Fundamentals of Nuclear Power Generation

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Lecture – 04
Different Types of Nuclear Transmutation

Hello friends, welcome back to our course. It is a sunny day at Guwahati, but I am sitting inside an extremely cold recording room and it is quite a bit uncomfortable to sit here, but we just have to continue our course and so let us focus back to the second module of our MOOCs course on the fundamentals of nuclear power generation, where we are discussing about this very intriguing topic of radioactivity and nuclear reactions.

In the first lecture on this particular topic, you were introduced to the term radioactivity which was defined as the spontaneous decay of some unstable isotopes or nucleus which led to the emission of several particles and some also generally release of a good amount of energy and this is a spontaneous reaction, because of which we have the process of transmutation happens that is 1 parent nucleus gets converted to our daughter nucleus.

The daughter nucleus itself can also be radioactive in nature leading to the formation of radioactive chains till the appearance of some kind of stable isotopes or stable nucleus and this disintegration of such radioisotopes is governed by such an exponential relationship, which we you have derived during our last lecture where N naught refers to the number of isotopes present at the beginning of some chosen interval while lambda is called the decay constant Lambda is characteristics of the radioactive particle itself or a radioactive isotope itself.

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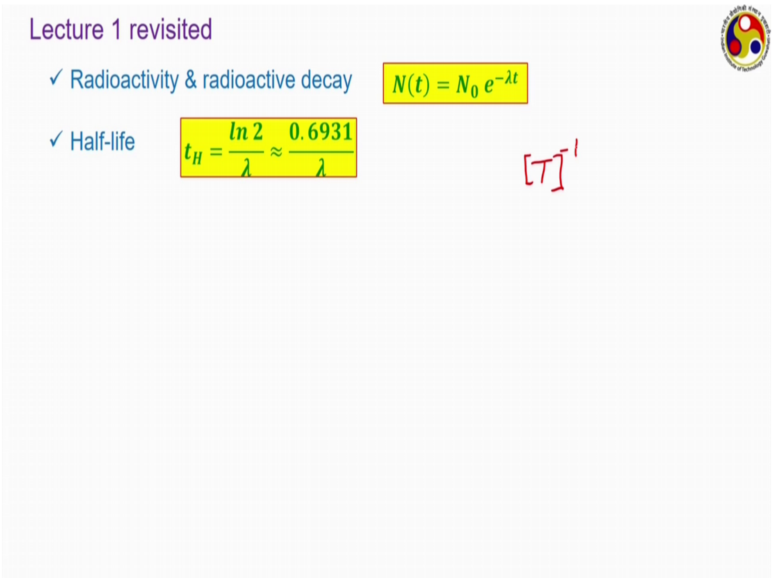

But a more important property which is extremely important to know about any radioactive isotope is called the half life, which is defined as the time required for the number of nucleus present in a sample to reduce to the half of this original value and this half life is related to the decay coefficient or decay constant by this simple linear relationship or you can say the half life is inversely proportional to the decay constant.

Now, half life is a very important parameter for any radioisotope because, each isotope has it is value of half life and the unit of half life of course is time, but it has a very wide range to cover for some isotopes it can be in the range of seconds or even sometimes even less than seconds; whereas, for certain other isotopes it can be in the range of a few billion years, like very common isotopes like uranium 238 or thorium 232 have extremely long half life, which is the reason for them still existing in the universe. But as half life is a unique parameter for any radioisotopes so decay constant also has to be a unique parameter; that means for a given isotope the value of decay constant also is a constant and I also say it is unique means 2 radioisotopes cannot have the same value of the half life and therefore same value of decay constants.

Now, we know that the unit of half life is time because, we had to we are talking about a time spent, then what should be the unit for this decay constant as they are inversely proportional to each other. So, the decay constant where the half life it is unit is time. So, the decay constant master is units have a time inverse. So, depending on what kind of material you are talking about, we can use secondary inverse or minute inverse or even a larger units to specify the value of decay constant.

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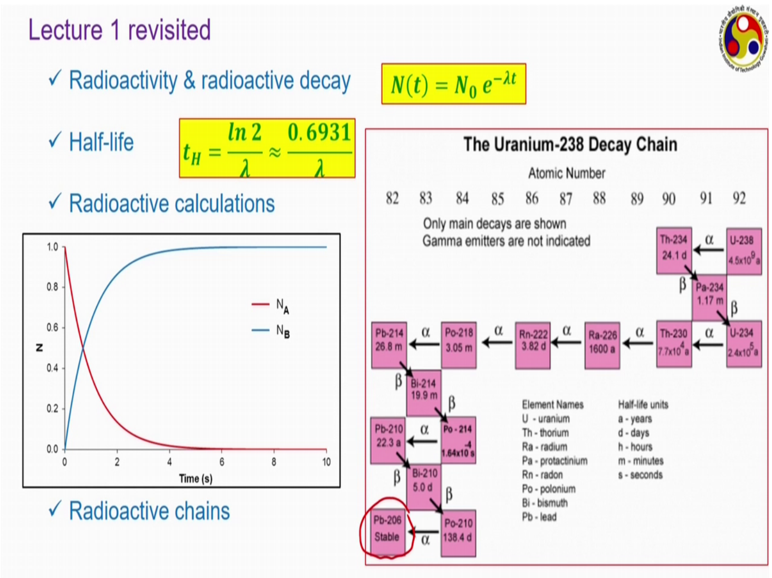

After knowing about this properties like decay constants, half life, mean life etc; you were introduced to this of radioactive calculations where we took a very simple relation or simple binary reaction from some parent isotope a convert into some daughter B and by solving their mathematical forms, we have seen that their number of nucleus will show a simple exponential relationships such as this, where a you will decrease exponentially and corresponding B will increase exponentially; but in real life you never get such kind of binary reaction rather we are always present with radioactive chains, that is a chain of reactions starting from some heavy nucleus in general and then going through several intermediate or daughter nucleus and still the final formation of some kind of a stable new isotopes.

Like the example of uranium 235 decay chain which was presented earlier also where we are starting with uranium 238 and finishing upon with lead 206 this PV 206, which is a stable isotope basically it is non radioactive and then only we have this chain complete, but in between you can see there are large number of intermediate particles. In fact, there are other isotopes of lead as well which are radioactive in nature, but this PV 206 is the final product is non radioactive and therefore, that is where the chain ends.

So, today we have to see how to analyze such kind of decay chain and then we shall be moving to study different kinds of radioactive reactions that are possible.

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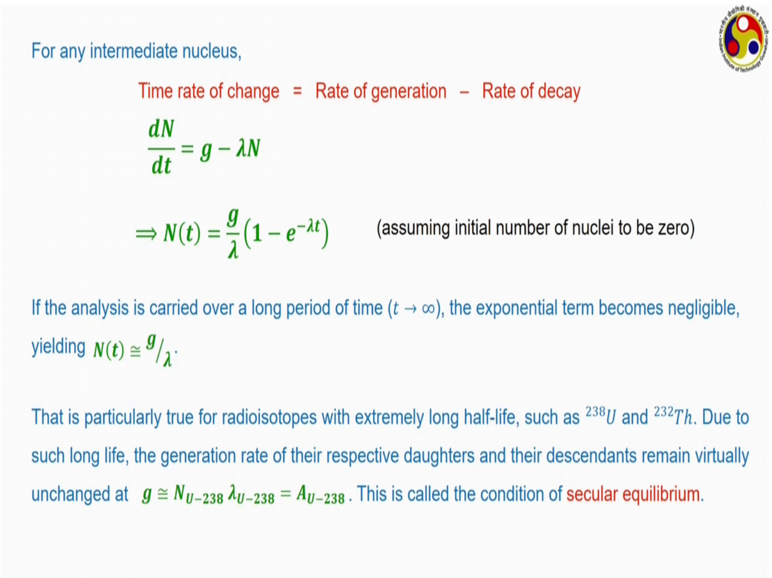

Now, if we talk about any of the intermediate nuclear that can appear somewhere between the radioactive chains, we always write a conservation for the corresponding nucleus as the time rate of change equal to rate of generation minus rate of decay or mathematically d N by dt is equal to g minus lambda N, where N is the number of nucleus for that particular species that you are talking about, g is the rate of generation and lambda is the corresponding decay coefficients. So, the rate of decay will be given by lambda N to N as per the decay law and mathematically solving this ordinary differential equation we can get a solution of this particular form, assuming of course the initial number of this intermediate nucleus to be 0.

Now, you can see here we have an 1 minus e to the power minus lambda t term inside the bracket, if we are talking over a very large time scale like when t tends to infinity or means infinite time are refers to certain time which is much bigger compared to or corresponding to the time that is important for from our phenomenal point of view; like say if we are talking about if your zone of interest or period of interest for a certain activities only say 1 second, then even 20 second is can also be treated as infinite and therefore this exponential term over a very long time interval of course tends to 0 or becomes negligible yielding this N t is equal to g by lambda.

This is particularly true when you are talking about an element with extremely long half life like u 238 or t h 232 extremely long half life, means extremely small value of lambda as well and because of their such long life their decay and slow rate of decay, their number of nucleus changes extremely slowly and therefore the generation rate of their respective daughters and descendants remains virtual constant.

Because the rate of generation of their daughters will be given as just the same as for this uranium 238 where N into lambda is a constant and N will change very small by very small amount over a reasonable period of time and therefore g will become equal to the activity of that U238 or whatever parent nucleus we are starting with, this kind of situation is called secular equilibrium this 1 we shall be coming back to after little bit of mathematical exercise.

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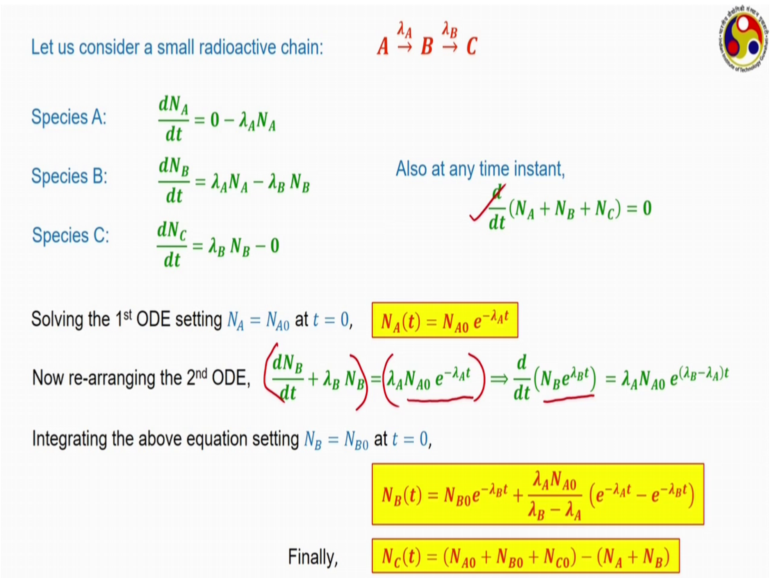

Now, let us take a very small radioactive chain which involves not 2 but now we have 3 elements, A is the initial parent which is decaying following a rate of lambda A to some daughter isotope B, but that also is a radioactive that also is radioactive in nature. So, it is also decaying to an isotope C following another coefficient lambda B. So, let us write the conservation equations for each of them first 4 element A as there is no source for generation of a it can only go through the decay and therefore you get this particular equation B.

Of course, can get generated because of decay of a and it is also getting decade or disintegrated and getting converted to C accordingly the conservation energy for B can be written like this, rate of change of B nucleus will be equal to lambda ANA which is the rate of generation and also the rate of decay of A, similarly the rate of decay of B is lambda B in to N B and the balance between this 2 terms will give you the rate of change of a isotope and finally the species C where there is only generation, but no further decay as in this elementary chain we are considering C to be a stable isotope and accordingly we get this particular rate of equations.

Now, this all 3 of them are single order or first order ordinary differential equations which requires simultaneous solutions, but we have another condition here at any time instant we can say that time rate of change of the total number of isotopes present in the sample will remain constant, that is quite straight forward because disintegration of 1 isotope of A will produce only a single isotope of B and similarly a disintegration of A single isotope of B can produce only a single isotope of C and therefore total number of isotopes in the sample has to remain the same.

Now, we can solve this equations solving the first ode with an initial condition of NA equal to NA naught at time t equal to 0, we get the familiar exponential decay form of the element A, further B let us put this expression of NA back to be and so now you have after rearranging the terms d NB d t is plus lambda BNB is equal to lambda A into NA and so that this is the NA part which has been replaced by the form just we got in a previous line.

Now, we multiply both sides of the equation that is both the right hand side and left hand side with e to the power lambda B t and accordingly I should say I am multiplying both side of this equation, where e to the power lambda B t, which can be treated as a the integrating factor in this particular situation and accordingly we arrived at this we can write the right hand side as the time rate of change of this product of NB into t to the power lambda Bt and left hand side of sorry.

The left hand side we can write as the time rate of change of this product of N B and e to the power lambda B t and right hand side is the straight forward form and this can be integrated from time t equal to 0, to what your time t we want taking N B equal to N B naught as the initial concentration of B or initial number of nucleus of B and accordingly we get this particular mathematical form of N B, this is simple mathematical derivation you can derive following the procedure that I have just mentioned and then making use of this particular condition, we can get the number of nucleus for NC variation with time. So, we have the mathematical solutions for NA and N B and NC and if we combine all 3 into single graph we are going to get a form like this.

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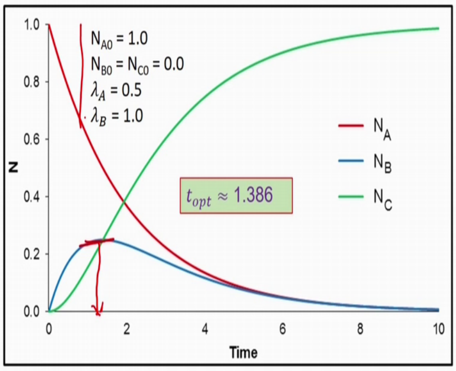

Identifying the time corresponding to the maxima in N_B can be an excellent optimization problem and can provide valuable information in certain situations. Setting $\frac{dN_B}{dt} = 0$,

$$t_{opt} = \frac{1}{\lambda_B - \lambda_A} ln\left[\frac{\lambda_B}{\lambda_A} - \frac{\lambda_B N_{B0}}{\lambda_A{}^2 N_{A0}}(\lambda_B - \lambda_A)\right]$$

Where a continuously decreases because if the it is not having any kind of source, whereas NC continuously increasing following the green line as it is not decaying anymore, but B is having both the source and also it is getting decayed accordingly it is a great initially increases, but then after reaching certain maxima it starts to decrease.

This location of the maxima of this element B or isotope B which seems to be somewhere here is a it possess a very interesting optimization problem while drawing this graphs we have assumed in A to B1 and N B and N C to 0 in the initial sample, lambda a has been taken to be 0.5 where B is taken as 1; now this optimization problem we can identify the location of the maximum number of nucleus of B and the corresponding time by setting d N B d t equal to 0 and accordingly I have written here the final solution, where we have the expression for the optimum time t basically we are referring to a time somewhere here which a corresponds to the maxima of this B nucleus; you can clearly see that it depends only upon the 2 decay coefficients NA and N B and sorry lambda A and lambda B and also it depends upon the initial concentration of A and B both isotopes.

Now, we can have several situations in this case, for the set of numbers that we have here that we optimize coming to be 1.386 and also it is interesting to note that the maximum concentration on maximum number nucleus for these just over 0.2 for this particular combination of parameters.

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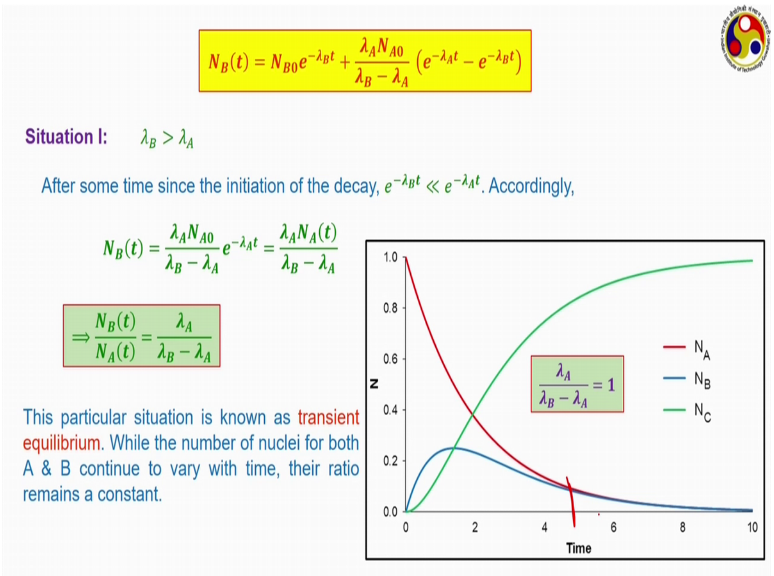

Now, we can have several cases here I have reproduced the expression for NB just for a easy reference. So, let first situation can be where lambda B is greater than lambda A; that means, the isotope B is getting decayed at a rate higher than the isotope A.

So, if we put that in a mathematical expression after some reasonable period of time, the exponential of minus lambda Bt will be extremely small compared to exponential of minus lambda At and accordingly the expression for N B reduces to this particular form final yielding N B upon NA is equal to lambda A by lambda B minus lambda A, which is definitely a constant.

Because please remember lambda A and lambda B both are unique to the remains A and B respectively and both of them are constants for the corresponding isotopes and therefore this particular ratio of lambda A minus lambda B lambda A divided by lambda B minus lambda A has to be a constant; whose value can be evaluated if we know the magnitude of lambda A and lambda B both and accordingly we can see that we can conclude that, the ratio of the number of nucleus of B and A after some period of this combined decay becomes a constant.

This particular condition is known as transient equilibrium and this is something we can always find in practice, like if we see the graph that was present in the previous slide you can see from sometimes somewhere here NA an N B are basically this 2 lines are overlapping with each other, because if you remember here while drawing this curves we have considered lambda A to be equal 2.5 and lambda B to be equal to 1.

Therefore the this particular ratio lambda A upon lambda B minus lambda in this case is equal to 1; that means, the number of isotopes of A and isotopes of B they will remain the same it does not mean that N A and N B are becoming constant rather the rate at which NA is going to change the same rate N B is also going to change, after some initial period of development which has been found here. Putting different values of lambda A and lambda B we can get different slopes for this curves, but the ultimate conclusion is whenever lambda B is greater than lambda A after some period of initial development, the ratio of the nucleus will become equal to a constant.

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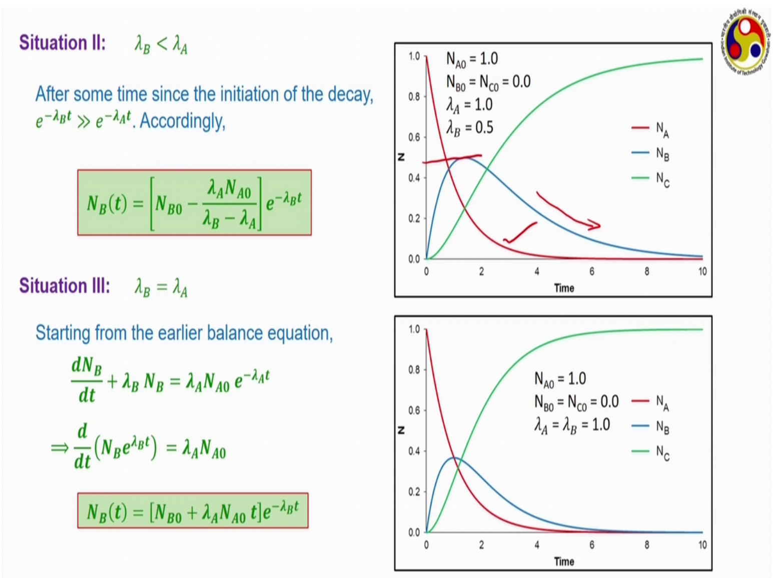

Now, we have the second situation where lambda B is less than lambda A after some period of initial development, now the exponential of minus lambda At becomes negligible, accordingly we get this party expression of N B and corresponding graph is this, which has been plotted considering lambda a to be 1 and lambda B to be 0.5 measure is more or less similar, but interesting observe here that the maxima in B is much larger, more at least double compared to the previous situation and that can be understood from our senses because here lambda a is greater. So, the rate of production of A is definitely larger compared to the rate of decay at least during the initial period, when the constant number of NA nucleus is quite high.

But once we reach this particular zone now number of N nucleus is quite small. So, despite lambda A being large the generation rate of the isotope B keeps on reducing giving an overall decaying profile of this isotope B, but C as usual keeps on increasing continuously and now the very interesting situation where we can have lambda A and lambda B to be equal to each other. Now the previous mathematical expression we cannot apply here because, that lead us to a 0 by 0 kind of situation, rather we can go back to the earlier balance equation to write something like this and we can straight away solve this again by multiplying both side with A to the power lambda Bt, we get this particular form and finally the corresponding expression of NB as something like this.

So, if we represent graphically this is the graphical form that you are getting which has been plotted considering both lambda N lambda B to be equal to 1, in this case again the maxima is somewhere in between the previous 2 cases that is expected and here the optima optimum time will have a different expression. which we can again obtained by maxima in this particular function in NB and that will come to be lambda B inverse, here for the given combinations of lambda N and lambda B this is coming to be equal to 1. I would urge you to develop this particular mathematical, form that is a just straight forward differentiation of this particular expression with respect to time and setting up to 0, which should lead to the t optimum of lambda B universe to the power minus 1.

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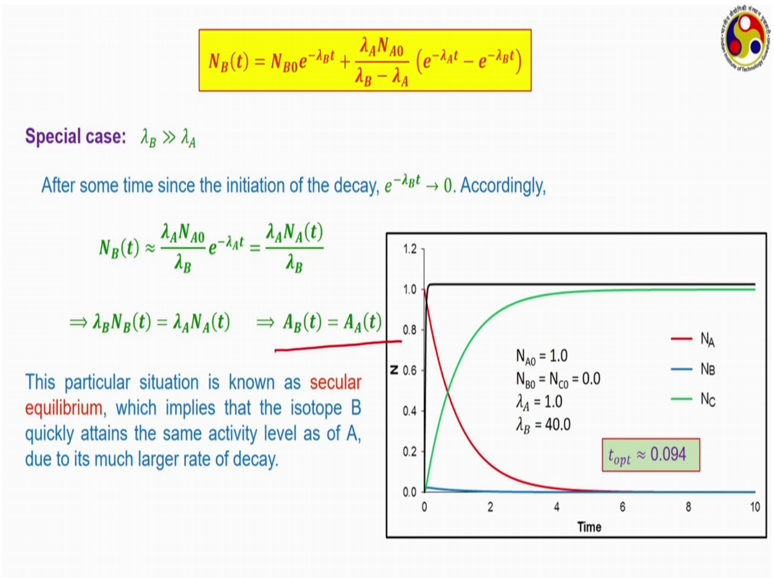

Now, we have a special case when lambda B is much greater than lambda A, if we prove this numbers through the expression original expression for lambda B, after some period of initial growth e to the power minus lambda B t tens to 0 and accordingly we have this mathematical development of lambda BNB is equal to lambda ANA or activity of B to be equal to activity of a these are very important relationship, this is what we call the secular equilibrium which I have mentioned couple of slides back.

The isotope B quickly attains the same activity level as of A due to it is much larger rate of decay, like if we see that graphically here we have the same 3 lines the red 1 corresponds to NA and the blue 1 which is hardly visible which is hiding somewhere here, it is N B the green 1 is N C; because the rate of decay of B is much larger while plotting this we have used lambda A equal to 1 and lambda B to be equal to 40, the B nucleus is getting a decayed as soon as it is generation initially a isotope being very large that is why it appears for a very short periods somewhere here, but after that it starts getting decayed at a very first fast rate and therefore we can hardly see B it can be almost assumed that the A is getting converted nearly directly to the isotope C.

In this case the time optimum comes to be 0.094 which is extremely small and therefore the whenever we are talking about very large difference in the activity or the I should say the decay constants values for 2 isotopes, particularly when the daughter isotope is having much higher rate of decay compared to the parent, then the daughter itself may almost vanish from the picture and lead to say similar activity level for both the parent and daughter.

So, that secular equilibrium condition we can be safely use whenever you are talking about an isotopes with extremely, a daughter with extremely small or extremely decay constant or extremely small half life, like for parents U238 and t h 232 they have very large half life and extremely therefore extremely small decay constant. So, in really their daughters will have much larger decay constant compare to them, leading to the appearance of this secular equilibrium.

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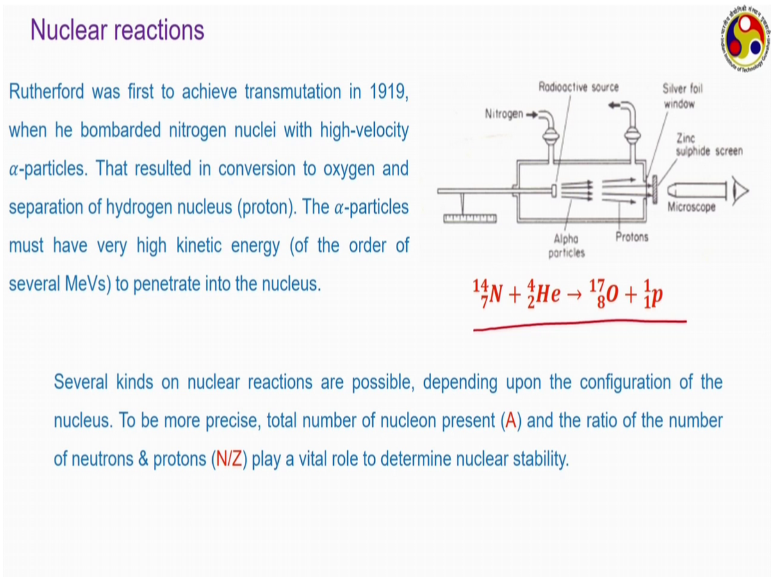

So, we have discussed a bit about mathematics so far, let us now come back to the phenomenon of radioactivity now radioactivity or corresponding transmutation is a phenomenon that was the first achieved in the laboratory scale by Rutherford in 1990, when he bombarded his nitrogen nuclei's some nitrogen nucleus is high velocity alpha particles and that resulted in conversion to oxygen and also release of proton; actually this is the experiment by virtue of which he proved the existence of protons as well.

But this particular nuclear reaction is given by this famous form, where we have nitrogen and helium nucleus which is the alpha particle as I have mentioned in the previous lecture and on the right hand side we have an isotope of oxygen O17 plus proton, this is first men you can say the first manmade or human controlled transmutation reaction that was reported or that has been reported; of course, everything was still not controlled by that time, but still it was done at the laboratory scale and therefore this can be considered to be a pioneering experiment in case of the transmutation phenomenon and another point to note here that here Rutherford used helium nucleus that is alpha particle to break up or the nitrogen nucleus.

Now, alpha particle if you remember carefully they comprises of 2 neutrons and 2 protons, therefore they are also positively charged they are having 2 units of positive charge. Now we are trying to break the nitrogen nucleus where we are having 7 number of photon new and 7 numbers of neutrons. So, that is also quite strong that is also carrying strong amount of positive charge we are trying to break that with another very positively charged particle and hence as the alphabetical approaches this nucleus it will be facing large amount of repulsion force because, of their identical sense of their charge and therefore the this particular reaction that is the alpha particle breaking the nitrogen nucleus is possible, only when the alpha particle has very high kinetic energy of the order of several mini volts, then only it is able to penetrate into the nucleus of nitrogen and cause this reaction.

But 1 thing to point out here this is not the only kind of nuclear reaction that is possible, there rather there are several kinds of nuclear reaction possible which we shall be discussing in the subsequent slides, but which kind of reaction that is going to take place in a political situation depends upon mostly upon 2 factors, 1 the configuration of the nucleus itself or I should say the number of nucleon present in the nucleus.

And second the ratio of the number of neutrons to protons, both are related to the configuration of the nucleus or and for a given nucleus both of them are generally known phenomenon and standing at present time; we can more or less predict what kind reaction 1 particular nucleus is going to have, just been knowing the number of nucleons present there and also the second one very important the ratio of the number of neutrons and protons.

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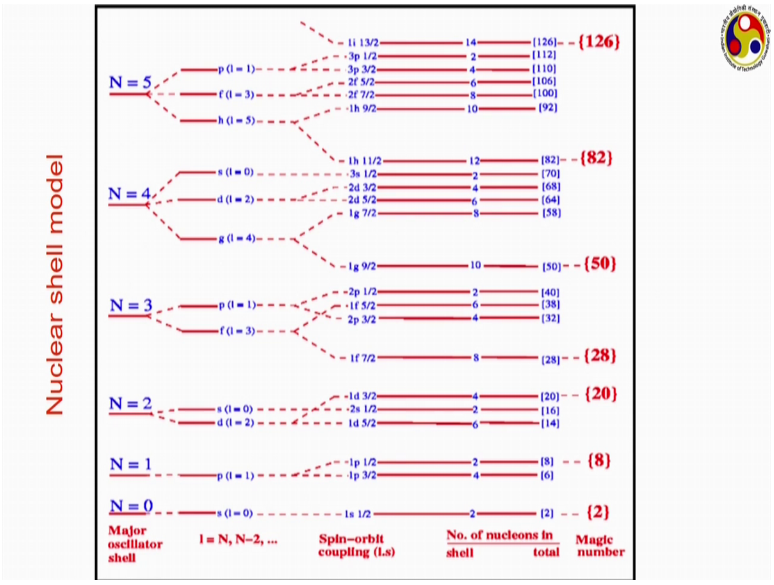

This is something called the nuclear shell model, now we are not going to enter into the detail of nuclear physics because that is far beyond our scope, but just for your information there are several theories of the structure of a nucleus and nuclear shell model is a very popular theory of their, which postulates that the neutrons and protons basically the nucleons are placed in several oscillating cells inside the nucleus, quite similar to the electrons in the outer orbits.

But the interesting thing is the last column here something called the magic number, the magic number refers to a certain number of nucleons present in certain orbits or I should say when the total number of nucleons are any of these numbers mentioned here that is starting from 2 going to 8, 20 to 28, 50 to 82 and 126 then that corresponding nucleus will be highly stable 1.

I repeat a nucleus is having any of this number of nucleons in it is nucleus, it is expected to be highly stable as per the nuclear shell model, but of course this is a very restricted case and most of the practical isotopes are not having nuclear sequel to the magic number and therefore they are vulnerable from this point of view and then comes the second factor which is the ratio of the number of neutrons and protons.

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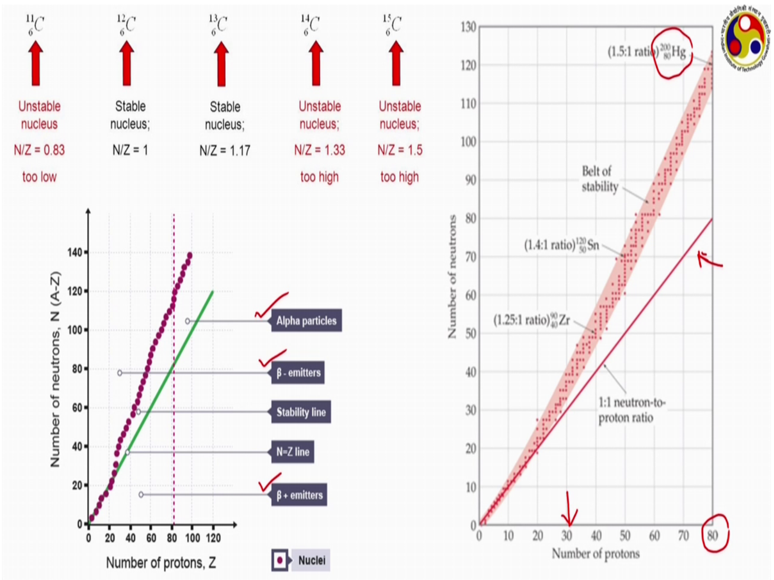

Now, look at what we have here we are trying to compare 5 different isotopes of carbon being carbon all of them are having 6 protons in their nucleus, but the number of neutrons vary; the first 1 is C 11 where we only 5 neutrons and the last 1 is C 15 where we have as many as 9 neutrons and it has been found that while 6 C 12 and 6 C 13 are very stable from nuclear reaction point of view, 6 C 12 having equal number of neutrons and protons so a ratio of 1; whereas, 6 C 13 is having just 1 neutron more than the proton and so N by Z ratio of 0.17 both of them are highly stable from radioactivity point of view.

But when we go to a low value of N y Z like for 6C11 when there are 5 neutrons, so giving an N by Z value of 0.83 or when we go to the territory of large N by Z ratio like for 6 C 14 or 6 C 15, 6 C 15 has 6 protons and 9 neutrons giving an N by Z ratio of 1.5 all both these 2 situations are generally quite unstable from nuclear reaction point of view; therefore, it we can conclude that and not only from this by considering several other isotopes that we can found in nature, any N by Z value just at 1 or slightly above 1 is quite stable, but N by Z value less than 1 or much higher than 1 generally leads to some kind of unstable nucleus.

This is 1 graphical representation again a phenomenological observation, where this particular line is the N by Z equal to 1, line that is equal number of neutrons and protons present in the nucleus and the orange band that is shown just on top of that that is stable band. So, the nucleus which are having N by Z ratio lying with in this band they are generally quiet stable from nuclear reaction point of view, but anything is lying outside that orange band is expected to be unstable.

So, for low value of atomic number that is up to something like this range, of atomic number of 30 28 around that we can see modulus N by Z equal to 1 is the condition for stability, but as we go to heavier elements N by Z ratio keeps on increasing and generally for an a Z value of 80, the corresponding stable limit as we can see particularly for these isotope of mercury 88 h g 200, where we have 80 protons and 200 neutrons giving a ratio of 1.5.

As we keep on that is also stable; that means, as the atomic number keeps on increasing the stable value corresponding or the N by Z ratio value corresponding to the stable nucleus that also keeps on increasing and reaches around 1.5 for such heavy nucleus. But the nucleus which are lying outside this band they try to go through some kind of nuclear reaction, which allows them to come back within this band and accordingly we can find several kinds of nuclear reaction like shown here, just similar but instead of that orange band we are having more a brown colored line here.

so the elements which are having N by Z ratio higher than this, that is more neutrons compared to the protons required for the element to be stable they are beta emitters or they go through the beta decay kind of reactions; whereas, the elements which are having low N by Z ratio that is they have more protons compared to the number of neutrons, they go through a beta positive emission or positron emission we shall be coming to this shortly and only for heavy isotopes that is when the atomic number is 80 or even higher we can have the alpha decay or emission of alpha particles.

So, we can clearly see there at least 3 kinds of nuclear reaction possible as per this particular curve, 1 thing we have to keep in mind that when we are talking about a very light isotope N by Z equal to 1 is sufficient, but when you go to a heavier isotopes the stable when corresponds to a higher value of N by Z can be around 1.5, that we can understand by considering the presence of more number of protons; as the number of proton keeps on increasing their repulsive force also keeps on increasing and to counter that repulsive force we need to have sufficient amount of binding energy present in the nucleus and that can be present only by adding more and more neutrons in this, but of course even new more number of neutrons then required will again lead to an unstable situations.

So, depending upon where the whether the (Refer Time: 31:19) ratio is higher than required or lower than required we can have 2 different kinds of radioactive reactions and of course we can also have alpha reactions or alpha decay which is a generally followed or identified for heavier isotopes only.

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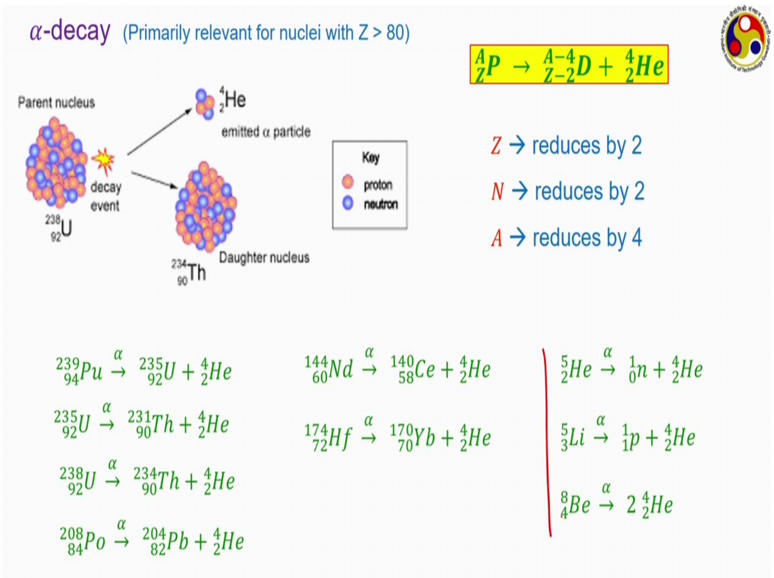

So, this is alpha decay which is primarily relevant for nuclei with Z greater than 80, but that does not mean that it does not happen below Z for Z less than 80.

But it is more prevalent when Z is greater than 80, this is an example of that a parent nucleus in this exam we have a uranium 238 alpha decay means very stable helium isotope that is 2He4 which is going out and because of that we have a transmutation process, where we have a daughter isotope forming with 2 protons and 2 neutrons less than the original 1; it can be represented form like this which we have seen in the last 1 also. If the parent is having Z number of protons and a number of a minus Z number of neutrons then the daughter will be having Z minus 2 number of protons and a minus Z minus 2 number of neutrons giving a mass number of a minus 4 plus of course the helium.

So, a helium decay leads to the reduction in Z by 2 because, 2 protons are going out reduction in the number of neutrons by 2 because, again 2 number of neutrons are also going out of the helium and therefore a total reduction of 4 in the mass number of this daughter isotope. Here are some examples related to heavy nucleuses we have plutonium 94 to the 239 undergoing alpha decay to form uranium 235, something a very common reaction in nuclear power plants.

Similarly, another common reaction U235 going through a alpha decay and forming Th231 and a few others there are a couple more examples which are for isotopes less than 80 and they lie in the group of rare earth materials, where we have Nd144 going through an alpha decay to produce C140 and another half neon of 174 producing Yb170 and some very interesting example in this particular group here for extremely light isotopes which are generally not associated with alpha decay, but what we can see here the first 1 is another isotope of helium itself helium 5, which can release 1 neutron and thereby gets converted to a helium 4 isotope.

So, we can visualize this in either way, we can either call this an alpha decay or you can also this as release of a neutron and lithium 3Li5 is again going through a process where you are getting a proton and a helium. So, it can also be talked about other as an alpha decay or a protein separation yes and the last 1 is very interesting exam of 4B8 here beryllium is going through alpha decay process to produced not 1, but 2 alpha particles that is 2 helium isotopes. But we definitely have such examples listed here in the second and third column, but a more practicable are the 1 presented at the left, that is relevant to the isotopes having a mass number of 80 or greater than that.

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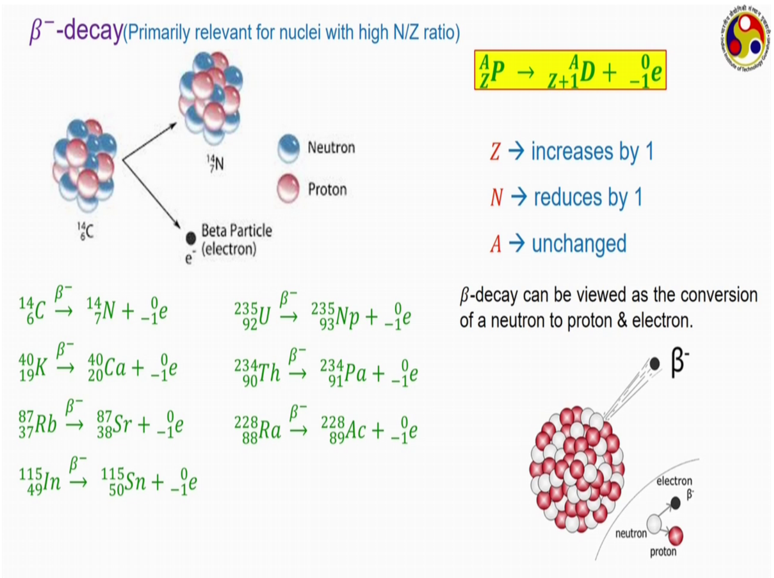

Now, I come to the beta decay, beta decay is relevant to any kind of nucleus heavy or light, but those which are having a high end 2 Z N by Z ratio, as a beta decay happens like on example shown here we have 6C14. So, 6C14 as mentioned in the previous slide here we have 6 carbons in this carbon isotope have 6 protons and 8 neutrons. So, the ratio of neutron to proton is 8 by 6 which is quite high and therefore it goes through a beta decay process, means it releases 1 electron from the nucleus and gets converted to a 7 N 14 isotope and this particular isotope of nitrogen is having now 7 proton and 7 neutron.

So, it is N by Z ratio of 1 and perfectly fine from nuclear reaction point of view, this can be the corresponding form for the general reaction; where the parent is having Z as the atomic number and a as mass number as we are having a mass of minus 1 loss in the atomic number point of view. So, the daughter will be having a Z plus 1 as the atomic number and a mass number will remains unchanged.

Accordingly we can summarize the beta decay as an increase of 1 in the atomic number and decrease of 1 in the number of neutrons. So, the total atomic number remains unchanged, these are certain examples ranging from very light to very heavy elements 6C14 going to a beta decay process and whenever you are having 6C14, whenever you are having a beta decay you have to remember that the daughter will be having 1 proton more. So, 6C14 will produce something which has having atomic number of 7 that is nitrogen and mass number will remain unaltered.

So, on the right hand side we have 7 and nitrogen plus the electron, similarly we have 3 other reactions these are a few for the heavier nucleus like U235 TH234 or radium 228 like the middle 1 may be the thorium 234 going to a beta decay to produce Pa 90 to 234 which is having 91 protons in it.

But it is quite interest to think that the nucleus is consisting of protons and neutrons and there are no electrons inside the nucleus, then how a nucleus can release beta particles or electrons there that is a very puzzling question, the answer lies here means the beta decay can be viewed as the conversion of 1 you have to think about which particular which element is more in the nucleus, of course neutron is more. So, the beta decay can be thought about a process of reducing the number of neutrons and increasing the number of protons and which can be achieved by converting on neutron to a proton and an electron such an element like this.

So, as the neutron gets converted to a proton and an electron, it is mass will be carried by the proton and neutron is electrically neutral, but the proton that is the 2 products here the proton is having plus 1 charge and electron is having minus 1 charge. So, that also remains balanced, but 1 issue is that the mass of proton neutron and electrons are given in a module 1, if you put all of them here you will find there is a significant amount of mass defect.

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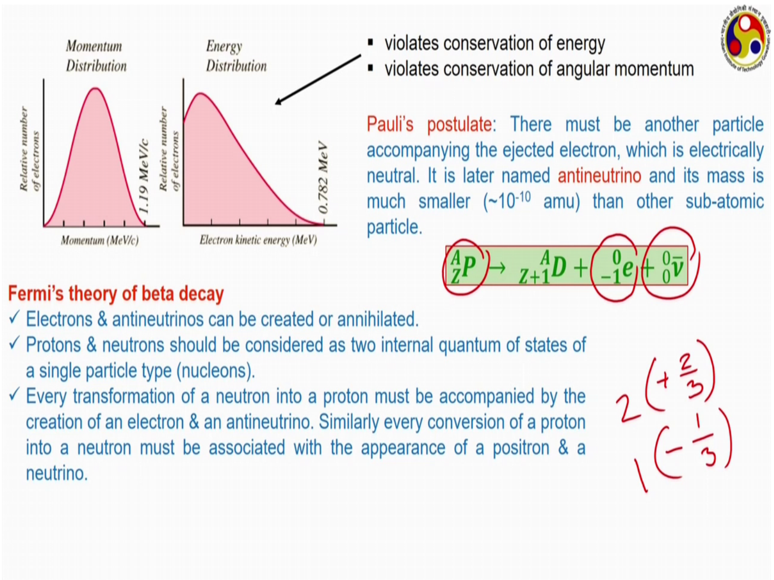

And another factor that has been observed that during beta decay the momentum distribution energies during that we get they are very regular curves, showing the distributions like this which is not true for other kind of radioactive decays, like for incase of alpha decay we get several bands with the different amount of energy levels and therefore this kind of behavior violates the consumption of energy and also the violates the conservation of angular momentum and therefore there must be something else which also is happening along in this beta decay.

That was first postulated by Pauli, who identified a particle which was named neutrino that time this is also accompanying the ejected electron it is electrically neutral and it is mass is extremely small of the order of 10 to the power minus amu compared to even electron also and then if we consider the presence of this neutrino and also amount of energy released during the beta decay process, then we can get a balance between the mass and momentum conservation and of course energy conservation as well.

So, the general expression or general mathematical form for beta decay, should not be the previous 1 whether this should be the correct form; where this parent ZPA is leading to the formation of a daughter plus 1 electron, the beta particle plus this is something earlier used to be called neutrino but now it is called antineutrino, where the term has been resumed in means showing respect to the presence of the electrons and neutrinos being the antiparticle of this electrons.

Here we have a 2 zeros along with this neutrino which represents this mass is 0 as well as it is charge is 0 and following the Pauli's postulates the theory of Fermi established the concept of beta decay properly, it is a very comprehensive or exhaustive statistical development, but we are just taking the gist from there. Which says that firstly the electrons and antineutrinos can be created or annulated during any such kind of beta decay process.

Secondly protons and neutrons should be considered as 2 internal quantum of states of a single particle type which is nucleons, basically again from nuclear physics points of point of view both type of nucleons comprises of quarks, there can be 2 types of quarks the up quarks and the down quarks. The up quark comprises of plus or carries plus 2 third element of charge where as a down quark carries minus 1 third element of charge; when we are talking about a proton a proton has 2 up quarks and 1 down quark in it is structure, which gives a total charge of 1 unit to a protons; whereas when we talk about a neutron for a neutron we have 1 unit of up quark and 2 units of down quarks giving it a total charge of 0 or making it electrically neutral.

Therefore the by just by conversion of this up quark to down quark or down quark to up quark, we can convert neutron to proton or proton to neutron and hence they should be treated as a similar kind of particle and the third point that we can get from Fermi's theory is that every transformation of a neutron into a proton must be accompanied by the creation of an electron and an antineutrino.

Similarly, when we are having the reverse process that is a proton is getting converted to neutron, that also must be associated with the appearance of a positron which is the opposite particle or of electron and a neutrino or it can also correspond to the disappearance of 1 electron and the antineutrinos.

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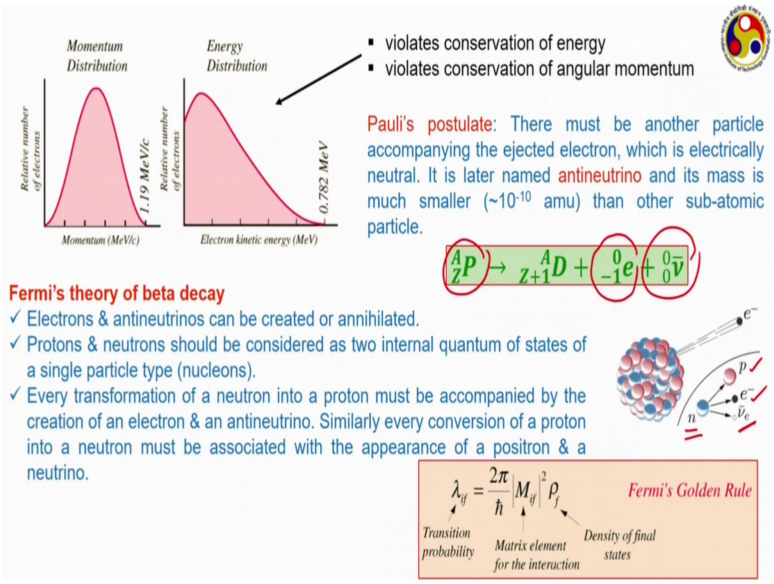

This now should be the correct way of representing beta decay, here we have the nitrogen which is getting broken into not 2 but into 3 components, now the first 1 is proton second 1 is electron there is a beta particle and finally, this is a new 1 that is a neutrino is or I should say antineutrino it is coming to picture.

The rate of this reaction is given by something known as a Fermi's golden rule, where on the left hand side we have this lambda just called the probability of transition from the initial state before decay to the final state after decay. Here rho f at the end is the density of the final state and m represents the coupling between the initial and final state and the age bar here is a Planck constant divided by 2 pi.

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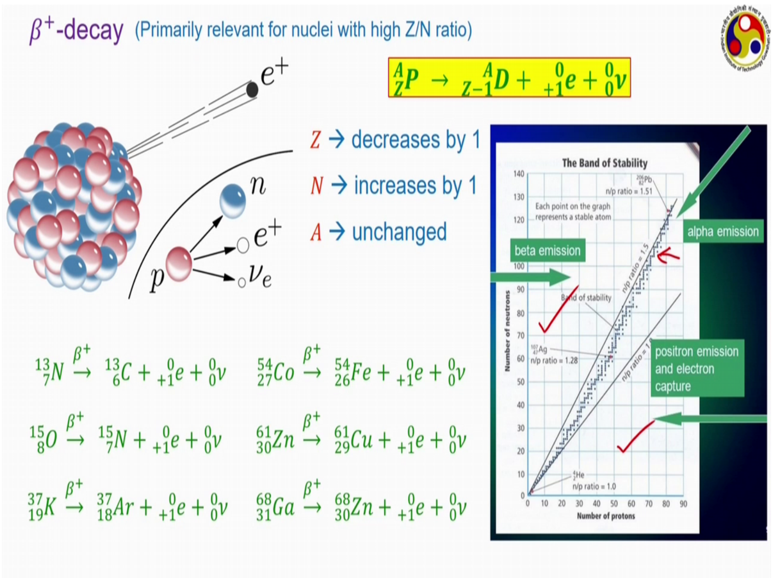

Now, beta decay is definitely the most common phenomenon that we can find in different nuclear reactions.

But there is a counter of that that is called the beta plus decay and also called the positron decay, positron is an anti particle of electron which is having the mass of the amount as of electron and same magnitude of charge but of opposite sense, that is a positron can we be viewed to carry for plus 1 amount of electrical charge, but it is mass is as the same as of electron.

So, positron decay or beta plus decay are associated with elements just it is a opposite situation of a beta minus decay or beta decay, the normal beta decay is associated with isotopes having high N by Z ratio. So, the beta plus decay is associated with nucleus is having a low N by Z ratio, here a proton gets converted to neutron or a I and also the electrons or I should say the positrons and neutrinos. So, this is the general for mathematical form we can write here the parent is having Z number of protons and a minus Z (Refer Time: 44:07) of electrons, number of electrons remains as it is or I should say Z a minus Z number of neutrons.

Now, because of this nuclear reaction total number of nucleons remains the same that is a, but total number of protons reduces by 1. So, the daughter is having Z minus 1 as it is atomic number plus we have a positron. So, by beta decay it is the opposite situation of electron decay or beta decay, this positron decay is associated with increase in Z by sorry decrease in Z by 1, increase in N by 1 with the mass number that is a remaining unchanged.

We are just going back to the diagram just to point out whatever we are discussing here, this is dotted line you can know which you can see here this is the band of stability . So, when you are talking about the beta emission or electron emission or beta minus emission often called, that is associated with isotopes having a large N by Z ratio. So, we are into this zone. But isotopes are having more number of neutrons compared to proton than required. Whereas, this positron decay is relevant to this particular situation, where the particles are having less number of neutrons or they are having excess protons compared to whatever required to have a balanced situation.

These are some examples like 7 N 13 going to have positron decay to form a 6 C 13 plus positron plus nutrients and there are a few other examples given on this slide.

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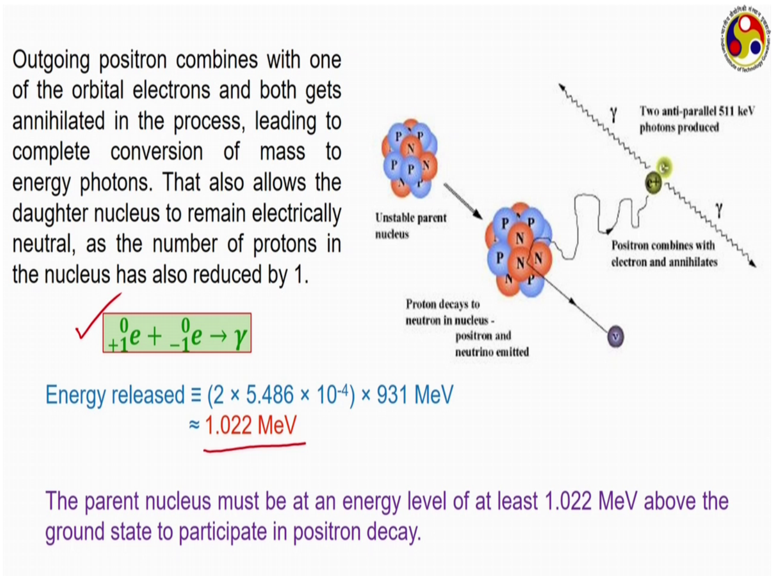

But one interesting situation is that whenever we have a positron decay, the number of protons has as you have seen in the previous slide the number of protons has gone down by 1 and one positron has come out of the nucleus that what to the positron then? And also let me go back once more let us talk about this particular situation.

Here initially we are having a nitrogen 13 isotope, which is having 7 protons and 6 neutrons in it is nucleus, and to make it electrically neutral of course, we are also having

7 electrons in the outside orbits. Now after the reaction is done we are having this particular isotopes 60 13; which because of the conversion of 1 proton to a neutron we it is now having 6 number of protons and 7 number of neutrons in it is nucleus. So, total number of nucleons remains to be 13 and the positron has come out.

But in the outer orbits we are still having 7 number of electrons; and if this electrons stays there that will make the entire atom electrical negative, but the positron that is carrying a positive way that is coming out. So, the position generally collides with the orbital electrons and both the orbital electron and the positron emitted by the nucleus gets annihilated by the process, leading to complete conversion of mass to energy. And because of that the daughter nucleus is also able to remain electrically in neutral.

So, this new reaction can be written like this where we have the positron first, which is coming out of the nucleus because of this beta plus decay, and then we have the electron from the orbits both getting annihilated and forming 2 photons of this gamma reactions or gamma radiation. Now as mass is getting converted to energy of course, that will be associated with large amount of energy release and we know that both electron and positrons are having same amount of mass.

So, if we use e equal to m C square then this particular reaction corresponds to an amount of energy release of 1.022 MeV. So, it is very important to note just having more number of protons or excess number of protons is not sufficient for an isotope to go through positron decay, rather it must be at an energy level which is at least 1.022 MeV higher than the base level, then only it is possible to have the positron decay. I repeat the parent nucleus must have this 1.022 MeV of energy, then only it can go through the positron decay process.

But what will happen when an isotope is having excess proton, but it is not having this amount of energy.

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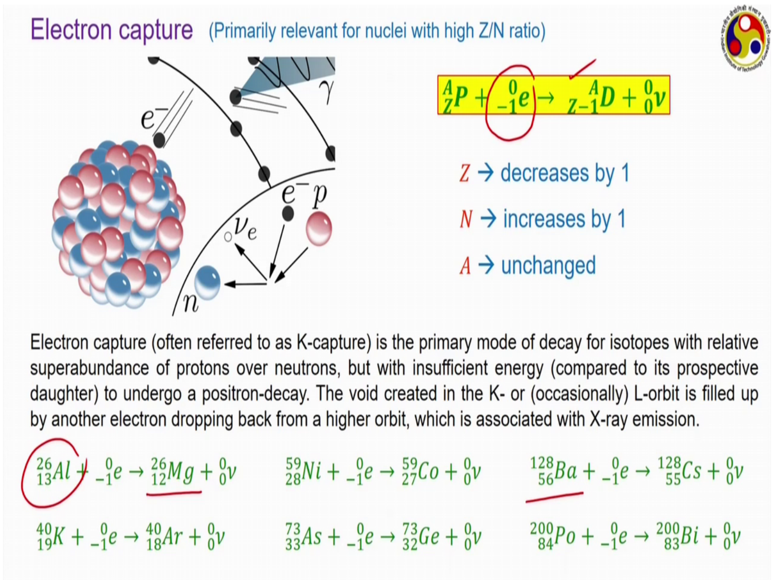

Then we have the other kind of reaction that is called the electron capture often called the K capture or L capture. It is an extremely interesting kind of thing reaction here the nucleus is having access proton, but it is not having enough amount of energy. So, that it can go through a positron decay then the it captures 1 electron from the nearest orbit 1 of the electrons from the orbit generally the k shell sometimes from the l shell, that is dragged back to the electron and now that electron combines with 1 of the proton that is present inside the nucleus leading to the formation of 1 neutron and also 1 neutrino.

So, electrical sorry the mathematical form will remain like this, where an isotope of Z a p is reacting with 1 electron mind you this electron is coming from the orbits, leading to the formation of this daughter which looks very similar to what we had in case of positron decay plus neutrino; but you have to keep in mind here in case of previous case we are having a positron coming out of the nucleus, and because and during that time a proton is getting converted to neutron.

Here also with electron capture also proton is getting converted to neutron, but no positron is coming out rather the n q particle of positron that is an electron is getting consumed by the nucleus. And once the electrons form the k shell or l shell is consumed the 1 another orbital electron which is rotating at some higher orbits will fall back to this orbit, and because and go to much lower energy levels. So, the energy excess energy that this electron is carrying that will be released to the surrounding in the form of x rays.

So, we know similar to the positron decay during electron capture also Z is decreasing by 1, that is number of proton is decreasing by 1, but total number of nucleons are remaining unchanged because number of neutrons has increased by 1. These are some examples of a starting with 13 A l 26 which is a consuming 1 orbital electron and getting converted to 12 M g 26 and we can have other several reactions involving potassium 40 nickel 59 and barium 128 here and several quite a few other reactions as well and. So, you have to keep in mind the difference between the positron decay and the electron capture in both cases we are having conversion of 1 proton to 1 neutron in both cases we are starting with a nucleus which is having excess number of protons and so, it wants to convert 1 proton to a neutron.

In both cases we are finishing up with a neutron a daughter sorry a daughter nucleus which is having a more number of neutrons compared to the parent, but in case of the positron decay the isotope or the nucleus is having good amount of energy at least something more than 1.022 MeV and therefore, it is able to convert 1 proton to an neutrons and eject 1 positron during the process whereas, in case of electron capture the isotope is not having that much of energy and therefore, it is join 1 orbital electron into it nucleus, and combining that with a proton to get a neutron as the final product.

All this 3 kinds of phenomenons that we have discussed, beta decay positron decay and electron captures generally fall under the category of beta decay. Yes and therefore, in several books and materials it will also find that beta decay can be of a 3 times that is beta minus decay or the conventional beta decay beta plus decay or the position decay and this electron capture or k capture.

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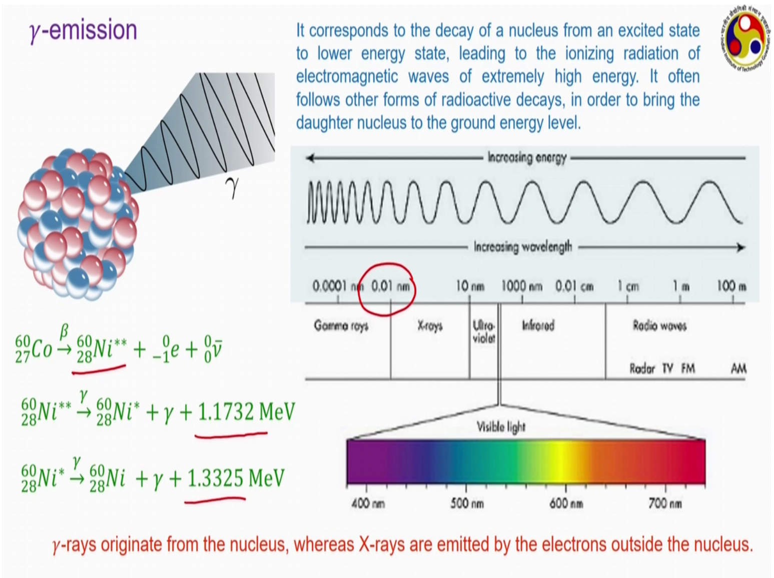

And the final the 1 that we have is the gamma emission; the gamma rays are electromagnetic waves of very high frequency of very extremely small wavelength.

So, gamma radiation generally is associated with all the reactions that we have discussed so far. Whenever we have a daughter nucleus formation that is generally at a very excited state and therefore, it releases that extra amount of energy in the form of gamma rays and comes to more level state or more ground state. Like the example here 27 60 cobalt is a going through a beta decay process a leading to the formation of this particular nickel 60 isotope, but that is at a very excited level. So, that goes through 2 levels of gamma radiation. In the first level it releases 1 gamma photon and 1.1732 MeV of energy, in the second step it releases another gamma photon and 1.3325 MeV of energy and following this 2 steps it is able to come back to the ground state.

So, by virtue of this gamma emission we basically are having isomer formation. If you remember the beginning of this module I mentioned about those terms isobars and isomer. Isomers are those which are having the same atomic number and mass number and number of neutrons, but they are difference is only in terms of energy level and gamma emission corresponds to that gamma rays are electromagnetic waves of extremely small wavelength it is the smallest among all of them like you can see here we are talking about 0.01 nanometer and lower than that where the zone of domain of gamma rays. So, it is much smaller than x rays also from wavelength point of view.

Therefore they are as the such kind of photons are the having in the energy of such photons are proportional to their frequencies using and we can calculate that as e equal to h into nu. So, gamma rays are extremely carry extremely strong amount of energy. So, their radiation point of view they are very much hazardous, and also they can penetrate virtually through almost everything. Whereas, alpha particles are heavy and they can be stopped by very small obstacles like a piece of paper. Beta rays are they are much smaller. So, they have more penetrating power compared to alpha particles, but the gamma they are that is nothing compared to the gamma rays and another important another important difference that you are having between gamma emission and the electron capture that we are having the previous case.

If you remember carefully I have mentioned after the electron capture is done by the nucleus, 1 electron from the higher orbit falls back to the k shell to fill up the void and during that the excess energy of that electron coming falling back from the higher orbit is release in the form of x rays. Where as in case of gamma emission an excited nucleus is falling back to it is ground level by gamma emission, and that is a big difference between x rays and gamma emission. Gamma rays originates from the nucleus whereas, x rays are emitted by the electrons.

Earlier days the difference between gamma rays and x rays where are drawn more in terms of the wavelengths, but nowadays we go more for this particular difference or nucleus is the place from where the gamma rays are originated whereas, whenever we have some radiation that is coming only from the orbits or from the orbital electron movements that is has to be x rays.

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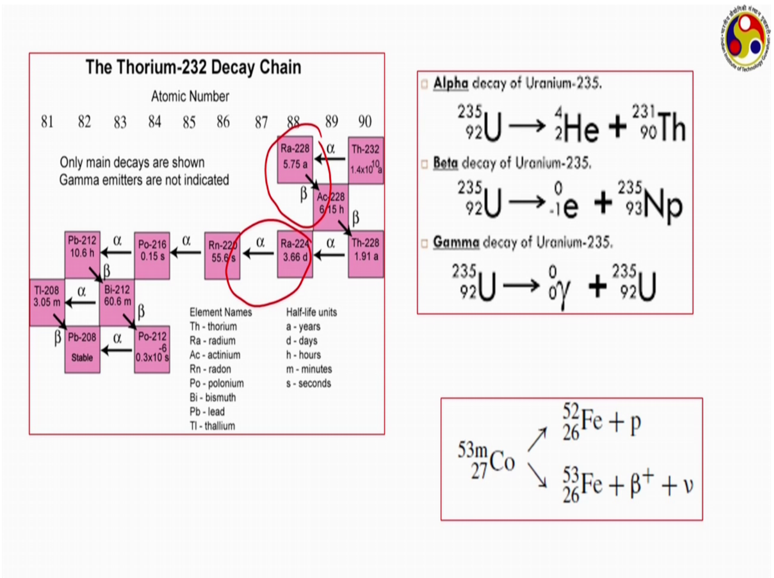

So, we have seen different kinds of nuclear reactions, but interesting thing to observe there I am going back to the sodium 232 decay chain that we have seen earlier, you just look at here. If you are a radium 228 is going through a beta decay process whereas, later in this chain here radium 224is going through an alpha decay process.

That is radium of course, there are 2 isotopes we are talking about can undergo different kinds of decay process here we have another one. Now instead of different isotopes we are basically the same isotope the uranium, uranium 235 only and depending upon the condition it can have all the 3 alpha decay, beta decay or gamma radiation from some excited states. Here I have another example a the cobalt 53 it can either go through a reaction which produces iron 52 and releases a proton, or it can go through a positron decay process producing iron 53.

That means the same isotope under different condition can go through different kinds of nuclear reactions and therefore, this new conditions that needs to be properly judges upon and there has to be some kind of properties of this isotopes as well, which governs exactly what kind of nuclear reactions a particular isotope is going to happen.

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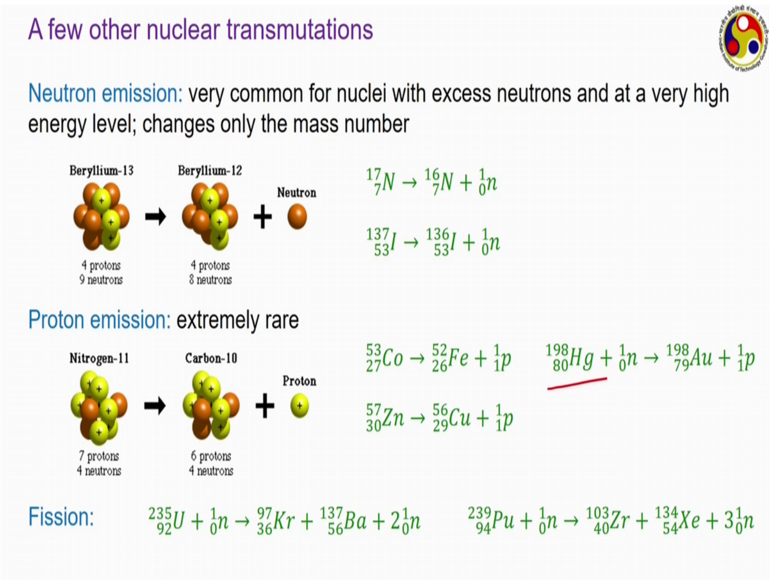

Finally before closing a few other nuclear transmutations that are also present along with this alpha beta or gamma decays, the neutron emission is very common for nucleus with excess neutrons particularly at the heavier nucleus and also at a very high energy level, it changes only the mass number atomic number remains the same like in the first example beryllium 13 is releasing on neutron, and from getting converted to beryllium 12. So, just another isotope of the same element couple of other examples here some very very rare case, we can also have proton emission; like in this example of nitrogen 11 ejecting 1 proton getting converted to carbon 10.

If you are couple of other examples which you can check out and a very interesting 1 where we are actually starting with a mercury isotope, and striking that with a neutron and getting at the result we are getting gold 198 plus 1 proton. This is something that was the dream alchemist for the to produce mercury from gold, and by virtue of this transmutation which we can control now a days this is definitely possible.

So, the first last one of course, is the conventional fission reaction couple of examples I have given here, but you shall be discussing more about this in a later module. So, that gist here is that a nuclear and radioactive isotope can go through different kinds of nuclear reactions, but exactly what kind of reactions it can go through depends upon several factors, and also several properties or characteristics of the isotopes. And in the next lecture where we are hoping to finish this particular module we shall be discussing upon those characteristics of the isotopes are only. So, thanks for your attention today and let us just wait for some time for the next lecture.

Thank you.