Nuclear reactions: Introduction

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Lecture-11, module-1

Hello everyone, welcome to the lecture on nuclear reactions. So far, we have discussed the properties of nuclei as well as radiations. And now we will switch over to another aspect of nuclear and radiochemistry that is nuclear reactions.

1. History of nuclear reactions
2. Conservation laws in nuclear reactions
3. Energetics of nuclear reactions

In nuclear reactions, we will discuss the energetics, the cross-sections, the mechanism of nuclear reactions and also production of isotopes that are useful in many applications. In the first part, I will talk about the energetics of nuclear reactions. But before discussing the energetics of nuclear reactions, it would be good idea to go through a little bit of history of the nuclear reactions and some of the laws that govern the nuclear reactions like what are the things that are conserved in nuclear reactions. So, suppose you want to set up a nuclear reaction or you want to complete a nuclear reaction if you know the conservation laws, then you can easily complete the reaction. So, that also we will discuss in today's lecture and little bit about the energies that are involved in the nuclear reaction.

The first nuclear reaction: Discovery of proton

Ernest Rutherford (1919)

$^{14}N + {}^{4}He \rightarrow {}^{17}O + {}^{1}H$

Positively charged particles → named as Protons in 1920

Discovery of neutron: James Chadwick (1932)

$^{9}Be + {}^{4}He \rightarrow {}^{12}C + {}^{1}n$

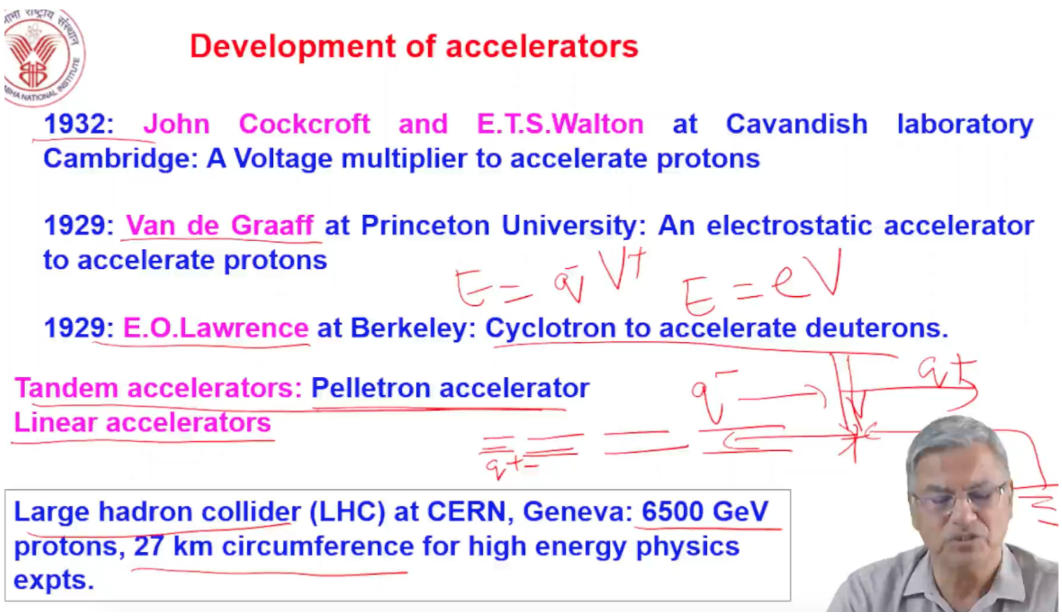
Alpha particles from ^{210}Po were used as projectile

But first let us see the historical aspects of the nuclear reactions. Maybe already you know that the first nuclear reaction was carried out by Ernest Rutherford in 1919. That is

the reaction which ultimately led to the discovery of proton. Rutherford in fact bombarded the nitrogen-14 target using the alpha particles that were available from the naturally occurring radioisotopes of radium and polonium. And so when he bombarded the nitrogen target with alpha particles from the naturally occurring radio isotopes like polonium-210, then the oxygen-17 and a positively charged hydrogen atom were produced. And this caused fluorescence or scintillations at the screen. And so he in fact based on the charge and so on, he concluded that these positively charged particles are nothing but the protons.
And that is how the, this was the first nuclear reaction where the atom was transmuted. But this reaction gave rise to stable products. In this particular reaction, oxygen-17 and proton both are stable products. So this reaction though being the first nuclear reaction produced stable isotopes. And so Rutherford in fact named this positively charged hydrogen atoms as protons in 1920.

Then subsequently, the neutrons were discovered by James Chadwick, the student of Rutherford in 1932. And in this reaction again, the alpha particles, the projectiles that were used were from the naturally occurring radio isotopes of polonium-210. So again, polonium alpha particle bombarding beryllium-9, even he also bombarded other isotopes like aluminum-27 and led to the discovery of neutron. So, so far till the 1920s, the projectiles that were being used were charged particles, mainly alpha particles available from the naturally occurring radio isotopes of radium, polonium. And the energy of these alpha particles as you know, was in the range of 5 MeV.

But when you want to bombard the heavier elements, isotopes of heavier elements, then the Coulomb barrier creates a hindrance in fusion. And therefore, there was a need to develop accelerators which will produce high energy charged particles. So that is where a big jump took place in the development of accelerators and the need arose to increase the energy of charged particles. The 5 MeV alpha particles available from radium, polonium would not cause reactions in heavier elements. And that is the time in 1920s and 1930s, you will find a lot of discoveries took place, developments of different types of accelerators.



I will just briefly go through some of them. In 1932, Cockcroft and Walton at Cavendish Laboratory, Cambridge, they developed a voltage multiplier by which you can generate the high energy particles. So basically, you have a cascade of electrodes and which you can charge to higher and higher voltage, like in a photomultiplier tube. The photomultiplier tube, you have the cathode and then you have the dynodes having higher and higher voltages. In this cascade generator, you have the electrodes having higher and higher voltage.

So you can multiply the voltage to higher and higher voltage and then you can accelerate the charged particles. So in fact, though it was developed in 1929, but they split the atom using these protons in 1932. And so they first time demonstrated that using the accelerated charged particles, you can cause a reaction in a nucleus. And for this, they got Nobel Prize in 1951, Cockcroft and Walton. So that was a landmark development in the early 1930s.

Concurrently with that, Van der Graaff at Princeton University USA developed an electrostatic accelerator. Electrostatic accelerator is very simple. Suppose you have a potential V and you have a charge q. So if you have a negative charge -q and you have a positive potential, then the energy that the charged particle will acquire will be qV. Like an electron accelerated to a potential of V volts will have energy 1electron volt.

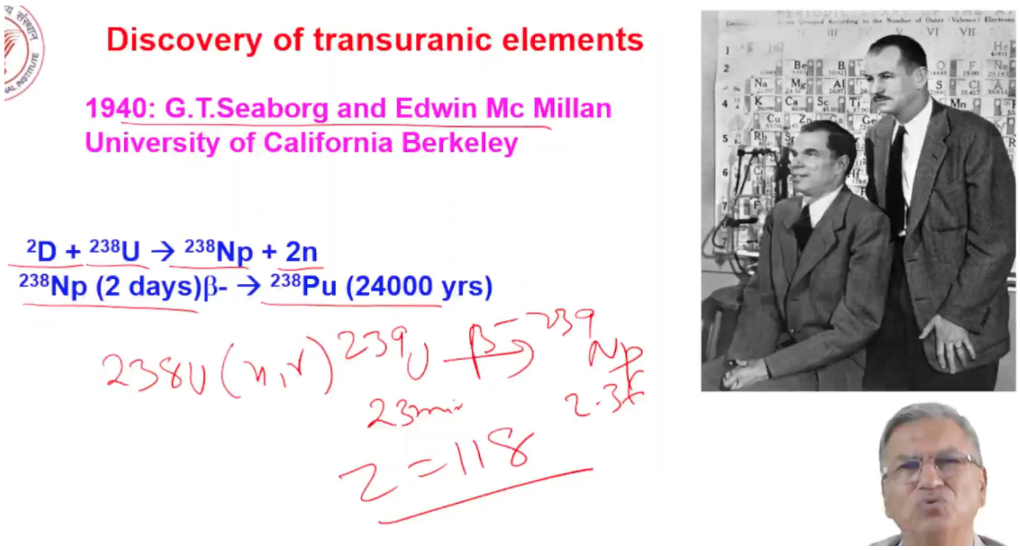
So, you can actually accelerate in an electrostatic manner, any charged particle accelerating to the opposite potential, it will acquire the energy equivalent to the charge into the potential. So that is the straight away electrostatically you can accelerate particles. And Van der Graaff in fact generated few MeV particles using electrostatic accelerators. In fact, there had been a course in NPTEL on accelerator physics. And so those students who want to know more about accelerators and the physics behind them, they can attend that course, which is currently going on.

In about the same time, Lawrence, in University of California, Berkeley, which later on became Lawrence Berkeley Laboratory, developed a cyclic accelerator. So that was called cyclotron, which can accelerate the charged particles between the D of a magnet and then accelerate to very high energy. So the diameter of the magnet actually will decide the energy to which you can accelerate the charged particles. So concurrently you will see electrostatic accelerators, cyclic accelerators were developed , when the need arose to accelerate the charged particles to higher energy than that are available from the naturally occurring radioisotopes.

In fact, later on in 1950s, other variants of accelerators became available, like one of them are called tandem accelerators. So tandem essentially means two stage. So you start with a negative ion, accelerate to a positive potential. And then so you have the potential and at this you put a stripper foil and then you will see q+ charged particles. So it is a two stage acceleration. One is from the negative ion to positive potential and then the positive potential will repel the positively charged ions to ground states. This is the two-stage acceleration called tandem accelerators. And one of the accelerators of this type are called palletron accelerators. The pallet charging, how you charge the accelerator is called by pallet charging, it's called palletron accelerator. And by tandem, now since it is a two stage acceleration, you can go to much higher energies than what you get from the electrostatic accelerators. So over the Van de Graaff, there is a big jump in energy when it came to tandem accelerators.

And later on linear accelerators became also very popular, wherein you can accelerate in steps. So small, small steps by an alternative potential. So you have a positive ion, you have a negative potential. And then again, you change the potential to negative. And so in subsequent steps of increasing length of the accelerating tube, you can accelerate the particles to much, much higher energy. And the linear accelerators are in fact the length of some of the accelerators are in few kilometers. In fact, the latest, the highest energy accelerator in the world today is at CERN Geneva, that is called the Large Hadron Collider, LHC, and which gives 6500 giga electron volt protons. It is a linear accelerator having circumference of 27 kilometers.

So the subject of accelerators in fact have advanced so much that in the high energy physics domain, there has been a need to develop high energy accelerators so that you can create different particles. So, in fact, it is called a proton-proton collider. So when the two protons collide, you can generate a lot of energy and from that energy, so many other particles like you know, the different particles, baryons, quarks and leptons, they can be produced. And so it's like a factory to produce different types of particles. So that is how the subject of high energy physics have advanced because of the development in the accelerators.



At the same time, the development in accelerators had led to other aspects like the discovery of trans-uranic elements. The trans-uranic elements, you know that the elements up to uranium were known in the 1930s and then the discovery of nuclear fission took place in 1938. In fact, the attempt by Enrico Fermi was to synthesize elements beyond uranium. And in the process, Hahn and Strassman discovered nuclear fission. But the experiments at Berkeley continued to synthesize heavy elements beyond uranium. And in 1940, Glenn T Seaborg and McMillan, in fact, used the cyclotron developed by Lawrence wherein they used a deuteron beam to bombard uranium-238 to get neptunium -238 plus 2 neutrons. This ^{238}Np is 2 days half life and by beta minus decay generates ^{238}Pu, which has a half life of 85 years.

^{238}U + ^{2}D □ ^{238}Np +2 n , ^{238}Np □ ^{238}Pu + β-

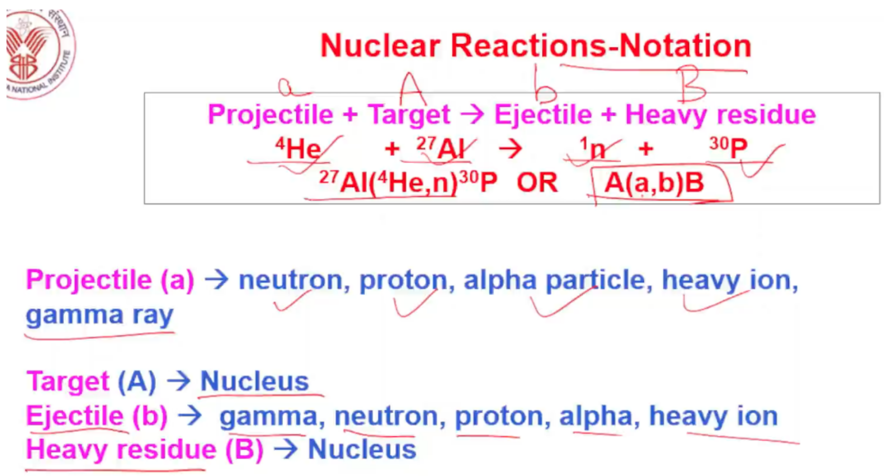
So this was the discovery of a new element plutonium, element atomic number 94. Prior to this, element 93, neptunium was discovered by neutron induced reactions on uranium that was

$$U^{238}(n,\ \gamma)U^{239}\ \beta - \rightarrow Np^{239}$$

Half life 2.3 days. ^{239}U half life is 23 minutes. So, the trans-uranic elements discovery was also contributed by the development of the accelerators.

And now as many of you will be knowing that the accelerators have contributed in the synthesis of heavy elements. Now the elements up to 118 have been discovered. All of them, elements beyond 103, beyond the actinides in fact now are possible only by means of accelerators. So by accelerators you increase the atomic number of the nuclei. And so this is a subject in itself where you can synthesize heavy elements, you can study the chemistry of heavy elements all using the accelerators.

So accelerators have impacted not only in the fundamental research extension of periodic table or high energy physics. Now you will see along in this particular lectures now accelerators have also provided the means to produce radio isotopes which are useful for applications in healthcare, industry, agriculture and so on.



Okay, now let us come to the nuclear reactions fundamentals. So any nuclear reaction we will follow certain nomenclature or some notation to develop a nuclear reaction. Suppose we want to complete a nuclear reaction. So we can write simply

a + A → b + B

A is the target, a is the projectile, b and B are products. So, we call them a is the projectile, A is the target. Ejectile means the smaller particle product and heavy residue is the heavier of the two products that were formed. So this whole thing can be written in terms of A (a,b) B that means A and B are heavier nuclei and a and b are smaller nuclei projectile and ejectile, respectively. Just to give you an example, when helium is bombarded on aluminum-27, the famous reaction for discovery of neutron and also the discovery of artificial radioactivity, you get a neutron and phosphorus-30.

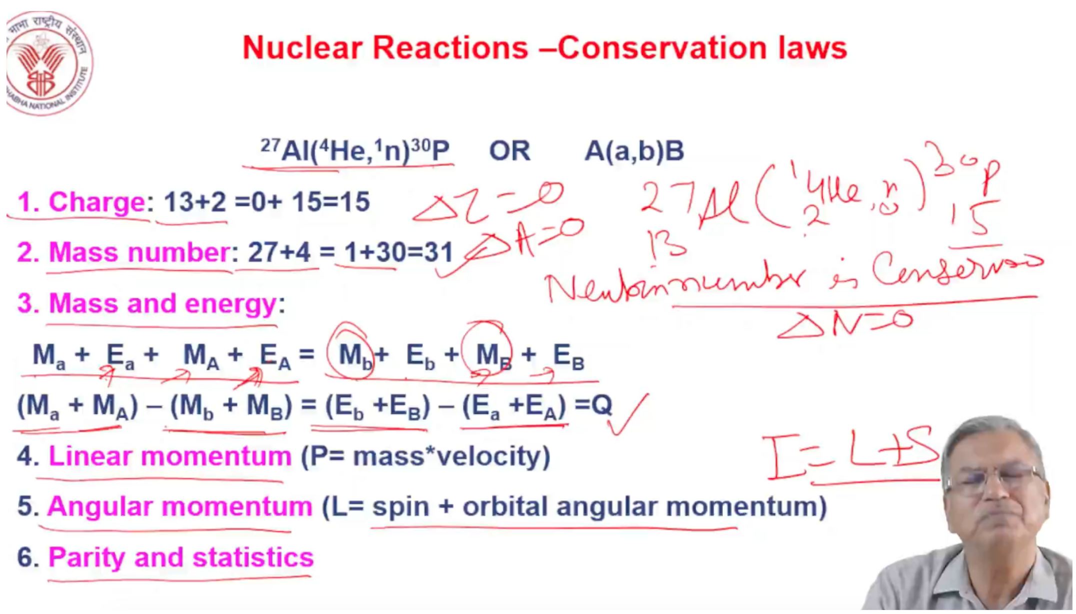
$$He^{4} + Al^{27} \rightarrow n^{1} + P^{30}$$

So alpha is the projectile, aluminum-27 is the target, neutron is the ejectile and phosphorus- 30 is the heavy residue. So the same reaction can also be written as,

$Al^{27}(He^{4}, n)\ P^{30}$ or A (a,b)B.

So you can write that notation for a nuclear reaction in this way. So the projectile for a nuclear reaction could be neutron, proton, alpha particle or it could be heavy ion like carbon, lithium, oxygen or you can even induce nuclear reaction using a gamma ray photon.

So, a projectile could be any particle. Similarly, the target, mostly the target will be mostly a nucleus, a heavier nucleus on which the projectile is bombarded. Then the ejectile means the particle that is emitted, the smaller particle that is emitted will be called ejectile, it could be gamma ray, neutron, proton, alpha or heavy ions, that can be emitted in the nuclear reaction and then you will be left with a heavy residue that mostly will be a nucleus.



So when you are setting up an equation, if you have to fill in the blanks, you can use these notations and certain conservation laws that I will be discussing shortly. So now let us discuss what are the conservation laws when we write a nuclear reaction and I will be using this as an example to illustrate the points the conservation laws. So

$$Al^{27}(He^{4}, n)\, P^{30}$$

is like a reaction which we will use to illustrate the points.

So in any nuclear reaction, the charge is always constant. So that will help you in writing the nuclear reaction. And for example, aluminum-27, 13 is the atomic number. So it is 15, 2 and 0. So 13+2 is 15 and it is 15 here. So atomic number is conserved. So essentially the number of protons in any nuclear reaction is conserved.

Similarly, the mass number in any nuclear reaction is always conserved. You can see here 27+4, 31 and 30+1, 31 is always conserved. And since the atomic number and the mass number are always conserved in nuclear reaction, so neutron number is also conserved. In any nuclear reaction, you will find the neutron number is also conserved. So you can also write $\Delta Z = 0$, $\Delta A = 0$, $\Delta N = 0$. So that will help you in setting up a nuclear reaction.

Now, when it comes to mass and energy, as you know that mass and energy are interconvertible. So when the nucleons combine to form a nucleus, energy is released or if you want to break a nucleus into constituent nucleons, you require energy. So mass and energy are interconvertible. So that is why when it comes to conservation of mass and energy, it is the sum total of mass and energy that is conserved, not mass alone. Mass alone is not conserved; energy alone is not conserved. It is the mass plus energy together they are conserved. So when I am putting E, it is the kinetic energy of the nuclei. So mass of the projectile plus kinetic energy of the projectile plus mass of the target plus kinetic energy of the target.

$$M_a + E_a + M_A + E_A = M_b + E_b + M_B + E_B$$

So this is the initial mass and energy equal to mass of the ejectile plus its kinetic energy plus mass of heavy residue plus its kinetic energy. So on the left hand side and right hand side, mass and energy together have to be conserved. Now you can rearrange this equation now.

$$M_a + M_A - M_b - M_B = E_b + E_B - E_a - E_A = Q$$

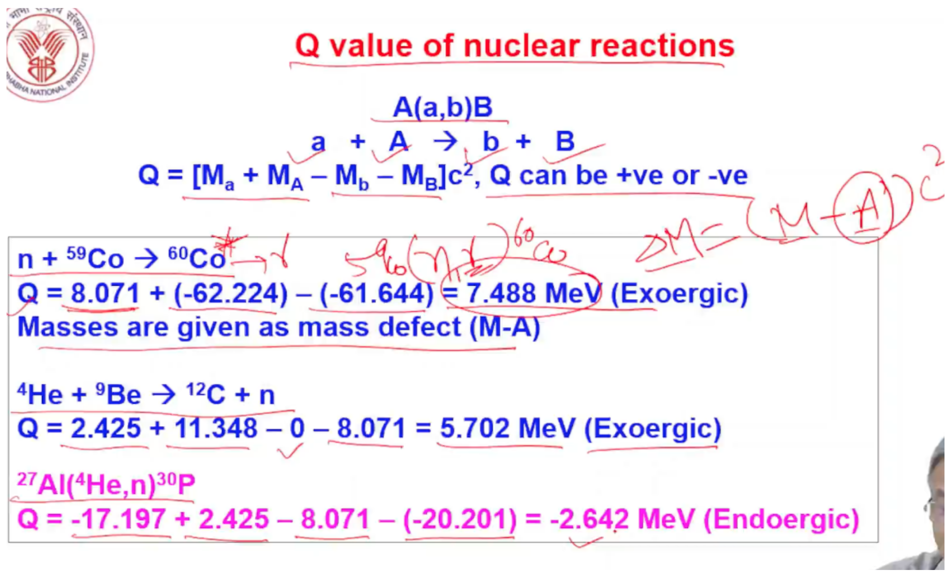
And so, this quantity, the difference in the masses of reactant minus product is called the Q value. And Q value can also be defined in terms of difference in the kinetic energy of products minus that of the reactants. This Q value is called the energy of a nuclear reaction. So, energy of a nuclear reaction is an important quantity. It could be positive; it could be negative. If Q value is positive, that means energy is released in nuclear reaction. These are called exo-ergic reactions. If Q value is negative, that means energy is required to cause a nuclear reaction. They are called endo-ergic reactions. Like in chemistry, you have exothermic and endothermic. In nuclear chemistry, we will call exo-ergic and endo-ergic. We will discuss more on the Q value subsequently.

Another quantity that is conserved in nuclear reactions is the linear momentum. Linear momentum is nothing but mass into velocity. And so linear momentum is also conserved and the corollaries of this linear momentum conservation will be clear very soon when we will have the subsequent lecture.

Angular momentum is another quantity which is conserved in a nuclear reaction. Angular momentum is the sum of the spin angular momentum and the orbital angular momentum, L + S. So, you can say I=L+S orbital plus spin angular momentum. So, this I is again conserved before and after the reaction.

And in addition to that, the parity and statistics. The parity, if you recall, the parity of a function is like $(-1)^L$, where L is the orbital angular momentum. Or you can say any function also has got a parity depending upon whether it will change the sign upon change of coordinates or not. Statistics, we have either Fermi Dirac statistics or Bose Einstein statistics for fermions and bosons respectively. So again, the statistics also is conserved before and after the reaction.

So, they are more into the details of nuclear reactions. But for the moment, the important quantity that we need to know about conservation is charge, mass number, and hence the neutron number, mass and energy, linear momentum and angular momentum.



Now let us just go into the Q values of nuclear reaction, how to calculate the Q value of nuclear reactions. So simply again, I can write the reaction as A(a, b)B. So this is a projectile, the target, ejectile and the heavy residue. And the Q value can be given in terms of the (mass of the reactant - mass of the products) c^2. If you write in terms of the atomic mass units, then you would say ΔMc^2. And this Q value can be positive or negative.

So let us work out some examples to demonstrate this point, what kind of masses we need to put into the nuclear reactions to calculate the Q value of nuclear reactions. I give you some examples, neutron plus cobalt-59 gives rise to cobalt-60. So, this is called a (n, γ) type of reaction, or neutron capture reaction. That means actually this cobalt-60 will be excited and it will emit a gamma ray to come to ground state. And that cobalt-60 in ground state is radioactive having half life of 5.27 years. But this cobalt-60 when it is excited, it will emit gamma ray within pico seconds.

So that's why it is called $^{59}Co(n, \gamma)^{60}Co$. This gamma is not the gamma ray emitted after beta decay of cobalt-60, but it is called a prompt gamma ray. So this reaction, the Q value will be

$M_n + M(^{59}Co) – M(^{60}Co)$

Here you see here, what I have shown here, the masses are the mass defects. Mass minus A is called mass defect (ΔM). So, this you can multiply by c^2. So, if you write the (mass in atomic mass units)- (the mass number) ×931, you will get the mass defect in ΔM MeV. That is what is written in terms of mass of a neutron, 8.071 MeV plus the mass defect of cobalt-59. So, it is -62.224. Now minus the mass defect of cobalt-60 minus 61.644, that is equal to 7.488 MeV.

$Q = 8.071 + (-62.224) – (-61.644) = 7.488$ MeV

See one thing you must note here is that, though I am writing here mass defects, the ΔA value for a nuclear reaction is zero because the mass number is conserved. So here it is possible to write the masses in terms of M-A because the A will anyway get cancelled.

So the difference in the mass defect is nothing but difference in the masses because the A will get cancelled. So, the masses are given as mass defect M-A when you want to calculate the Q value. There are certain cases which we will discuss. You cannot substitute the mass by the mass defect when you are calculating the recoil energy or center of mass energy, which will become clear very soon.

Now these neutron capture reactions you will find are always exo-ergic reaction because you are combining a neutron to a nucleus. So, whenever a nucleus combines with the neutron, energy equivalent to the binding energy is released. So this energy is nothing but the binding energy of neutron in cobalt-60. So such reactions, neutron capture reactions are always exo-ergic. That means energy is released. The energy released is equivalent to the binding energy of neutron in the product nucleus.

Another example is

$^{4}He + {}^{9}Be$ □ $^{12}C + {}^{1}n$

$Q = M_{4He} + M_{9Be} – M_{12C} - M_n$

$= 2.425 + 11.348 – 0 – 8.071 = 5.702$ MeV

So this is the Q value for the reaction is 5.702 that is positive and hence it is exo-ergic reaction. There are some reactions like $^{27}Al(^{4}He, n)^{30}P$. Here you can see aluminum-27 is -17.197 MeV, alpha particle 2.425, neutron 8.071 and phosphorus-30 is -20.201. And this reaction has a negative Q value of -2.642 MeV. So this reaction having negative Q value is called endo-ergic reaction because energy is required to induce this reaction. Whereas for exo-ergic reaction, energy is released in the nuclear reaction.

So, for nuclear reactions, the Q value will be in the range of few MeV and it could be positive or negative. So the nuclear reactions, the energetics are the important property of nuclear reactions. And as you will see subsequently, you can use the energetics to calculate the threshold of the nuclear reaction, how much energy is required to induce a nuclear reaction that we will discuss in the subsequent lecture. Thank you very much.