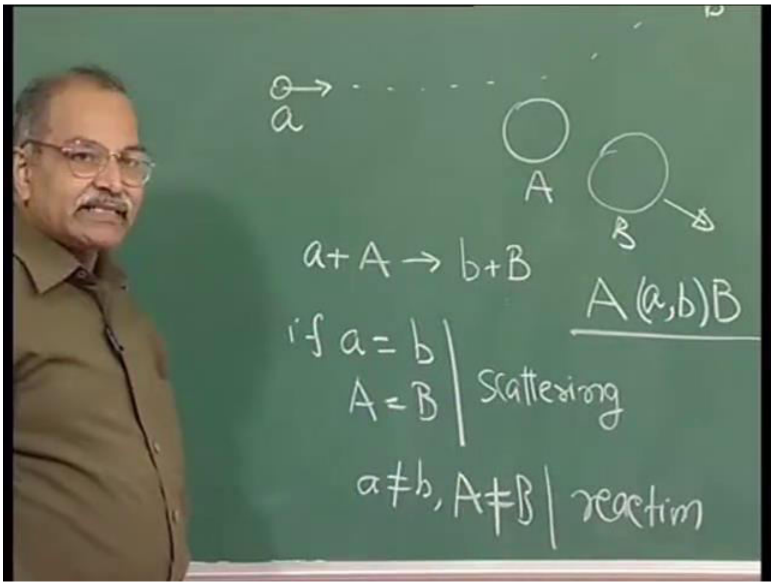
So, that the velocity of this center of mass in the forward direction, this is towards right in this figure action from the lab now if we go to center of mass frame, the center of mass itself is at rest in that frame. So, you have to subtract this from these lab velocity. So, in the center of mass frame velocity of this particle m a, which is in this direction is this v 1 and minus this v c n and if we work out this v 1 and minus this. So, this m a will cancel out and this velocity will be m capital A v one and divided by m a plus m capital A.

And this particle which was at rest in the lab, in the center of mass frame it will move with this speed in the opposite direction. So, in the center of mass frame this capital A particle this m a is moving in this direction and with velocity this is speed of m a times v 1 by m a plus m capital A. So, you can work out the kinetic energy now, the kinetic energy in the center of mass frame kinetic energy is half into m a into m capital A v 1 by m a plus m capital A square.

And then plus half m capital A and then speed is m small a v 1 by m a plus m capital A square of that and you can work out what it is, half you can take out m a into m capital A that you can take out and m a plus m a square you can take out. So, half you have taken out m a you have taken out 1 m capital A you have already taken out and therefore, one capital, 1 m a this will be there this v one square also you can take out, so it is this and from here similarly you have this m A.

So, one of these two factors will cancel out and you will have at reduced mass m a m capital A by m a plus m capital A and then given square and half m a v one square is the kinetic energy in the lab frame. So, this is kinetic energy in the lab frame half m a v. So, this is this into m capital A by m small a plus m capital and that is E lab divided by 1 plus m a by m a symbol relation. So, you can convert from the lab frame kinetic energy to the center of mass frame kinetic energy, when you have to compare the results. Similarly one can also work out what angle theta in lab corresponds to angle theta center of mass frame to compare with the theory. Now, let me talk about nature of reactions to some extent.

(Refer Slide Time: 37:04)



So, the target nucleus is A and then you have this for the time nucleus small a take it as charge particle the only uncharged nucleus is a neutron and neutron reaction we can talk separately. So, if the particle approaches this, you have Coulomb repulsion before that nuclear interaction can start in, so that Coulomb barrier will be there we had talked about Coulomb barrier during that alpha decay process. So, there it was alpha particle was coming out of the nucleus here this is small a is going towards the nucleus by the same kind of barrier that it will encounter.

So, if this is positively charged this is positively charged and the distances are large it is the coulomb potential energy that will be the effectively that will be the potential energy. But, if this distance decreases, then the nuclear interaction will start coming in and the potential will be dominated by the nuclear interaction nuclear. So, if you plot this potential as a function of separation between the two particles is the same if this r is large it has to be a coulomb interaction.

So, q one q two by four phi epsilon not r and then if this r is small ones is it gets into the nuclear is m you have some kind of nuclear potential. So now, we are coming from the large r side to low r side. So, initially if the total energy somewhere here the initially r is very large and therefore, it is be as it is approaching if it has to interact with the nucleus through nucleon interactions, nuclear forces then it has to go through this potential barrier and then only it can tunnel through, it has to tunnel through this barrier.

So, for very small energies on this projectile particle it is not able to tunnel through and then it just gets scattered elastically, this is small a just gets scattered elastically. And in fact, it is not nuclear reaction as such in these cases it is the coulomb interaction you do not have nuclear interaction between these two if the energies are, so small that it is not able to penetrate. This another force alpha particle experiment from metal foils it is a is that kind, so that is elastic columbic scattering, but if the energies are increased this will be the case when you have energies say few mega electron volts, so this will be the case.

But now, when you increase the energy and it is able to penetrate into that nuclear region then you have this nuclear reactions. So, in that case also you can have scattering even when your energies are such that it is going through that nuclear interactions then also it depends it can be just scattered here or it can do some reconfiguration of these nucleons. So, if it just go through this, so that go final particle is also the same this is B here and this nucleus which is recoiling is B here.

So, generally we write this nuclear reaction as a plus A is going to b plus B by the way the there is a symbol for this reaction and the symbol is the initial nucleus here, than parenthesis then this particle a and then this comma and this particle b and this capital B. So, this is a short form of writing this equation, so you call it a b reaction like p d reaction; that means, proponent neutron reaction, so proton is coming and neutron is the final outgoing particle, so this is a short form of writing this.

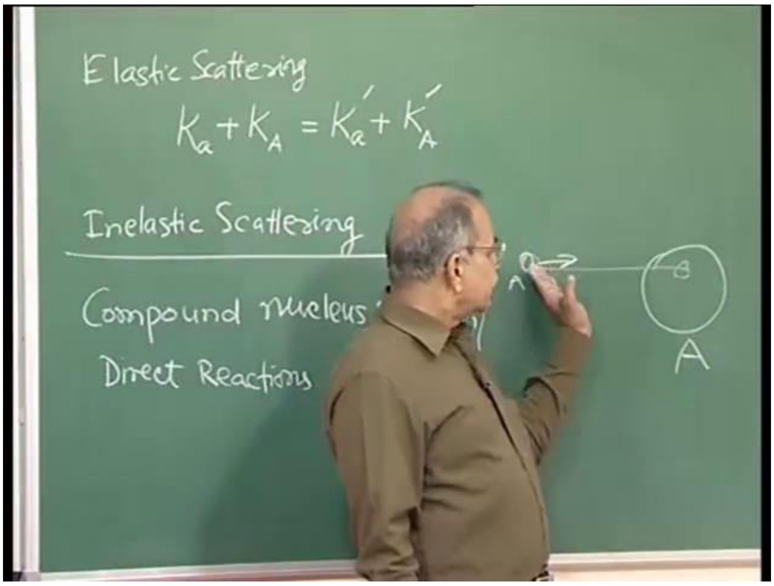
You can have more than one particle emitted here, so you can have say one neutron and one proton coming out and this capital B is there then you will write a comma n p, so this is the short form of this. So, if a it is same as b and then the capital A will be same as capital B this is known as scattering; that means, nuclear interaction is taking place now, we have a sufficient energy.

So, that is going close to the nucleus and nuclear interaction is taking place, but a scattering is in the because this is scattering because of the nuclear interaction, because there is change in the direction change in the speed that also is because of some kind of force there and that force is coming from the nuclear forces, so that is nuclear scattering. But, then is this the same is a no reconfiguration of nucleons in this system, then you have the same particle coming here and same nucleus going in some other direction in the target material, so that is known as scattering.

And they are really different a and b are really different and this capital A capital B are really different, so some nucleons have gone from this particle to that particle and so on; then you generally call it nuclear reaction. Although this whole thing can also be termed as nuclear reactions, but normally is a loss term, this a scattering perfect and if a is not equal to b and this capital is not equal to b this is nuclear reaction, but then this also nuclear reactions. So, nuclear reaction is a bigger word, but inside that bigger word, we still call this as a scattering and this has reaction.

Now, this scattering can also be of two types, one is where the this nuclear target nucleus capital A it has been given a speed, because of the interaction it has been given a velocity, but then it remains in it is nuclear ground state. So, in that case the kinetic energy of this incident particle and this target nucleus, initial kinetic energy will be same as the final kinetic energy, nuclei are not changing. So, the rest mass energy it is same and then the nucleus is in ground state initially as well as finally, then the kinetic energies will remain same and that is known as elastic scattering.

(Refer Slide Time: 44:39)



So, kinetic energy of this small a plus kinetic energy of this capital A before it is same as kinetic energy of a after the event and kinetic energy of capital A after the event. So, this is known as elastic scattering, where the kinetic energies are same, the nucleus remains in its ground state, so that is this. And the other possibility of scattering is in elastic scattering it is possible that this projectile particle gives of some of energy to this target nucleus, which takes to one of the excited states.

And that much energy gets absorbed inside internally and rest appears as kinetic energy, that is in elastic scattering. So, in elastic scattering what will happen if I take this diagram. So, initially the capital A nucleus is addressed and this small a is coming and then this small a is going this way and this capital a is going this way. So, the final kinetic energy will be smaller than the initial kinetic energy and that part of it will go into the excitation is going from ground state to some higher energy state.

And then you have reactions the these reactions where the particles are really changing a is not same as b and capital A is not same as capital B. So, then also energy of this incident particular plays a big role to decide what kind of interaction, what kind of reaction will take place. Typically we have two categories of nuclear reactions and these two categories are one is called compound nucleus reactions and other is called direct reaction.

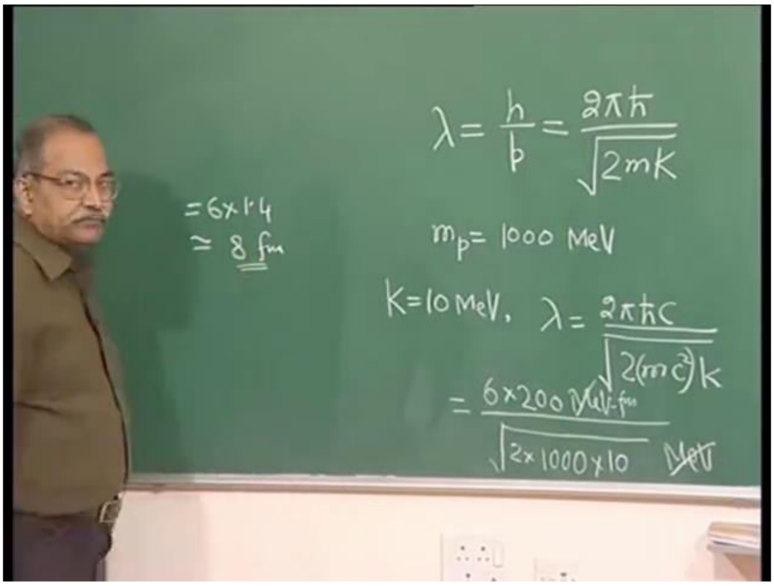
So, what is the difference here you have this capital A and then this small a is coming, now depending energy of this small a, it can interact with few nucleon and the surface of this capital A or it can react with all the nucleons of this. So, initially it will react with few nucleons here and then the energy is transferred through that and then depending on case in some cases that energy can be distributed redistributed in other nucleons.

And if sufficient time is available then this becomes part of this bigger nucleus, we say that a compound nucleus has formed, this nucleus small nucleus here gets here. So, one possibility is that just it interacts one or two nucleons here and goes away a quick reaction fast reaction that is what we called direct reaction. And the other possibility is that it interacts with not only with this one nucleon or two nucleon, but with all these nucleons this energy it shared by this whole nucleus.

And then some kind of bigger nucleus is formed although it is not stable, but some kind of that is formed for sometimes 10 to the power minus 15 seconds or 10 to the power minus 16 seconds and then after that it emitters another particles small b and the remaining is capital B, so that is known as compound nucleus reactions. So, how do we distinguish between these two in terms of energy at what energy is compound nucleus reaction is more probable at what energy is direct reactions are more probably you can make a small calculation of de Broglie wavelength.

So, if the energies are much that de Broglie wavelength of this incident particle is comparable to the size of the full target nucleus. Then it is more likely to go through compound nucleus reaction, because now it is kind of interacting with, so many nucleons at a time. Whereas, if the de Broglie wavelength of the incident particle is small of the order of size of one nucleon, it is only reacting with or only interacting with that one nucleus nucleon and the direct reaction will be more probable. So, let us work out what is the typical energy is involved.

(Refer Slide Time: 50:32)



So, now de Broglie wavelength is h by p that is 2 phi h cross by square root of 2 m kinetic energy again we are taking non relativistic expressions, because any nucleus you take for small a it is going to be 1000 MeV to 2000 MeV or, so on. And the energies we are talking of n MeV's or few tens of MeV like that, so that is de Broglie wavelength. Now, let us estimate, let us a proton incident particle is proton, so it is 938 MeV. So, something like say 1000 MeV, let me take k equal to 10 MeV and see what happens.

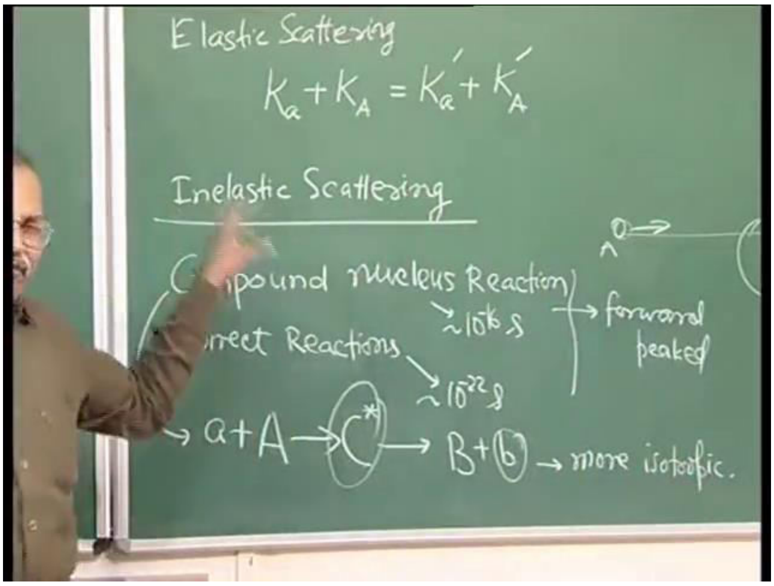
So, lambda will be equal to 2 phi h cross multiplied by c here and multiplied by c here. So, it is 2 m c square into k 2 phi h 6 h cross c is 200 MeV femtometers these are all approximate values and 2 times m c square it is a 1000 MeV m c square for proton is 938 MeV and kinetic energy let us a 10, so 10, so MeV square, so outside it is MeV, so that the whole thing is in femtometers. Now, how much is this, this is 100 here and root 2 here, so 100 will go with this root 2 will make it root through.

So, this will be equal to something like into root 2 it femtometers, so kind of size of medium weight nucleus. So, typically if the energy is around say 10 MeV 15 MeV like that then you will have this compound nucleus formation, but energies are, so big that the wavelength here is say 1 MeV 1, 1 femtometers or 2 femtometers like that if energy is increased if energy is increased double. So, it is ten MeV 40 MeV it will be femtometers.

So, if this energy it is such if I increase the energy then though in increase beyond say twenty 25 MeV's then you will have a chance that it interacts not with the whole nucleus, but with only few nucleons and in that case you will have direct reaction. So, one is time scale time scale, because direct reaction means it is interacting with hardly one or two nucleons in the nucleus.

So, it just interacts gives energy and does something it can pick up one nucleon from there or it can leave one nucleon there and then go. So, although it is a big nucleus, but it is essentially doing it is one interaction with small number and so the time scale are very fast these are nuclear time scales this type of direct reactions will be around say 10 to the power 22 seconds are so…

(Refer Slide Time: 54:12)



So, the direct reactions the time scale will be something like 10 to the power minus 22 seconds. Whereas, if the energy is low the energy of that incident particle is low the de Broglie wavelength is larger and it is interacting with all these nucleons it is sharing it is energy with all these nucleons. So, then the reactions will be slow and it will be a statistical quasi type of equilibrium that will be reached their and after that the reaction particle will be emitted by that compound nucleus.

So, that time scales are much larger. So, this is 10 to the power minus 15 or minus 16 seconds or So, one is this difference another difference is and it is all coming because of the incident particle energy another difference is in the angular distribution of this final reaction particle going in going out. So, if it is a direct reaction what will happen it will forward peak because is coming with a large energy and then making those interactions and then going there, so it will be something like forward peak distributions.

Whereas, if it is compound nucleus reaction then after this equilibrium is achieved after that compound nucleus is formed after this is small a it becomes part of this nucleus which we call compound nucleus, this capital A and small a make one nucleus. Then the dynamics of that compound nucleus that will emit or inject that small particle b it is a kind of evaporation process the energy has been deposited energy of this small a has been deposited into it distribution in the whole thing.

So, it is like a hot water, so lot of particles are evaporating; similarly from this compound nucleus you can evaporate one particle which will cool down the energy and take it to the more equilibrium stable state. So, the those reaction particles small b that are coming are coming from that statistically equilibrated nucleus and therefore, the angular distribution is more likely to be close to something like isotropic, it will not be peaked in one direction.

Whereas, indirect reaction it will be peaked in one direction, which is normally forward direction, but for compound nucleus reactions this compound nucleus reactions, where this a goes into this capital A and make this compound nucleus to C and that after this equilibrium is reached that goes into B plus b. So, this b is ejected from here. So, this will be say forward peaked and this will be more isotropic not exactly isotopic, but more isotopic of these are some of the characteristics, we will continue with this next lecture.