Fundamentals of Nuclear Power Generation

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Lecture – 03
Radioactivity and radioactive decay

Hello friends. Welcome back to our mooch course on the fundamentals of nuclear power generation. Today we are going to start our second module on the very interesting topic of radioactivity and nuclear reactions. I hope the module 1 has gone down well and you have understood the basics of the topic of nuclear power generation. If you remember carefully in the module 1, we discussed only a few fundamental terms and concepts associated with nuclear power called atomic power. Actually in this particular juncture I should mention clearly that the term atomic power. While it is a very common terminology used in several different kind of resources that you will find.

It is actually not a correct representation of whatever we are discussing here. Because, like we have seen in the last set of lectures or in the previous module that this entire discussion of nuclear power generation is associated with the nucleus. The source of energy is actually associated with the mass defect the concept of mass defect. Whenever we have a nucleus it is actual mass is a always found to be slightly less than the individual mass of his constituents and that particular difference is termed mass defect and that is generally visualized to have converted to energy and is able to bind all the nucleons together in a very small volume.

That energy is called binding energy. And whenever a nucleus breaks into it is constituents that binding energy is released. So, this entire discussion on nuclear power generation is associated only with the nucleus and it has nothing to do with the electrons that are orbiting around the nucleus. Therefore, it is not correct to call the same as atomic energy. And we should be sticking to this term nuclear power generation and nuclear energy only.

Now, in the previous module it was mentioned that there are 2 common types of nuclear reactions fission and fusion. Depending upon their mass number any unstable nucleus wants to go through some kind of reaction which gets it is binding energy per nucleon higher close to the maximum level possible and for which they always try to go towards the mass number around 60. Accordingly those who are having a low mass number participated in fusion reaction and those who are having higher mass number participated in fission reaction. But none of those, fission in particular are spontaneous in nature. A nucleus cannot participate in a fission reaction on it is own rather some kind of external agent or external influence is required.

Now, the details of that mechanism we shall be discussing a later chapter or later module, but for this moment.

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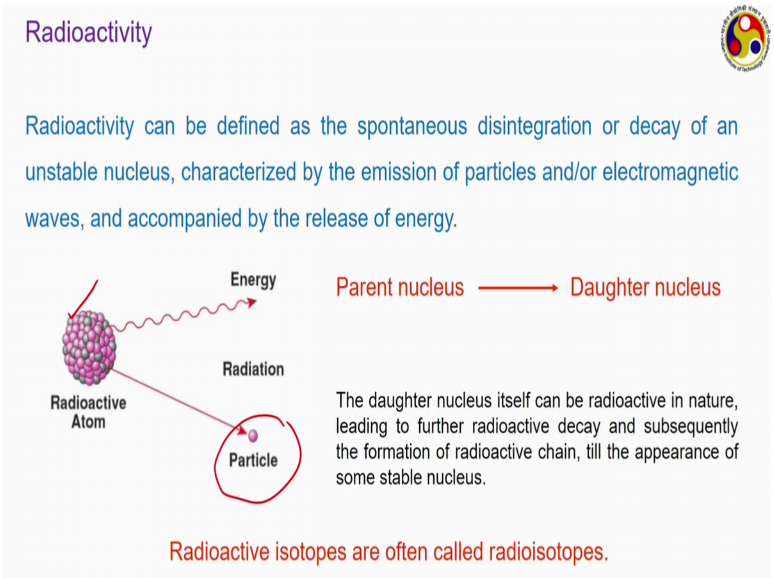

Let us focus on something that is more spontaneous, which is radioactivity. Radioactivity can be defined as the spontaneous disintegration or decay of an unstable nucleus which is generally characterized by the emission of particles and/or electromagnetic waves and also accompanied by release of large quantity of energy.

So, it is a spontaneous phenomenon because of which one nucleus gets converted to another nucleus. The nucleus with which it starts in this case this particular one we call that parent nucleus and the product nucleus is generally termed as the daughter nucleus. And this particular conversion of one nucleus to some other nucleus is always associated with the emission of some kind of particle and also large amount of energy and of course, not only particles it can be just electromagnetic waves also whichever situations, but this is single step kind of reaction is generally not a very common one because most of them this daughter nucleus itself is radioactive in nature and that can undergo some further disintegration to produce it is own daughter.

Accordingly we may have the formation of a radioactive chain which starts from some very heavy nucleus and goes on through a series of different daughters. All of which are generally radioactive in nature. And that chain is able to finish or able complete only when we have some kind of stable nucleus form that is which is not radioactive and therefore, is not able to go through any kind of disintegration. The radioactive isotopes are often called radioisotopes and we shall be also using this particular terminology. So, a radioisotope can undergo spontaneous disintegration which we are calling as radioactivity and because of this spontaneous disintegration it produces some other kind of nucleus; that means, this phenomenon of radioactivity is associated with conversion of one nucleus to another one.

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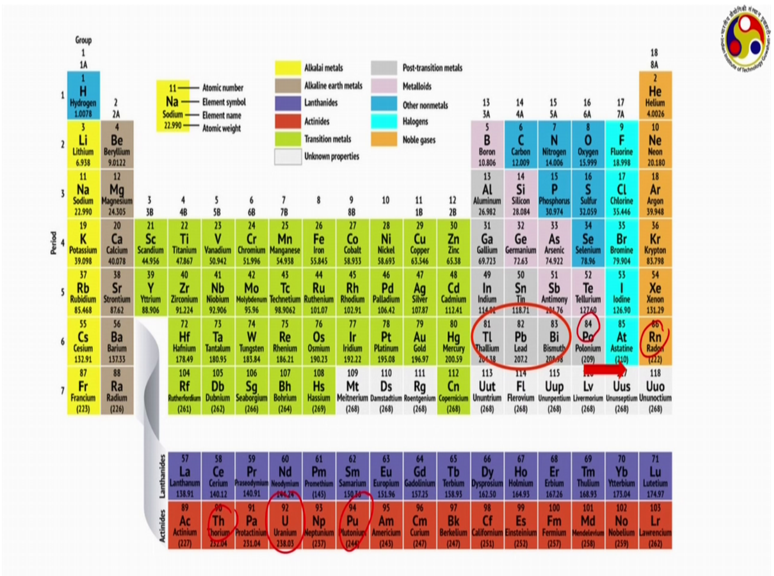

If we go to the periodic table something that we have used in the previous module also. Generally it has been found that some of the isotopes of this group of elements like thallium, lead and bismuth some of the isotopes are radioactive while some of their isotopes particular for lead and bismuth most of the isotopes are stable, but some of them can be radioactive, but for elements after bismuth that is elements having atomic number greater than 83, all their isotopes are radioactive in nature. That is starting from polonium having an atomic number of 84 towards whatever we have known so far. They are all radioactive in nature. They are all isotopes are radioactive in nature; that means, we are talking about elements like radon, elements like thorium, elements like uranium, plutonium which are very common in case of nuclear power generation. And of course, radium which I have not mentioned earlier. They are highly radioactive in nature and therefore, they cannot have any kind of stable isotopes. All the isotopes participated in some kind of radioactive decay or disintegration.

But it is not that only from this atomic number of 81 onwards we shall be talking about radioactivity. Rather several elements with very low atomic number can have radioisotopes or can have radioactive isotopes like some of the isotopes of sodium or potassium can be radioactive in nature. Corresponding examples will be coming later on.

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Transmutation

Transmutation refers to the conversion of one nucleus to another. As any isotope is characterized by the number of protons & neutrons in it, the term implies a change in either or both of them. Therefore, the process of nuclear transmutation can generate another isotope of the same element (change in neutrons) or isotope of a different element (change in protons and/or neutrons).

	isotopes	isotones	isobars	isomers
Same	Z	N	A	A, Z, N
Different	A, N	A, Z	Z, N	energy states
Example	$^{59}_{27}Co$, $^{60}_{27}Co$	$^{14}_{7}N$, $^{15}_{8}O$	$^{32}_{15}P$, $^{32}_{16}S$	$^{131}_{54}Xe$, $^{131m}_{54}Xe$

Natural transmutation was first reported by Rutherford and Frederick Soddy in 1901, as they observe the conversion of thorium to radium during their experiments.

And now we have a new term that is transmutation. Transmutation refers to the conversion of one nucleus to another that is by the radioactive reaction. Whenever one parent nucleus gets converted to a daughter nucleus that particular phenomenon we term as transmutation.

Now, transmutation can be of different kinds. We know that any isotope is characterized by the number of protons and neutrons in it. So, whenever there is change in either in the number of protons or in the number of neutrons or may be both that definitely is a transmutation. Therefore, the phenomenon of nuclear transmutation can generate an isotope of the same element when there is change in only in the number of neutrons or can generate altogether different element when there is change in the number of protons as well. And here I would like to introduce a few more terms isotopes was of course, discussed earlier which is very important from nuclear reaction point of view. An isotope we know that refers to nucleus which are having the same atomic number, but different mass number because of the presence of different number of neutrons.

We have got examples earlier. Here we have examples of 2 different cobalt nucleuses. Both are having 27 numbers of protons, but the numbers of neutrons are different and accordingly one is having a mass number of 59, other is 60. So, they are isotopes of each other, but now you have 3 more terms. First one is isotones. It refers to those nucleus which are having different number of protons in them, but the same number of neutrons and accordingly their atomic number or mass number both are different, but only the number of neutrons are same like here we have the examples of nitrogen and oxygen or one particular isotope of nitrogen and one particular isotope of oxygen.

The natural nitrogen isotope has 7 protons and 7 neutrons in it giving a mass number of 14; whereas, this particular isotope of oxygen is having as usual 8 protons, but it is having 7 neutrons and thereby mass number of 15. So, both this 2 isotopes nitrogen and oxygen they are having different mass number and different atomic number, but the number of neutrons are same and they are called isotones. Other is isobar. Isobar means, the mass number is the same, but their number of neutrons and number of protons in the nucleus they are both different, but because of their combination the mass number is same. Like here we have the examples of 2 isotopes. First one is phosphorus, which is having 15 number of protons and 17 number of neutrons. Whereas, the other is sulfur which is having 16 number of protons and 16 number of neutrons.

So, their mass number is same both are 32; however, their atomic numbers are different. This is isobar and final is isomer. Isomer basically refers to the isotope of the same element 2 different isotopes or. In fact, I should call that 2 different isotopes because they are having the same number of protons and neutrons. So, giving the identical values of atomic number and mass number; however, their energy states are different. Like here we have examples of 2 different xenon isotope. Both are having mass number of 131 and atomic number of 54; however, this particular is having m associated with it. Which actually refers to an excited state. That is it is having higher amount of energy content with it and whenever this second isotope of xenon undergo some kind of transmutation process which is associated with the release of only energy. It can get converted to the other one.

This topic of nuclear transmutation was first reported by Rutherford and Frederick Soddy in 1901 as they observed the conversion of thorium to radium during their experiments. It was completely a natural phenomenon which they observed.

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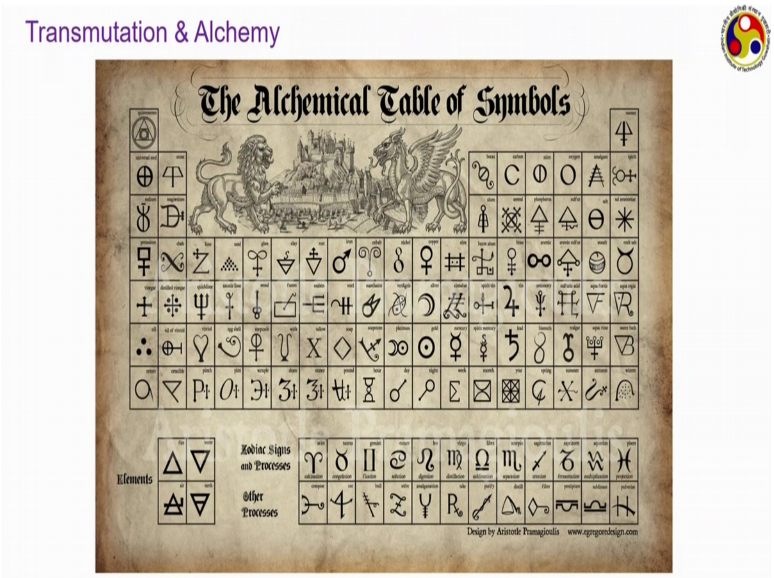

Before I come back to this I should establish the relationship between transmutation and alchemy. Alchemy is you probably know it is a dark side of science something that has been practice since as old as 9th or 10th century where alchemist try to have a some kind of process by virtue of which they can convert some less precious metal or element to some more precious one. Very common example can be the attempt to convert lead to gold or mercury to gold.

So, basically what they are trying to achieve that is transmutation only. To convert the nucleus of lead or mercury to the nucleus of gold. This is some kind of periodic table that they used to use that time. Now alchemy is a very much debated topic and it is a doubtful. Well, there were several alchemist claimed to have some kind of success. It is doubtful whether there was any kind of truth into that, but the phenomenon of transmutation when that was first identified by a Frederick Soddy and Rutherford. That is definitely the first reported phenomena of transmutation.

Actually there is a very funny a story associated with this. It is said that when they first observed this particular phenomenon of conversion of one nucleus to another Soddy screamed oh we have seen transmutation or we have got transmutation and it is reportedly said that Rutherford just tried to be very cautious and to ask him not to be. So, anxious or not to be so joyful. Because, they may get their head off thinking this is alchemy only.

So, alchemy is something that is generally not permitted in the scope of science and once this phenomenon of transmutation was achieved in 1901. Several researchers went after that proving that the conversion is definitely possible, but just to differentiate it from alchemy it has been proved that it is definitely possible to convert something like lead or mercury to gold. The process is generally associated with extremely high cost. Which is definitely much more than the actual price of gold and. So, there that is not something that is suggested from industrial point of view, but the objective of alchemist was completed different.

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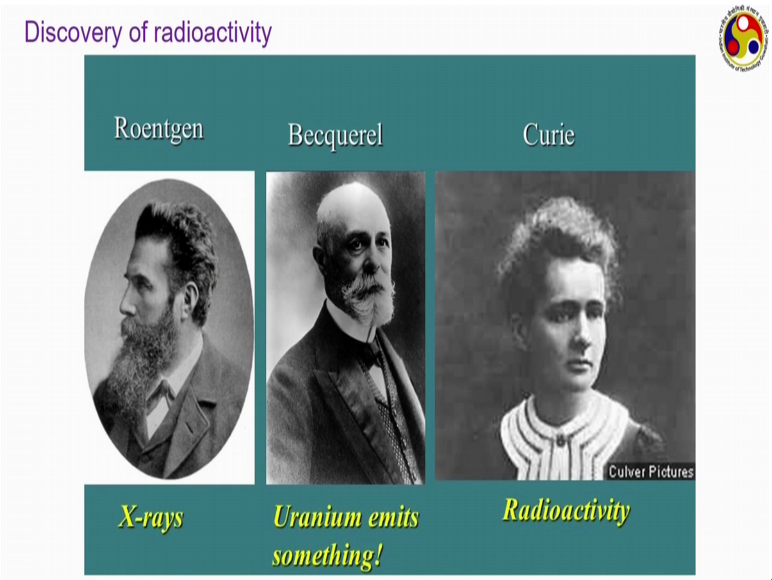

Now, the discovery of the phenomena of radioactivity probably started when the exposure invented by roentgen around 1895 and then came the experiments of Becquerel. Becquerel that time was the working with the phenomenon of fluorescence. And after hearing the discovery of X rays, he thought about checking or finding the relationship between fluorescence and X rays and therefore, he took his sample which is believed to be uranium sulphate. And put it into the sun light and also took a few photographic sales covered that with black paper and place that close to his samples.

So, if there is any kind of radiation emitted from the samples that will be detected by the photographic plates. There will be impression printed on the plates and. So, that will establish. I did feel that establish the presence of any kind of emissions, but unfortunately for him that time the skyline of Paris was cloudy for several days he was unable to do the experiment. And there finally, he had to abort the idea and he put his photographic plates and also his sample into a drawer. As there is no scope for doing any further experiment because of the lack of proper sunshine, those samples remained inside the drawer for several days, but probably just out of (Refer Time 14:31) some few days later Becquerel decided to develop his photographic plates and to his surprise he got something like this.

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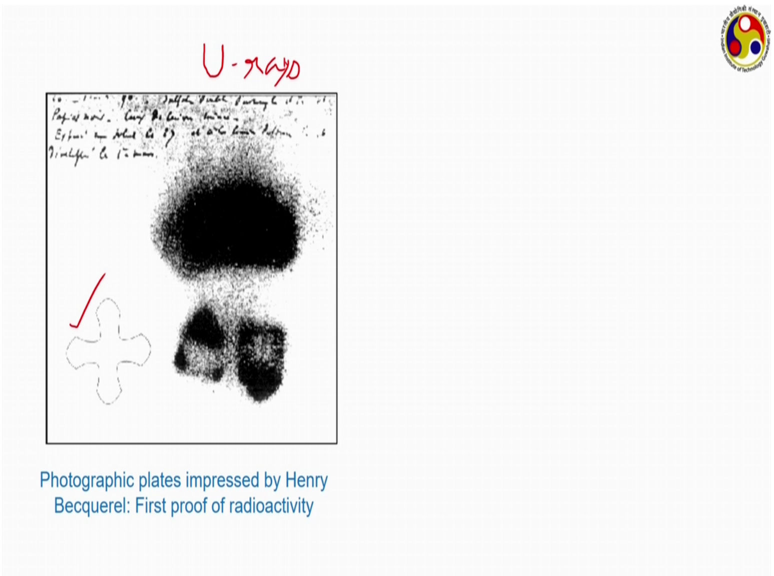

This is a believed to be the photo picture of this photographic plate which Becquerel developed. Clearly there was impression.

Now, this cannot be expressed. This impression proves that the sample has definitely emitted something and that has been captured by the photographic plates. In fact, here you can see a cross kind of structure. There was actually a cross that was tape on top of that photographic plates and those photographic plates and clearly an impression of that one is also visible, but this one cannot be expressed because there was no source of power and X rays requires some kind of energy source electricity or sun light or something. As per the belief that time and therefore, what Becquerel identified definitely something that is different from X rays.

So, he termed that as U rays. Whatever the Becquerel discovered that time, he called that U rays just to differentiate it from the X rays bit he was not able to characterize this for later on or that time he was unable to characterize this any further and what the contribution from Becquerel probably was limited only to this. From that point it was taken forward by the curie family. Basically, Marie curie started her PhD more or less at the same time around 1896 and decided to work on this U rays. Soon after along with her husband Perry curie she identified several things. Firstly, they identified that thorium is also radioactive similar to uranium and then they identified another element which was found to be at least 1 million times more reactive than uranium.

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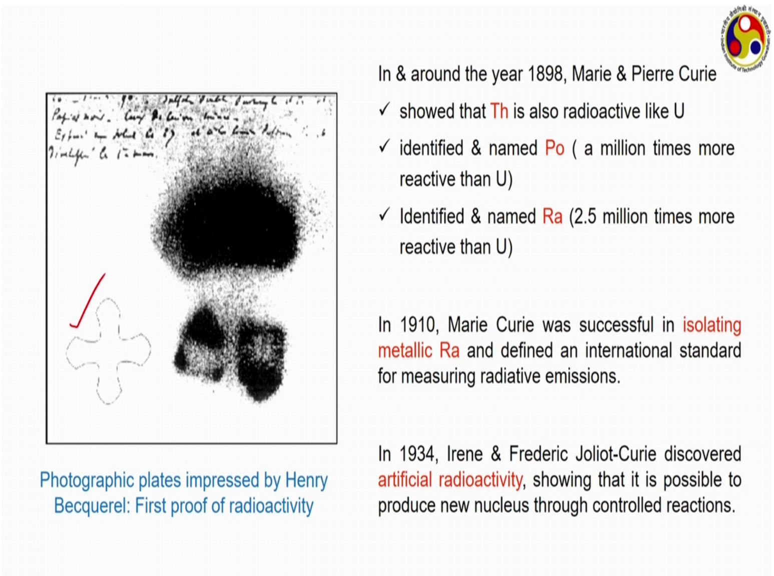

And in memory of their birth land Poland they name that polonium. And then they identified radium. Also the name was given by themselves only and radium was found to be 2 point 5 million times more reactive than uranium. The term radioactivity was also coined by them.

So, in acknowledgement of their discovery and their seminar work on this field of radioactive emissions Marie and Pierre curie and also Becquerel received the Nobel Prize in physics in 1903. Marie curie was the first woman to receive the Nobel Prize later on around 1910 Marie curie alone that time following the date of Pierre curie around 1906, she was successful in isolating the metallic radium and also defined an international standard for measuring the radioactive emissions. Now again in acknowledgement to her work in isolating the metallic radium, she received the Nobel prize in chemistry I think in 1913 and she remains to be only one of the 2 persons, who have receive Nobel prize in 2 different disciplines.

There are several works followed by different groups of researchers on the relative emissions, but that time radioactivity was something purely natural. That is people just where able to observe the reactivity or emission coming out of different elements, but was not able to control that radiation. Only in 1934 Irene the daughter of Pierre and Marie curie, she along with her husband Frederick Juliet curie discovered the phenomenon of artificial radioactivity.

It is actually believed that iron and Frederick Juliet curie discovered the sub nucleon or sub nucleonic particle neutron before James Chadwick in 1932, but they were not able to characterize that properly and Chadwick received the Nobel prize, but Irene and Frederick Juliet curie jointly received the Nobel soon after the discovery of artificial radioactivity. Because this is the discovery which showed that it is possible to control the radioactivity. And therefore, it is possible to control the phenomenon of transmutation; that means, if we can provide proper conditions we can convert one nucleus to something else as per our wish almost. That is definitely something path breaking, which shall led to this led to several kinds of discoveries in future.

Now, you are talking emission from the particles. Commonly in or emission from the parent nucleus, commonly there are 3 kinds of emission that we are generally accustomed in alpha, beta and gamma emissions of often called the a b c of radioactivity alpha particles are nothing, but helium nucleus.

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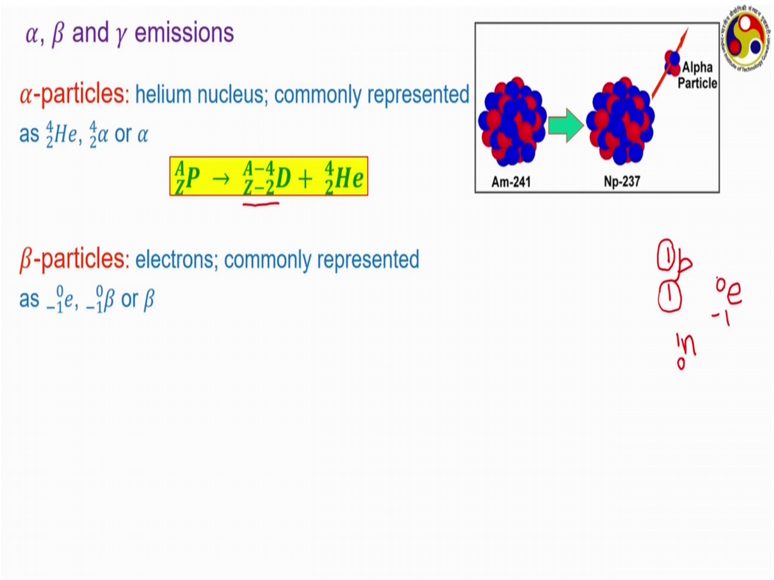

Therefore they are heavy in nature. They comprises of 2 protons and 2 neutrons giving a total of 4 nucleons and as per the terminal that we are following, they are commonly represented by 2 He 4 or 2 alpha 4 or just alpha.

So, whenever a particle a parent nucleus I should say, undergoes some kind of alpha emission or alpha decay as is often called. Basically there are 4 nucleons, that is going out of it is nucleus. Total number of protons and total number of neutrons present in the parent's nucleus both will be reducing by 2H and therefore, the daughter nucleus will be having 2 protons less and 2 neutrons less.

Accordingly we can say if the parent nucleus is having an atomic number of Z and mass number of A. The daughter nucleus will be having an atomic number of Z minus 2 and a mass number of A minus 4. Because 4 number of nucleons, 2 protons and 2 neutrons have gone out of place. Plus of course, the helium particle or the alpha particle that will come out of this a common example, but I shall be coming back to this examples later on. Here we have a nucleus having 241 mass number gets converted to H union isotope having 237 mass number. The second is the beta particle. Beta particles are much lighter elements. They are basically electrons. Electrons we already know from the atomic structure. Beta particles are the same and they are common represented as per the symbol of electron that is minus one e 0 or minus 1 beta 0 or just beta.

In this context I would like to mention a few things like proton, neutrons and electrons. They are often represented in doing nuclear reactions. The same way we represent isotopes. That is say for protons if we use P for proton, then we know that a proton is having a mass of 1 or a proton basically comprises of just 1 proton itself. So, it is having a mass of 1 and also 1 unit positive charge. Accordingly it is said that it is having atomic number sort of thing is 1 and it is mass number sort of thing is also 1. At this particular 1 is associated with the charge and this particular 1 is associated with the mass; if we follow the same convention for neutron.

Now we know that a neutron is also having a mass of about one amu, but it is neutral. So, neutron is represented by a 0 here and a mass and 1 here. And for an electron if we see, electron is having a 1 element of negative charge or 1 unit of negative charge. So, minus 1 comes here, but it is mass is extremely small compared to the mass of proton and neutron. We shall be using a 0 here just what is shown here itself and this is the convention they refer. We are using or we shall be using for rest of this particular course. To represent proton, neutrons and a electrons and if required some similar elements.

So, whenever a particle undergoes a beta decay, that is a beta particle is emitted from the nucleus of course, there will be minus 1 amount of charge is going out of this.

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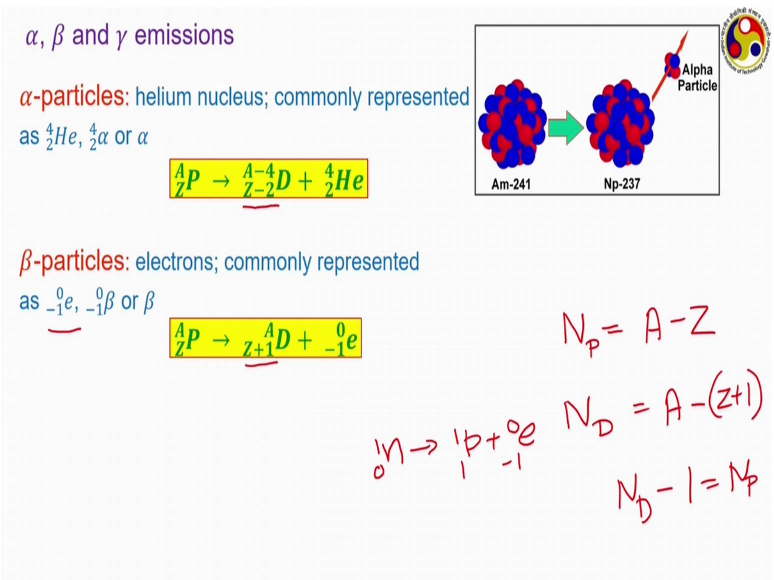

And accordingly if the initial nucleus is having Z as the atomic number, the daughter actually will be having 1 proton. More you can visualize this particular emission as conversion of neutrons to proton and electron.

If you see in the parent the total number of neutrons N is equal to A minus Z and the second one for if this says parent and for the daughter it is remains the same, but the number of proton has increased by 1. So, it is very clear if we compare between the 2 that the daughter is actually having 1 neutron less than the parent and this can be visualized as 1 neutron; as per our convention which we are representing as 0n1 gets converted to 1 proton and 1 electron. As per our convention proton is having plus 1 charge, electron is having minus 1 charge. Electron mass is 0 and proton mass is 1.

So, both the atomic number and mass number remains balanced and accordingly a beta of emission or beta particle decay can be visualized as the conversion of one neutron proton and electron. The proton is used to increase the atomic number of the daughter by a unit whereas, the electron goes out in the form of the beta particle; however, the mass number of the daughter remains unchanged. Because while it is the number of neutron has reduced by 1, the number of proton is increased by 1.

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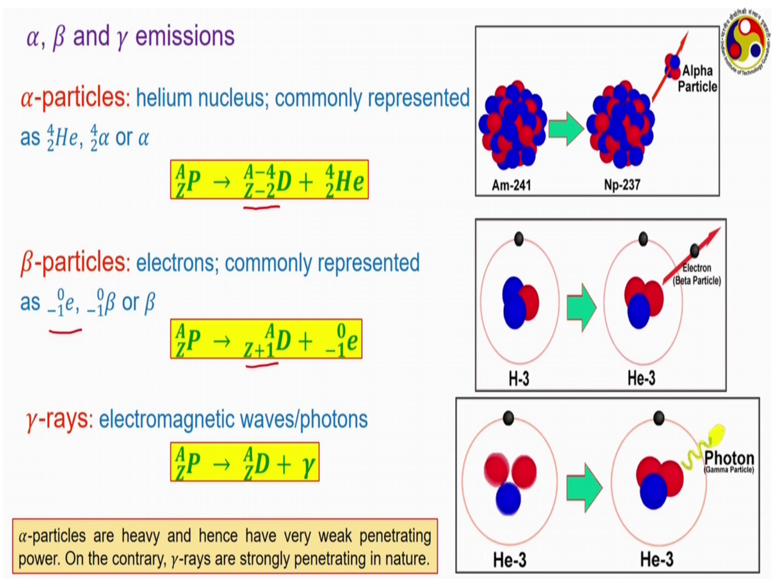

This is one typical example where the tritium that is the third isotope of hydrogen is undergoing beta particle decay and getting converted to helium. Both are having a mass number of 3, but while in tritium we are having 1 proton and 2 neutrons. In case of helium we are having 1 neutron and 2 protons and the third one is gamma rays. Gamma rays are actually not particles; they are just electromagnetic waves of photons. A very high energy photon.

So, whenever a radioactive reaction is associated with a gamma emission which is basically produces the same isotope or I should say the atomic number and mass number of the daughter remains identical to that parent; however, it is energy level will be lesser compared to the previous case. It is an example of isomer or we can say that the daughter is an isomer of the parent. Because it is having the same number of protons and neutrons, but it is energy level is lesser; gamma rays being electromagnetic waves.

This is one example here; gamma rays being electromagnetic waves. They are highly penetrating in nature, whereas the alpha particle is being the heaviest. They have very weak penetrating power. Actually they can be stopped just by very thin piece of paper. Beta rays are having penetrating power in between the alpha and gamma rays. There are 2, 3 other kinds of nuclear reactions possible, but we shall be coming back to this reactions plus the other one is which may be possible in the next lecture. Here let us just focus on this topic of radioactivity only.

So, now we know that a radioisotope can undergo some kind of disintegration or decay to produce a daughter.

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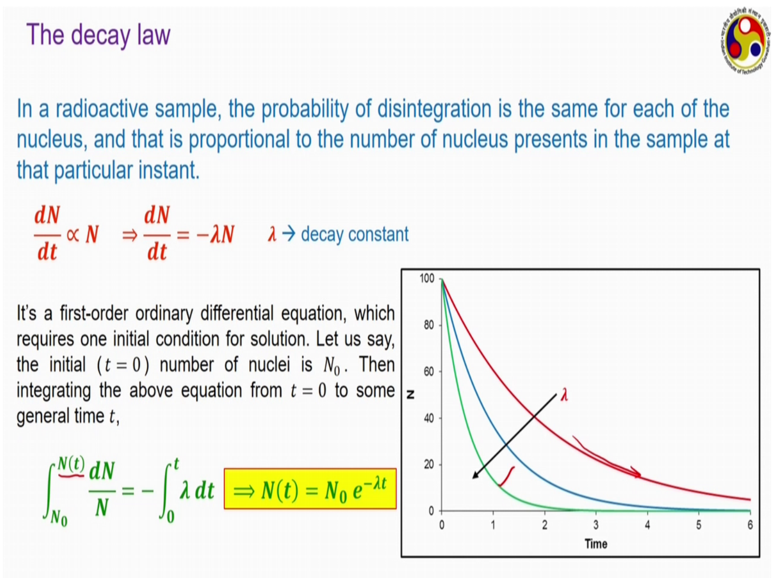

Depending upon the nature of emission alpha, beta or gamma or something else that daughter and parents number of nucleons and protons can be related, but this kind of reaction has to be following some kind of laws or rather that is the question whether that is kind of radioactive decay follows any kind principles or not. Here we cannot have any kind of mathematical proof for this. Because whatever we are going to say that is purely phenomenological in nature. Analogous to say all the principles of thermodynamics and several principles of heart transfer and fluid mechanics; that means, this particular decay law or the law of disintegration is purely from observations or experiments.

It has been found that there are 2 points. Number 1 the probability of disintegration is the same for all the nucleus; that means, say we have a sample of 100 nucleus. Now each of the nucleus present in the sample are equally probable to undergo decay in the next instant; that means, at the next decay can be of particle number 1 or can be a particle number 59 or can be corresponding to the particle number 93. We cannot for sure. Similarly if we focus on any particular nucleus say if we focus on particle number 50. It can undergo decay in the next instant or may undergo after 5 minutes or may undergo after 30 years. It is not possible to say is it purely a probabilistic phenomenon, but the second point is that this particular probability or their probability of disintegration is been found to be propositional to the number of nucleus. That is present in the sample at that particular instant.

That means if we put in mathematical term. If N is the number of nucleus in a sample, then it is rate of disintegration that is dN dt will be proportional or number of nucleus itself and introducing a constant of proportionality lambda which is called the decay constant. dN dt is equal to minus lambda into N here. The minus sign indicates that the number of nucleus basically N reduces with increase in time. So, it is a very straight forward relationship, if we have idea about this decay constant lambda. This is the first order ordinary differential equation from mathematics point of view and to solve this you need to have one initial condition.

Let us assume the initial number of nuclei is equal to N naught or N0 at time t equal to 0. Therefore, if we integrate this equation from some time t equal to 0 to some general time t, then we have this at time t equal to 0 number of nucleus is N naught and N t represents any general number of nucleus at in general time t and after performing this integration, this is what you have. N t is equal to N naught into t to the power of minus lambda t.

That is it follows an exponential form or if we see on graphs, it is just a representative graph if we start with 100 number of nucleus at some instant t. Then with time it reduces for exponentially depending upon the value of lambda of course, the slope of the curve will depend upon the value of lambda.

If lambda increases that is decay constant is higher; that means, are more number of nucleus that is getting decayed within a given interval or we can say the rate of disintegration is very high and accordingly well for a low value of lambda, we get a quite smooth curve like where this red line here, when the lambda is quite high, we get this green line which represents a very sharp rate of reduction, but it is simple straight exponential relationship. That is being followed by this radioisotope.

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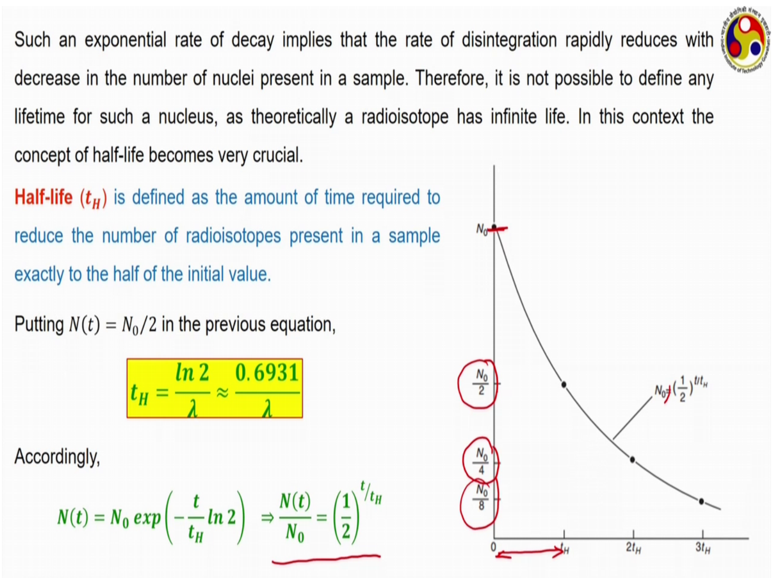

Such an exponential rate of decay also implies that it is not possible for the number of nucleus to approach 0 or it can approach 0 only at infinite time. Of course, the rate of disintegration keeps on a reducing with time as the number of nuclei present in the sample gives on reducing, but it will never theoretically rich as 0.

Therefore in this context we have the concept of half life. That is coming to picture. Half life is defined as the amount of time required to reduce the number of radio isotopes present in the sample exactly to the half of it is initial value; that means, if initial number of radioisotopes in a sample is N naught, then the time it requires to have exactly n naught by 2 number of isotopes in the sample is called the half life. If we put this into the previous example or previous mathematical expression rather putting in equal to n naught by 2. We get tH is equal to log 2 by lambda or approximately 0.6931 by lambda. A very important relationship from radioactivity point of view.

We can clearly see the half life and the decay constant have inversely proportional and their product is equal to log t. Also putting this idea of tH into the previous expression we can also represent n t by n naught as half to the power t upon Th. now we represent this on a graphical platform set time t equal to 0. We are starting with n equal to n naught. So, if we follow or the time after tH amount of fuel is elapsed. That is an amount of time exactly equal to the half life. Then the number of elements present in the sample also will become exactly half that is n naught by 2.

If we go another tH amount, that is from tH to 2 Th, then it will become half of this n naught by 2. That is n naught by 4. If we go another tH amount. That is from 2 tH to 3 tH. It will become half of this n naught by 4. That is n naught by 8 and this way the curve becomes more moderate as we move on in time and the total number of nucleus keeps on reducing exponentially, but it will be requiring infinite amount of time for this number of articles to reach an absolute 0. Here this equality should not be there. Actually it is just n naught into half to the 40 by Th. As we have already seen in this expression the previous expression.

Now, the concept of half life is an extremely important one from radio activity point of view because half life for a radio isotope is similar to our figure prints. Each radioisotope has it is own half life. And therefore, the knowledge of half life for a isotope is sufficient to identify this one. I repeat every radioisotope has an unique value of half life and it is not possible for 2 radioisotopes to have the same value of half life. Therefore, half life measurement is one popular way of identifying radioisotopes.

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Isotope	Half-life	Principal Radiations (Type, MeV)
Neutron	614 s	β, 0.782
Tritium (H-3)	12.33 y	β, 0.0186
Carbon-14	5715 y	β, 0.156
Nitrogen-16	7.13 s	β, 4.27; γ, 6.129
Sodium-24	14.96 h	β, 1.389; γ, 1.369, 2.754
Phosphorus-32	14.28 d	β, 1.710
Potassium-40	1.25×10^9 y	β, 1.312
Argon-41	1.82 h	β, 1.198; γ, 1.294
Cobalt-60	5.271 y	β, 0.315; γ, 1.173, 1.332
Krypton-85	10.73 y	β, 0.15; γ, 0.514
Strontium-90	29.1 y	β, 0.546
Technetium-99m	6.01 h	β, 0.142
Iodine-129	1.7×10^7 y	β, 0.15
Iodine-131	8.021 d	β, 0.606; γ, 0.284, 0.364
Xenon-135	9.10 h	β, 0.91; γ, 0.250
Cesium-137	30.2 y	β, 0.514; γ, 0.662
Radon-222	3.823 d	α, 5.490; γ, 0.510
Radium-226	1599 y	α, 4.870
Uranium-235	7.04×10^8 y	α, 4.152
Uranium-238	4.47×10^9 y	α, 4.040
Plutonium-239	2.410×10^4 y	α, 5.055

$${}_{0}^{1}n \rightarrow {}_{1}^{1}p + {}_{-1}^{0}e$$

Most of the natural radioisotopes are heavy nuclei. Common exceptions are ^{3}H, ^{14}C and ^{40}K, which are produced continuously during natural nuclear reactions and are available in plants & animals. Natural potassium contains about 0.0117% ^{40}K.

If we see this particular list here we have several elements listed and along with that half life values and also the principle kind of reactions that they generally suffer. Like if you see the tritium is having an half life of 12 point 3 years, that is if we are having a sample of tritium containing 500 number of isotopes to start with only after 12 point 3 years the number will become 250 and for reducing 250 to 125, it will require another 12 point 3 years.

Ah, but of course, the range of half life is quite large as you can see whereas, we start with the value of 614 second. Some of the isotopes can have extremely large value of half life by you can see for uranium 238. It is of the order of 10 to the power 9. I think thorium is missing from this chart. Thorium can also have an half life value even higher of the order 10 to the power 10 years. Here this y refers to years whereas, s refers to second then h refers to hours.

So, some isotopes can have very small half life like here we can see nitrogen 16 has an half life of only 7 point 313 seconds. That is only within a period of 7 seconds, the number of nitrogen isotopes will become half of his initial value, but some of them can definitely be much larger and the last column in table shows the principle kind and of a decay that they suffer like nitrogen is generally associates with the decay of nitrogen 16 associated with the emission of beta and also gamma rays. Whereas, for uranium 228, it is generally associated with alpha decay which releases 4 point 040 amount of mega electron volt amount of energy.

Now, the top of the chart we have neutron. This is very interesting one. As I have mentioned earlier a radioactive decay of neutron as is associated with the production of 1 proton and 1 electron and as we can see from the chart a free neutron is able to undergo a decay with an half life of 614 second. Thereby producing 1 proton and 1 electron, most of the natural radio isotopes are heavy in nature, but as I have mentioned there are exceptions and several of them are listed in this table very common examples can be tritium or carbon 14 or potassium 40. Which all of them are produced during natural nuclear reactions and generally are available in plants and animals like potassium 40 is quite common in several kinds of plants.

Natural potassium contains it is about 0.0117 percent. Is whereas, tritium is also present in a very trace quantity in normal water, but most of the isotopes that we need for energy productions are the heavier one in a shell and thank fully all of them are having quite high half life. Like uranium 238 is having half life of 10 to the power 8 years, whereas uranium 235 and uranium 238 is having even higher of the order of 10 to the power 9 units.

That is very good information to have or I should say thanks to their very large half life. They are still existing in this nature existing in this universe has their half life being very weak. They would have vanished long back or within a very much shorter period of time. Only because of their long half life they are able to survive on this universe.

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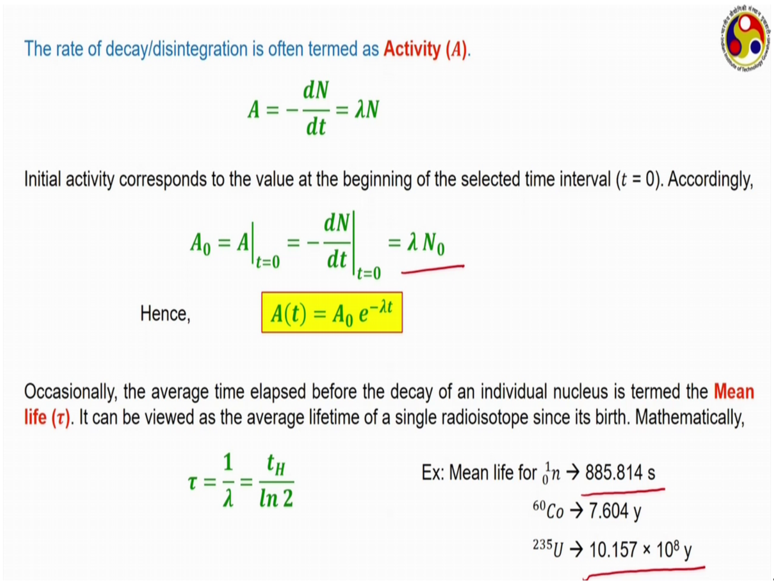

So, we move on to define another term. That is called activity. Activity is nothing, but this rate of decay or disintegration and it is equal to minus dN dt or equal to lambda N, where lambda is a decay coefficient. So, initial activity corresponds to the value of the activity at the beginning of the selected time interval t equal to 0. Accordingly we can write initial activity A naught is equal to activity e at t equal to 0 that is minus dN t. At t equal to 0 is equal to lambda into n naught where naught as per our previous notation this is the initial number of nuclei present in isotope.

So, putting this expression for A and A naught in our original expression. We get 80 equal to A naught into e to the power of minus lambda t. That is the change in activity with time can also be related to the decay constant lambda. This again another exponential curve if you plot it graphically it will represent the similar kind of nature as we have seen for the decay law. Occasionally there is another term that is used to characterize nuclear fuels. That is the mean life define given by the symbol tau. It is the average time replaced before the decay of an individual nucleus.

It can be viewed as the average life time of single radio isotopes since it is birth. Mathematically it is found to be proportional or rather inversely proportional to this decay constant and. So, we can also write it as the half life divided y log 2. So, all these information that is half life, activity, mean time they all are associated with a radioactive fuel. And these are important functions to know whenever we are trying to choose some kind of radioactive fuel in any kind of application that we are looking for. There are a few examples of the mean life like we have seen for a free neutron it can undergo a very prompt decay because it is half life is extremely small.

Accordingly it is mean life is coming to be only 885 point 8 seconds whereas, uranium 235 has a mean life of the order of 10 to the power 9 years ; that means, if we have one uranium 235 nucleus it is very likely to survive on an average a period of 10 to the power 9 years and. So, it is quite easy to store this fuel and use them for whatever purpose that we would like to have.

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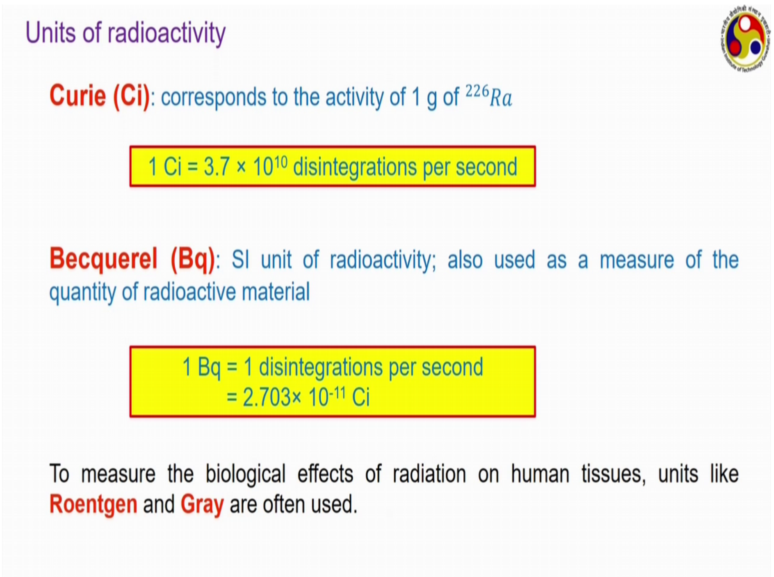

This term activity is a measured with the unit of curie. I have mentioned earlier that Marie curie proposed one international scale for measuring the activity of the radioactive isotopes and that is equal to the activity of one gram of radium to 26 and in her memory that is called the curie which is actually 3 point 7 into 10 to the power of 10 disintegrations per second. That is within one second if the 3 point 7 into 10 to the power of 10 number of isotopes are suffering disintegrations, then you call this particle to have activity of one cuie, but this generally a very large number to have as you are talking about disintegrations per second of the order of 10 to the power 10. So, quite often the other unit Becquerel symbol Bq is often used this is a actually the SI unit of radioactivity of course, I do not need to mention about the source from how this name came, but at this SI unit of Becquerel can also be related to the curie as 1 Becquerel is equal to 2 point 703 into 10 to the power minus 11 curie.

Becquerel again is a very small unit. So, quite often we have representations in terms of kilo Becquerel or mega Becquerel; that means, multiplied by 10 to the power 3 or 10 to the power 6 or similar also to measure the biological effect of radiation in human tissues. There are units like roentgen and grey which are often used and, but we shall be discussing more about them in a letter module and we shall be talking about the biological effects of radiation.

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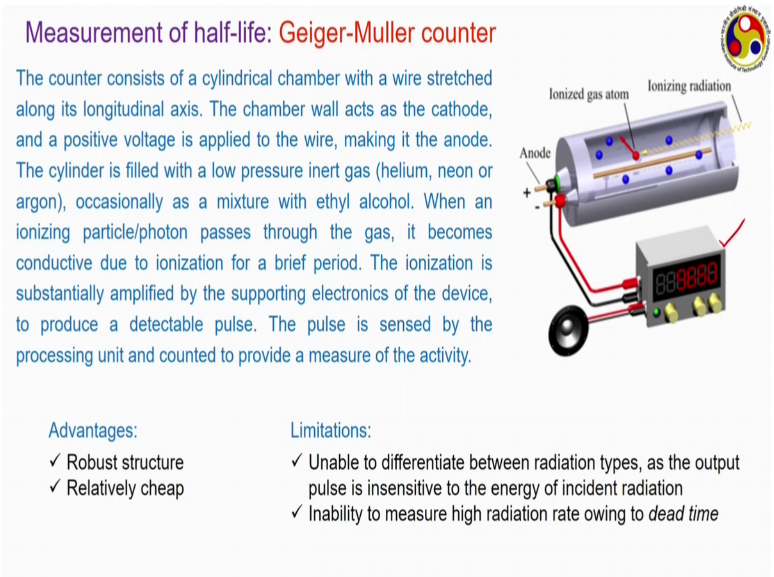

The measurement of half life is a very important one because just by measuring half life. We can easily identify the radioisotope itself. We do not need to know the number of protons and neutrons separately. There are several ways. This is one of the classical ways of doing this that is by the Geiger Muller counter. This counter is actually a cylindrical chamber which is having wire stressed along with longitudinal axis. So, the chamber wall is charged to become the cathode, whereas, the positive voltage applied on the wire making it the anode. The cylinder is a filled with a low pressure inert gas like helium, neon and argon. Quite often you will find a mixture of argon and ethyl alcohol. I will put into the cylinder whenever there is some kind of ionization particle or photon. That is passing through the gas. It becomes conductive due to the ionization for a very brief period

This ionization is sensed by the electronics of the device. This amplifier to a much larger amount and it therefore, it produces a very detectable pulse. The pulse is measured by this particular counter. Which just counts the number of pulses that is observed during an experiment. Now this pulse is counted to provide a measure of the activity of this particular and once we know the activity or we can always calculate the decay constant and the half life of that.

Geiger Muller counter being a very classic element is generally robust in structure and also relatively very cheap, but it has a few disadvantage like it is unable to differentiate between different kinds of radiation. Or as the final output pulse that we get, that is independent of the energy of the incident radiation. So, we shall not be able to say exactly at what energy level the radiation is able to reach the counter and. Secondly, inability to measure high radiation rate owing to dead time.

Now, once the tube undergoes one set of actuation it requires some time to recover and that time is referred to as the dead state. So, when the relation rate is very high, it will not be of any value, but there are several other kinds of counters (Refer Time 42:39) counters and other a few other kinds of counters are also available in modern days which are used for measuring amount of radioactivity or the half life in general. We would like to discuss about them later chapter.

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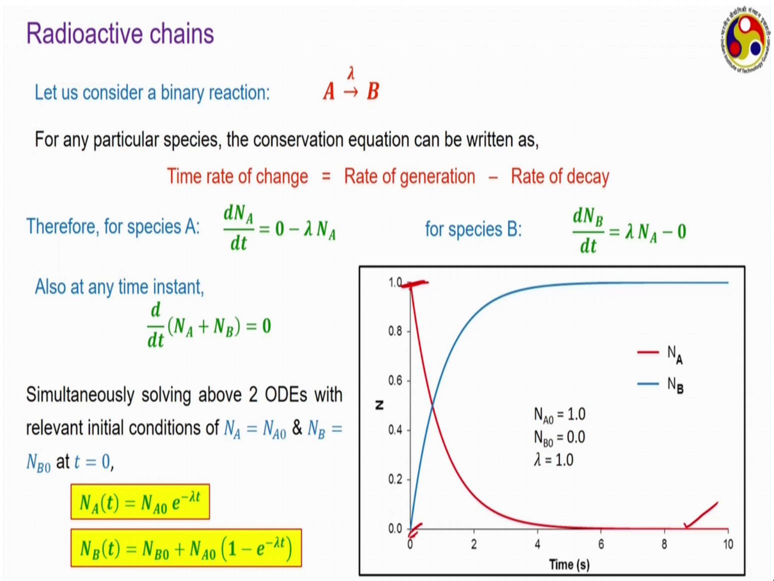

Now, we come to the radioactive chains as I have mentioned whenever we are having one radioactive element undergoing decay on radioactive isotope undergoing a decay. It produces a daughter. That daughter is very commonly it is a radioactive in itself and accordingly the daughter nucleus can also undergo some kind of reactions, but before we go to such kind of chains, let us just stick to a binary reaction. Here we have a single step reaction. Where A is the parent nucleus and it undergoes a radioactive decay following a decay constant of lambda and produces an isotope B.

Now, for any particular species the conservation equation can be written as the time rate of change is equal to the rate of generation minus the rate of decay. it is a very straightforward valence equation. So, for the species a we can write that it is time rate of change that is dN dt, it is equal to there is a no source for A. So, the rate of generation is 0 and the rate of decay as per the principle that we have studied earlier that is proportional to the number of nucleus for A itself and so can be given as lambda in to N A.

Similarly, for the species B dN B dt is equal to it has a source from A that is whatever is the reduction in the number of molecules for a following this decay rate the same will be the gain in the number of isotopes of B. And So, dN dt is equal to lambda in a minus 0 as v is not undergoing any further disintegration and also at any time instant we can say that the time rate of change of the total number of isotopes present in the sample has to be equal to 0. This can be understood from common sense because an isotope of B can be formed only because of the degradation or decay of the isotope A. Or whenever there is decay of 1 isotope of A. We get precisely one isotope of B only therefore; total number of isotopes remains constant inside the sample that you are talking about.

Now, we have 2 ordinary differential equations. This is our equation number 1 and this is our equation number 2 and we need to solve them using 2 initial conditions. Here our condition is N equal to N A naught and N B equal to N B naught at time t equal to 0. Putting that and also taking into consideration the condition of d dt of N A plus N B equal to 0. We get these are the final solution where N A follows the exponential relationship as usual whereas, N B is also having a modified kind of exponential form and this can be a graphical representation of whatever we are talking about earlier.

Here in A is reducing sharply this given by this red line and correspondingly N B is increasing at the same rate here total number of a nucleus has been non dimentionalized by the initial number of nucleus. So, that it is scaled to a final value of one. Where 1 is the initial number of nucleus, A is having this particular case uses N A naught equal to 1 or N B naught equal to 0 and take a lambda value of 1. Accordingly initially the value of A isotope is equal to 1 value of B isotope is equal to 0 and their summation remains balanced that is remains equal to one throughout the duration that you are having.

You can also see in this period it is seems that the number of a isotopes is equal to 0 and same for B is equal to 1. Actual there is a very tiny gap that remains and A can become 0 only after a infinite period of time. Now this is only a single step reaction, but in practical cases radioactive reactions happens in chains each reaction is followed by another one and then another one as often the daughter nucleuses are also radioactive in nature.

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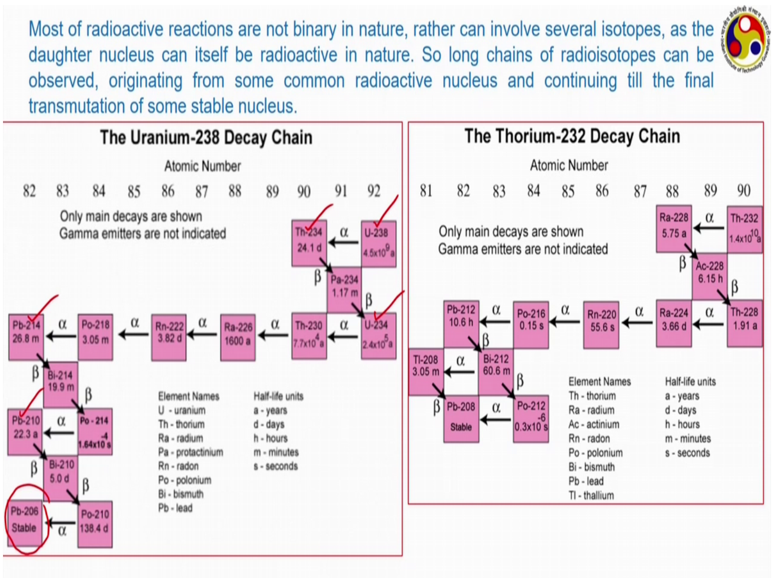

And this kind of chain continuous till appearance of some non radioactive kind of element like here we have the example of an uranium 238 decay chain if you follow here we are starting from this particular point u 238 it follows an alpha decay.

So, alpha decay means we have seen in a alpha decay means the atomic number will be reduced by 2 and the mass number will be reduced by 4. Following that we get this particular thorium isotope which undergoes beta decay. Bow beta decay means we have already seen that the mass number will remain the same, but atomic number will increase by 1. So, uranium is having an atomic number of 92. Whereas, thorium is having an atomic number of ninety and this palladium sorry this product (Refer Time 47:57) is something in between that is having an atomic number of 1 and this chain continuous with the subsequent alpha and beta decays till we reach this particular state of lead 206 which is a non radioactive 1. So, no further disintegration allowed.

Actually you can find that during this chain where we are starting from uranium 238 actually uranium 234 comes back somewhere in between whereas, while you will ending up with lead 206, there were other elements like lead 210, which is also lead 214. Which are radioactive in nature. So, they undergo some kind of decay, final to end up with lead 206. Similarly we have the chain for thorium here thorium 232 again we are starting with thorium 232 and it undergoes an alpha decay. So, the product is having a mass number of 4 less than thorium, an atomic number 2 less than thorium, where you find it as the radium and that keeps on undergoing subsequent alpha and beta decays finally, to end up to the lead; one interesting thing here to note that after reaching this bismuth 212.

There are 2 kinds of reactions possible. One where the bismuth undergoes a beta decay to produce polonium and then which goes to alpha (Refer Time 49:23) and alpha decay to lead to lead. The other possibility is that the bismuth undergoes an alpha decay. Producing thallium here and this thallium undergoes a beta decay to produce the lead. So, it is possible to have different kinds of radioactive reactions and this kind of chain formation is very common in any kind of radioactivity. In fact, all the heavier nucleus that we can associated with radioactivity. They undergo such kind of chain and most often the not you will find that lead is the last element where everything is finishing on.

In the next lecture we shall be starting with the analysis of one such chain we have seen the analysis of a binary radiation reaction in the previous slide. Where we are having just 2 isotopes in word. Now in the next lecture we shall be taking 3 isotopes together. Which can be visualized as sum in between step of this radiation chains and analyzing that for to identify the mathematical expressions with which we can represents their rate of decay. So, thanks for your attention hopefully. In the next class you will be coming with a better idea about this radioactivity. So, that we can proceed further to understand different kinds of possible nuclear reactions.

Thank you. Thanks a lot.