Types of nuclear reactions

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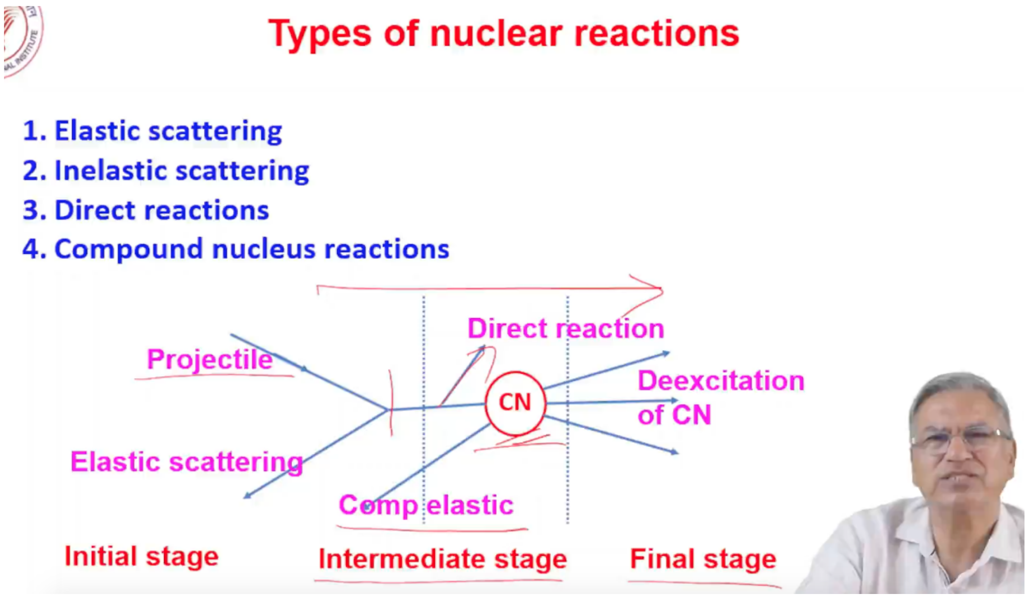
Lecture-13, module-1

Hello everyone. Welcome to this lecture. Last lecture we discussed the cross sections of nuclear reactions. We discussed the cross sections for neutron induced reactions and the charged particle induced reactions. In the case of neutron induced reactions, cross section decreases with increasing energy of the neutron. Then in the intermediate region there are resonances. Whereas in the case of charged particle induced reactions, cross section increases beyond a threshold value of Ecm equal to Vc and after that it goes rising. We also saw how to determine the cross sections experimentally by measurement of excitation functions or even by measurement of particle spectra and angular distribution.

Today we will discuss the mechanism of different types of reactions and mostly I will be focusing on the dominant mechanism that is the compound nucleus reaction. So just let us see in a nutshell what are the different types of reactions that occur when a projectile bombards a target.



Types of nuclear reactions

1. Elastic scattering
2. Inelastic scattering
3. Direct reactions
4. Compound nucleus reactions

So I have given a schematic here. This is actually in the time zone, as a function of time how it is happening. So the projectile is bombarding a target nucleus and many a times what will happen, in fact it is always there, a component of elastic scattering. Elastic scattering is nothing but a sort of a billiard ball collision between the two bodies, a projectile and a target. I will be discussing very shortly what are the things that are conserved, which are not conserved and so on.

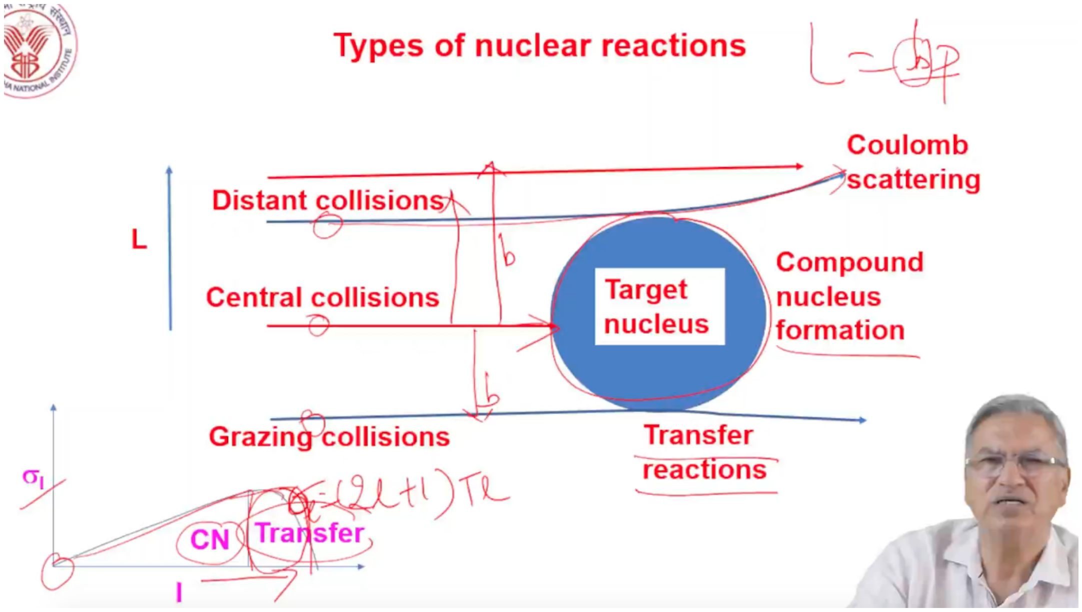
But this is actually not included in the nuclear reaction cross section. And this elastic scattering is always there whenever a reaction is there. So it can happen immediately, that is what is shown, initial stage that projectile just collides with the target and undergoes elastic scattering. In fact that Coulomb scattering or Rutherford force scattering is also common in the category of elastic scattering. Then we come to the intermediate zone where the projectile is now coming in close vicinity of the target nucleus.

And before that, in fact before it is completely fusing the target there is a type of reactions called direct reactions. That means the projectile comes close to target nucleus and there is a transfer of few nucleons from projectile to target or vice versa. So that happens at a much smaller timescale than the compound nuclear formation which we will discuss in length later. And many a times they can form a compound nucleus. The compound nucleus part we will discuss in detail in this lecture.

And the compound nucleus can again give rise to the projectile back. So this is what is called the compound elastic scattering. The projectile, it is like, you know, the projectile goes into the well of the nucleus and comes back with the same energy as it entered. So this is called the compound elastic scattering. There is a very small difference in the phenomena of elastic scattering and compound elastic scattering.

And then the last stage is the compound nucleus formation that takes place after a lot of time. Now the timescales in nuclear reactions will be elastic scattering and direct reaction 10^{-22} seconds. For the compound nucleus formation 10^{-17} seconds. So that is the kind of timescale that we are talking about. So when you say compound elastic scattering, it happens in the timescale of 10^{-17} seconds.

So the compound nucleus lifetime is the order of 10^{-17} seconds and in that lifetime, the projectile and target combine together on a mono-nucleus equilibrated in all degrees of freedom and then the subsequent de-excitation of the compound nucleus can take place by emission of particles, gamma rays and so on. So that is what is called the final state. So on the way the projectile can have different types of reactions with the target nucleus, namely elastic scattering, compound elastic scattering, direct reactions and the compound nucleus formation. These are the main types of reactions and the timescale is as you go from left to right, the timescale of the reaction is increasing. You can also explain the different mechanisms that take place when your projectile bombards the target.



Types of nuclear reactions

L = bp

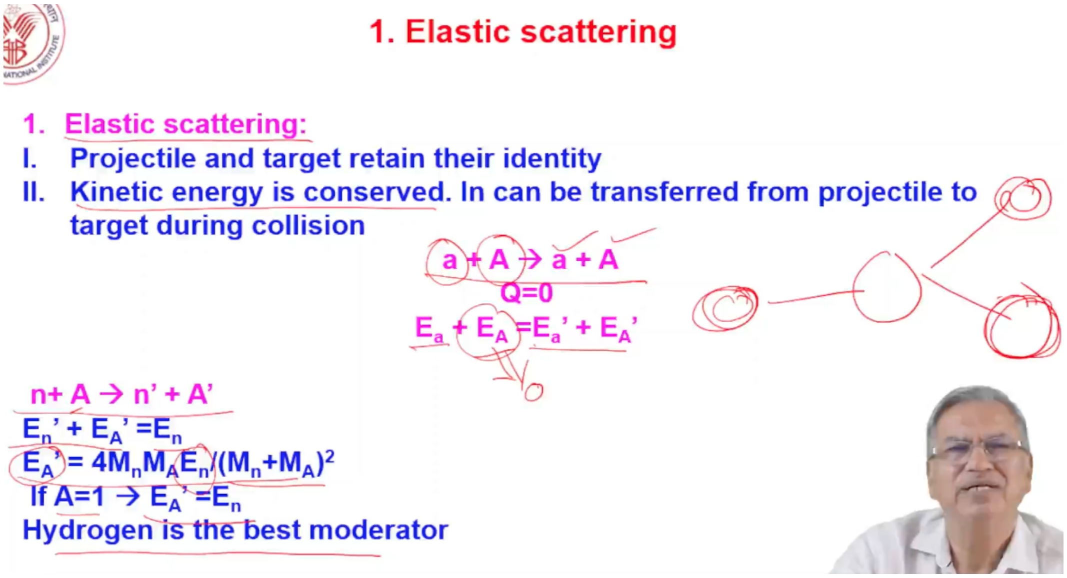
And in fact, this is in the context of a projectile which is rather heavy compared to a neutron, a proton and so on. So when we say this, what I have drawn in this schematic is the target nucleus and the projectile is coming at different distance from the center of the target. So if you recall the previous lecture, we defined the angular momentum involved in a nuclear reaction and so the angular momentum for the central collisions, that means the impact parameter is zero. So angular momentum if you recall is equal to b×p impact parameter into the linear momentum. So when the impact parameter is close to zero here, so this is what is the impact parameter.

So the central collisions mean impact parameter is close to zero, for them the angular momentum is zero, so it is here. What I have plotted also here, the angular momentum dependent cross section versus the angular momentum. And so it is nothing but the

σ_l= (2l +1) and you can have the transmission coefficient (Tl) also. So this triangle is actually like 2l+1.

So for the central collisions where the angular momentum is low, the projectile will be fusing with the target forming a compound nucleus formation, which is also called as the complete fusion. The projectile and target nuclei fuse together to form what is called as the compound nucleus. When you go to little bit away, so it is either we go this way or this way, it is symmetric. So this is an impact parameter where they are just grazing. When we say grazing collisions means they just touch and go. So during the touching process, there could be a transfer of nucleons from projectile to target or target to projectile. The grazing collisions lead to transfer reactions. So where they just come and touch each other and during the time scale, there could be some transfer from one to other. So they are at the higher impact parameter.

And then there are distant collisions which are beyond the physical boundary of the target. So the distant collisions are like coulomb scattering. They come in the coulomb potential, the vicinity of each other's coulomb potential and escape. So that is like Rutherford scattering. As we go away from the target center, the angular momentum is increasing and so the different reactions are taking place that I have tried to explain. And so the different cross-sections for different processes, compound nucleus, transfer reaction, the coulomb scattering will not come in the category of nuclear reactions. Of course, they do not come in the vicinity of the nuclear potential of each other. The nuclear reactions take place when they experience the nuclear potential of each other. And so they only come in the coulomb potential of each other. So we say they are not nuclear reactions. So cross-section σ_l vs l will take care of only the nuclear reactions like compound nucleus, direct transfer and so on.



1. Elastic scattering

1. Elastic scattering:
   - I. Projectile and target retain their identity
   - II. Kinetic energy is conserved. In can be transferred from projectile to target during collision

$$a + A \rightarrow a + A$$

$$Q=0$$

$$E_a + E_A = E_a' + E_A'$$

$$n + A \rightarrow n' + A'$$

$$E_n' + E_A' = E_n$$

$$E_A' = 4M_nM_AE_n/(M_n+M_A)^2$$

If A=1 → $E_A' = E_n$

Hydrogen is the best moderator

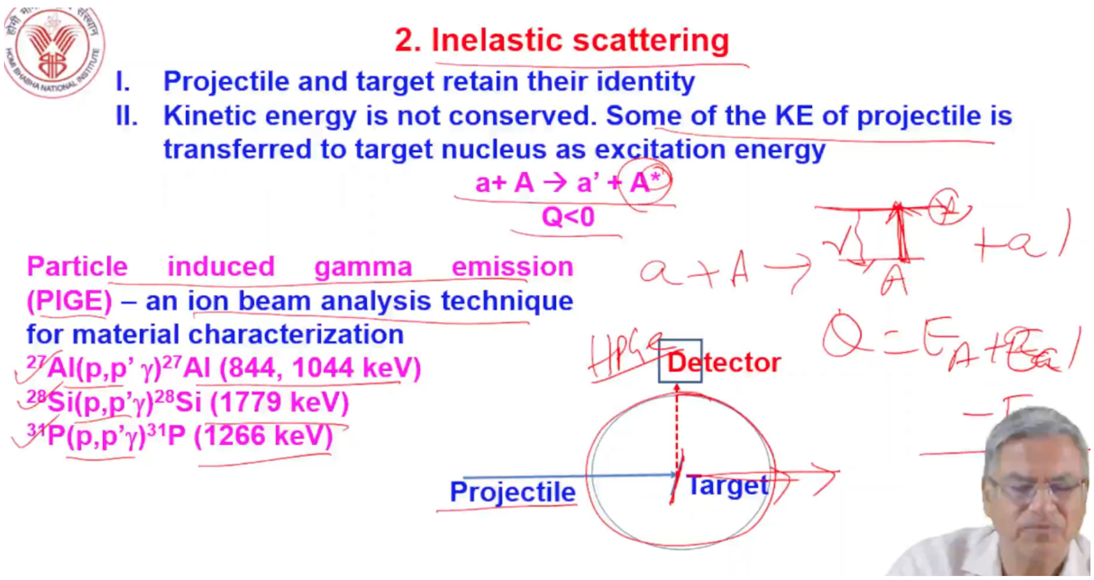
Okay, let us now see these reactions in more details. The first type of reaction though we will not call it as a reaction cross-section does not include the elastic scattering. But it is good to know exactly what are the different types of processes that are happening. So in the elastic scattering, as I have mentioned already here, this is a projectile and this is the target. The projectile and target collide with each other and they go away from each other, they retain their identity. Secondly, the most important is that the kinetic energy is conserved. Kinetic energy is conserved means the projectile may have some energy E_a, for example, it could be zero. So it can transfer some kinetic energy to the target nucleus, this is zero. Normally when the target nucleus is stationary, then E_A is zero. Now the projectile can transfer some part of its energy to the target nucleus. Both of the projectile and target are now having some kinetic energy. When the projectile is colliding with target, then they can go in different directions. So some energy of projectile has been given to the target nucleus, but it remains as kinetic energy. So total kinetic energy of projectile and target after the scattering is same as that of the projectile. That's what we mean that the kinetic energy is conserved. So it is only transferred, it can be transferred from projectile to target during the collision. But it is not lost or it is not transformed to other type of energy like excitation energy and so. Important criteria in elastic scattering is that the kinetic energy is conserved.

So I have tried to give an example of neutrons when the neutrons are reducing their energy, they are moderated. So they collide with the target material with energy E_n and in the process, neutron will give some kinetic energy to the target nucleus. So the final energy of neutron and target nucleus is equal to initial energy of neutron. And if you recall the previous lectures, then the energy of the target nucleus, maximum energy that will be given to target nucleus is given as

$$E_A' = \frac{4M_n M_A E_n}{(M_n+M_A)^2}$$

And so, for example, when A =1, then $E_A = E_n$. That means if the mass of the neutron and mass of the target nucleus is same like hydrogen, proton, then it can give all energy in one collision. So proton, that is why we say hydrogen is the best moderator. In one collision, all energy of neutron can be given to hydrogen. So hydrogen, hydrogenous material will reduce the energy of neutron fastest. So that is the reason why we say hydrogen is the best moderator. Moderator means we are trying to reduce the energy of neutron from whatever energy neutron has to begin with and we are trying to thermalize.

So the number of collisions that are required to bring the neutron to thermal energy, that number is much less for hydrogen. If you have a higher mass number material, you will require more collisions. For hydrogen, even one collision is sufficient. So that is the way we explain the moderating power of a target material for neutrons.



2. Inelastic scattering

I. Projectile and target retain their identity

II. Kinetic energy is not conserved. Some of the KE of projectile is transferred to target nucleus as excitation energy

$a + A \rightarrow a' + A^*$

$Q<0$

Particle induced gamma emission (PIGE) – an ion beam analysis technique for material characterization

$^{27}Al(p,p'\gamma)^{27}Al$ (844, 1044 keV)

$^{28}Si(p,p'\gamma)^{28}Si$ (1779 keV)

$^{31}P(p,p'\gamma)^{31}P$ (1266 keV)

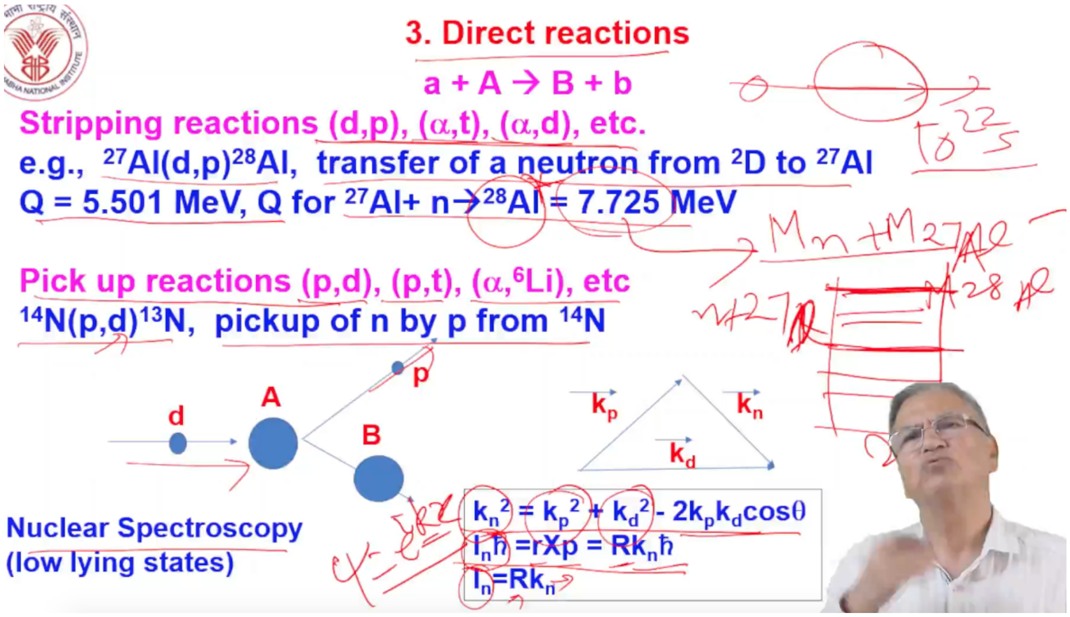
Next type of reaction is the inelastic scattering. Inelastic scattering again, again says it is in the name itself, but reveals it is scattering. That means the projectile and target retain their identity like $a+A\rightarrow a'+A^*$

So I have put a star because now the kinetic energy of projectile is not conserved. Some part of the kinetic energy of projectile is transferred to target nucleus, so the target can get excited. So total kinetic energy before and after the scattering is not conserved now. So some part of kinetic energy was transferred to target nucleus which gets excitation energy. And in fact, such reactions, though the masses of the projectile, the reactants and products are same, but the target is in an excited state. You have the target, it is now in an excited state, $a+ A\rightarrow a' + A^*$. So it is excited plus a'. So this much is the Q value of this reaction, though the nucleus is same, the mass in terms of the masses the Q value is zero, but this much energy is tied up. So this excited state of nucleus has an excitation energy and that much energy is required from the initial projectile energy.

So you can say the Q value is less than zero. Q value is also given as $E_A+ E_{a'} - E_a$. So now this value is negative because some part of the energy of the projectile has been transferred to target nucleus. In fact, there are applications of inelastic scattering in the form of some ion beam reactions. So this is called the particle induced gamma emission (PIGE).

So you can have excitation of a target nucleus and then this excited nucleus can emit a gamma ray and then gamma ray carry the signature of that nucleus. So if you count the gamma rays, these are prompt gamma rays emitted instantaneously. So then this technique, this is an ion beam analysis technique for material characterization. So when you bombard the target nucleus with a projectile like proton, so p,p' inelastic scattering of proton with target materials of aluminum, silicon, phosphorus and so on. Then the excited nuclei of aluminum, silicon and phosphorus, they de-excite by emission of its characteristic gamma rays and these gamma rays can be measured by a Germanium detector.

And so the intensity of the gamma ray essentially tells you the concentration of these elements. So for the material characterization, inelastic scattering is utilized in the form of ion beam analysis technique. So this is a simple setup for PIGE. You have a scattering chamber. It can be having a diameter of 50 centimeter or even more than that, under vacuum, 10^{-6} torr or better. And we have a target material in the form of a foil or a pellet. And so the projectile will be going in the forward direction. But this, whenever there is inelastic scattering, then the gamma ray can be emitted in all directions and you put a detector at 90 degree. Because in the forward detector, you cannot keep the detector because the projectile beam will be passing through that zero degree. So you put at 90 degrees, the background is much less and you detect the gamma ray. So you can put a HPG at 90 degrees with respect to the projectile beam and record the gamma spectra. It is an online experiment. While the beam is falling, gamma rays are being measured. You measure it for some time and then, so you can record the gamma spectrum of the products that are formed. So these characteristic gamma rays tell you what are the elements. You can take the peak area and you can use some standards. You can find out the concentration of these elements in the material. So impurities or even bulk material characterization can be done in the using inelastic scattering.



3. Direct reactions

$a + A \rightarrow B + b$

Stripping reactions (d,p), (α,t), (α,d), etc.

e.g., $^{27}Al(d,p)^{28}Al$, transfer of a neutron from ^{2}D to ^{27}Al

Q = 5.501 MeV, Q for $^{27}Al + n \rightarrow {}^{28}Al$ = 7.725 MeV

Pick up reactions (p,d), (p,t), (α,^{6}Li), etc

$^{14}N(p,d)^{13}N$, pickup of n by p from ^{14}N

Nuclear Spectroscopy
(low lying states)

$$k_n^2 = k_p^2 + k_d^2 - 2k_pk_d\cos\theta$$
$$l_n\hbar = r \times p = Rk_n\hbar$$
$$l_n = Rk_n$$

Then comes the direct reaction. Direct reaction happens in a very short time scale of the order of 10^{-22} seconds. Essentially this time scale is because of the time that the projectile will take to cross the nuclear dimensions. So that happens in the region of 10^{-22} seconds. And so the direct reactions means they come in contact with nuclear potential of each other, but they do not amalgamate to form a compound nucleus. So the energy is not equilibrated, the mass is not equilibrated. They're just one step process. You just knock out a nucleon, a proton or a neutron from the target nucleus or it can strip its particles in a very short time scale.

So the type of reactions that are taking place are like this (d,p) reaction. Deuteron colliding with the target nucleus and the proton is coming out. So deutron is stripped of a neutron. The neutron is captured by the nucleus. Here, ^{27}Al(d,P)^{28}Al. Similarly, (α,t) alpha is stripped of one proton, tritium is going out, proton is fusing with the target. (α,d) one deuteron is fused with target and one deuteron goes out. So like this, mostly you will find these reactions take place with the low Z nuclei like lithium, tritium, deuteron and so on.

One of the very interesting aspects of these direct reactions particularly here the transfer reaction is you are transferring a neutron from deuteron to aluminum-27 where the energetics are quite different from if you consider a neutron captured by aluminum-27. When a neutron is captured by aluminum-27, then the energy that is released is binding the neutron in aluminum-28, 7.7 MeV. This is the mass of neutron plus mass of ^{27}Al minus mass of ^{28}Al. This is the energy released and this much energy will go in the excitation of aluminum-28.

So the de-excitation of aluminum-28 from 7.7 MeV will take place by means of gamma rays. Whereas by d,p reaction, you are not exciting this to that high energy because the Q value is different for this reaction. And so if you consider the nucleus in a different excited state, neutron plus ^{27}Al □ ^{28}Al, then you will find that in the case of neutron capture reaction, you may populate it here. But in the case of d,p reaction, you may populate it here. And so you see a different energy state populated in this kind of stripping reaction. So you can study the nuclear reactions at different energy state and different angular momentum.

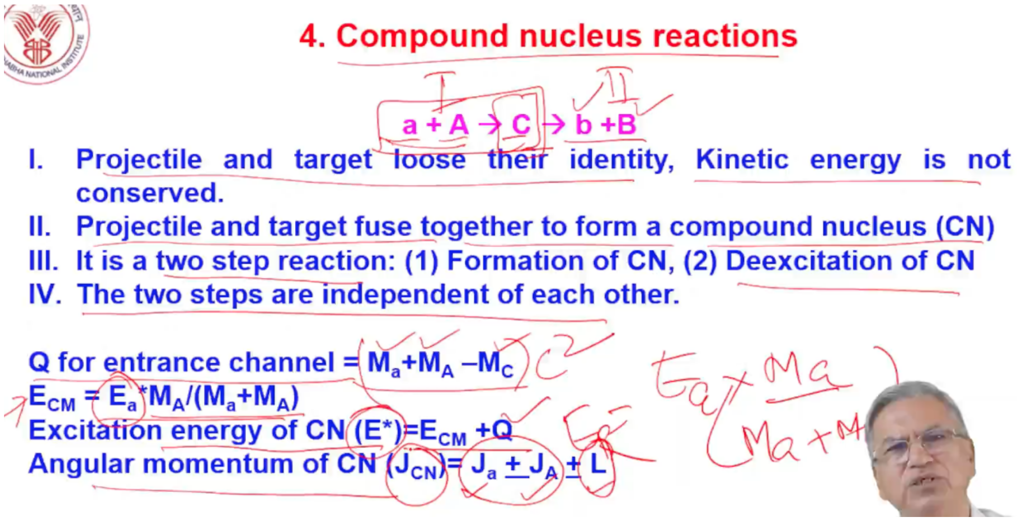
Another type of reaction is pickup reactions. That means a projectile picks up a nucleon like here a neutron, here a proton to neutron and so on. So projectile picks up a particle, a nucleon or a cluster from the target like here, ^{14}N(p,d)^{13}N. So proton is becoming deuteron and escaping. So it is picking up a neutron from nitrogen-14 and goes out as a deutron. So these kind of reactions are also direct reactions. They all take place at a much smaller timescale. So I tried to give a schematic of this. Deutron comes close to the target nucleus and then picks up a neutron from the target nucleus. And so this is a stripping reaction, not the pickup reaction. The neutron comes to the target nucleus, gives a neutron to the target nucleus and proton is going out and the target plus neutron nucleus is going in that direction.

So these are the kind of reactions where you populate the low lying states of the nuclei because their Q values are not very high. And in fact the nuclear physics people who study such reactions, they study the spectroscopy of low lying states by using transfer reactions of stripping or pickup type. So here it is the momentum transfer. So when you say a nuclear reaction, the projectile wave given below.

$$\psi = e^{ikx}$$

So k is the momentum of the particle. For example here this (d,p) reaction, so the projectile is transferring a neutron to the target nucleus. So the neutron momentum can be given in terms of proton momentum, the deutron momentum and see vector sum of proton and deutron momenta to give you the neutron momenta. So how much momentum is transferred to the target nucleus that is k_n and that can be given in terms of the momentum of the proton, you know the momentum of the deuteron, you can tell how much is the momentum transferred to the target nucleus and that momentum then you can transform to the angular momentum in terms of r×p. So p is kħ and $r_{maximum}$, since they are peripheral collisions, they are surface reactions, so r can be replaced by the nuclear radius. So the angular momentum transferred in these nuclear reactions result from the neutron momentum and the radius of the target nucleus.

So they are the kind of reactions where you transfer some angular momentum and you can see those targets certain states having that kind of angular momentum. So people are trying to see spectroscopy of low lying states of target nuclei by means of these direct reactions. So the nuclear physics community trying to study spectroscopy of low lying states utilize the beams of lower charged particles like protons, deutrons, so on to study the spectroscopy.



4. Compound nucleus reactions

I   II

$$a + A \rightarrow C \rightarrow b + B$$

I. Projectile and target loose their identity, Kinetic energy is not conserved.
II. Projectile and target fuse together to form a compound nucleus (CN)
III. It is a two step reaction: (1) Formation of CN, (2) Deexcitation of CN
IV. The two steps are independent of each other.

Q for entrance channel = $(M_a+M_A-M_C)c^2$

$E_{CM} = E_a*M_A/(M_a+M_A)$

Excitation energy of CN $(E^*)=E_{CM}+Q$

Angular momentum of CN $(J_{CN})= J_a \pm J_A \pm L$

$E_a \times \frac{M_a}{(M_a+M}$

So now I will come to the last nuclear reaction mechanism and that is the most important one that is the compound nucleus reactions. In the compound nuclear reaction, the projectile and target fuse together to form a compound nucleus C and subsequently this will de-excite by emission of particles or gamma rays. So we can say this is an ejectile and this is the heavy residue. We will discuss more on this subsequently. The important aspects of this are the projectile and target loose their identity. That means the compound nucleus does not know what way it was formed. Kinetic energy is not conserved in the compound nuclei reactions. All the energy, rather, most of the kinetic energy of the projectile will be converted into the excitation energy of the compound nucleus.

The projectile and target nucleus fuse to form a compound nucleus. So formation of compound nucleus is the first step. It is a two step process. In the first step, projectile target fuse together form a compound nucleus and second step, the compound nucleus deexcites by emission of particles and gamma rays. And the most important aspect is these two steps are independent of each other. So whatever is the compound nucleus excitation energy and angular momentum, they decide how it will de-excite. It does not depend upon which projectile and which target fused together to form this compound nucleus. So this is the important assumption and they have been verified also subsequently.

So the compound nucleus formation a+A is called the entrance channel, how it was formed. So for the entrance channel that means formation of compound nucleus from projectile and target we will call it the first part of the reaction and that is called the entrance channel. Entrance channel means how the projectile entered the target to form the compound nucleus and for that Q value is (mass of the projectile + mas of target - the mass of the compound nucleus) × c^2. If you write in terms of the ΔM values in MeV then we do not need to multiply by the c^2.

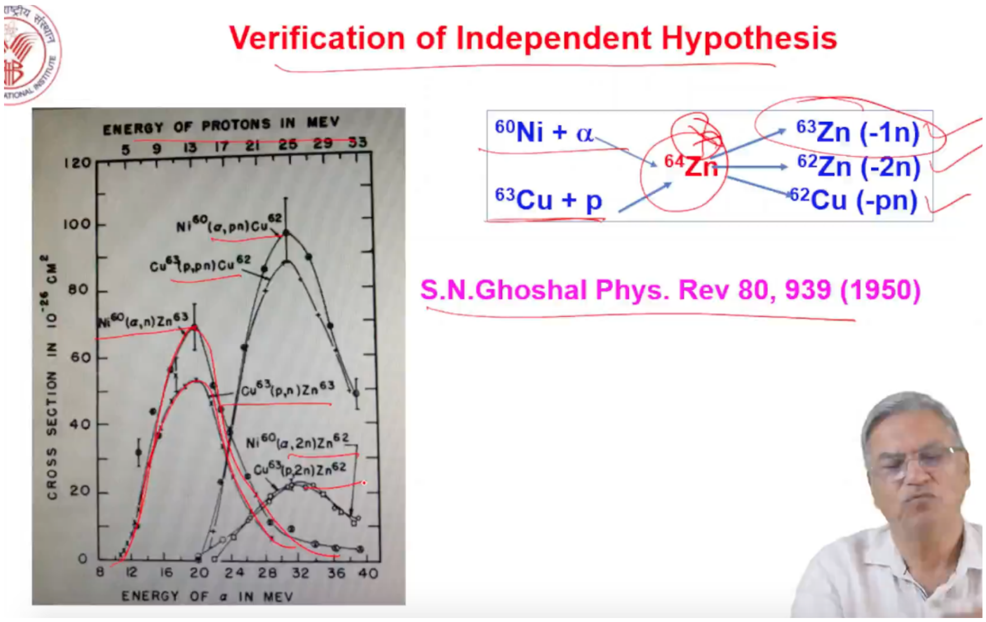
Secondly, the energy available in the central mass system E_{cm} is equal to projectile energy in the laboratory into mass of target upon mass of target plus projectile. So it is the mass fraction of the target to total mass. Suppose the target is heavier, then the majority of the energy of projectile goes to centre of mass energy and a small fraction will go into the kinetic energy.

So what goes into kinetic energy ?

$$E_{CM} = \frac{E_a M_A}{M_a + M_A}, \qquad E_R = \frac{E_a M_a}{M_a + M_A}$$

E_R is also called as the recoil energy. So some part goes as the recoil energy, some part goes as the Ecm energy available in the centre mass system and that energy available in the centre mass system adds to the excitation energy of the compound nucleus. So the compound nucleus excitation energy is equal to energy available in the centre of mass system $E_{CM} + Q$.

Another important property of compound nucleus is the angular momentum of the compound nucleus which is the projectile angular momentum plus target angular momentum and then the orbital angular momentum that the projectile brings in the l value for a particular collision. So these are the spins and this is the orbital angular momentum. They couple vectorially to give rise to a resultant angular momentum. So the de-excitation of the compound nucleus depends upon excitation energy and the angular momentum. These are the two important properties of the compound nucleus that will govern how the nucleus will decay.



Verification of Independent Hypothesis

^{60}Ni + α → ^{64}Zn

^{63}Cu + p → ^{64}Zn

^{64}Zn → ^{63}Zn (-1n)

^{64}Zn → ^{62}Zn (-2n)

^{64}Zn → ^{62}Cu (-pn)

S.N.Ghoshal Phys. Rev 80, 939 (1950)

The independent hypothesis I was talking about that means the formation of the compound nucleus and its decay, these are two independent steps in the compound nucleus mechanism and this has been verified by one experiment of an Indian scientist S.N. Ghosal way back in 1950. A very interesting experiment he carried out that is he formed the same compound nucleus Zinc-64 by two different reactions alpha+^{60}Ni→ ^{64}Zn, p + ^{63}Cu→ ^{64}Zn. And this compound nucleus is excited. This excited compound nucleus can emit a neutron, two neutrons or proton and neutron giving rise to different products zinc-63, zinc-62 and copper-63. So what I have shown here on the left hand side in this graph is the variation of the cross section of a particular product formed by two reactions.

For example, this first reaction, let us see zinc-63, 1n product. Zinc-63 here you can see nickel- 60(alpha,n) zinc-63, copper-63(p,n)zinc-63. So for nickel-60 this is the reaction and for copper-63 this is the reaction. So you can see here the ratio of the cross section for the two different entrance channels are nearly constant. The small difference in the cross section value actually maybe due to angular momentum because it is very difficult to match the excitation energy and angular momentum.

So you can see the proton energy and alpha energy are matched. So that will give you the same excitation energy but angular momentum could slightly vary and that is why there could be small difference. But by and large you see other product copper- 62, (alpha,pn) and (p,pn) both the reactions give similar cross section. Zinc 62 you can see whether you form by nickel-60 plus alpha or copper-63 plus proton the cross sections for the individual products are nearly same. That was the experimental verification of the independent hypothesis that means whatever channel you use to form a compound nucleus, the de-excitation of the compound nucleus is independent of that. That is what I try to explain using the experiment of S N Goshal for a compound nucleus process.

I will stop here and discuss the detailed mechanism of compound nucleus in the next part. Thank you.