Radioactivity

B.S.Tomar

Homi Bhabha National Institute

Lecture-1, Module-1

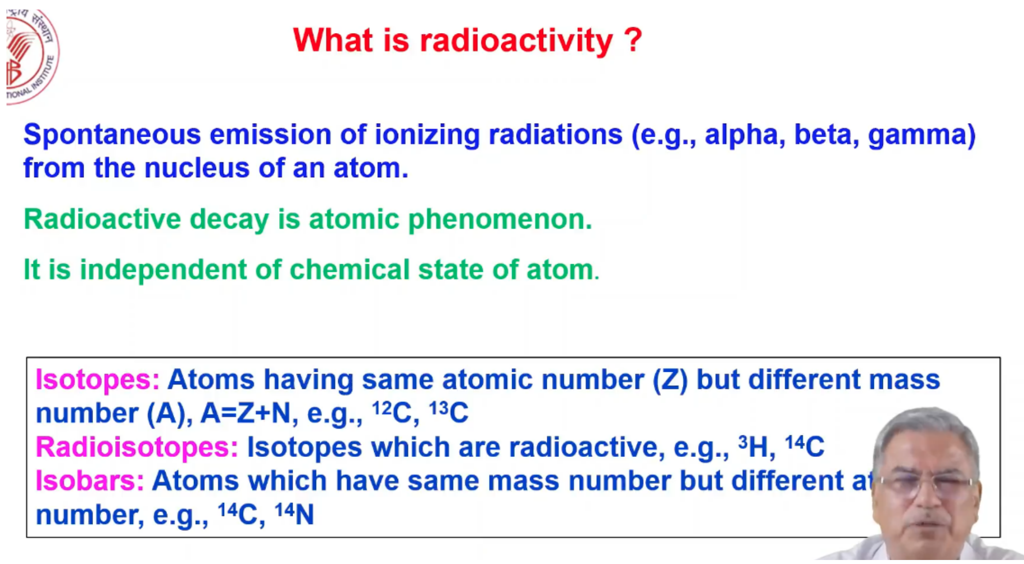
Hello everyone. This is the first lecture in this course on nuclear and radiochemistry. And in this first lecture, I will introduce the subject of radioactivity. While most of you might have already read this part in your science classes in high school, intermediate or even BSc, I thought it would be good to start with the introductory lecture to bring all the students on the same page so that you understand what I am going to discuss next. So this lecture, I will put in terms of asking some questions or at the end of this lecture, the students will be able to answer the questions that I have shown here.

Questions

1. What is radioactivity?
2. Why do radioactive atoms decay?
3. Why are some isotopes radioactive, while others are not?
4. What is natural radioactivity?
5. What is artificial radioactivity?

What is radioactivity? Why do radioactive atoms decay? Why are some isotopes radioactive while others are not? What is natural radioactivity? And what is artificial radioactivity ? So these questions you should be able to answer after attending this particular lecture.

Let's come to the first question. What is radioactivity?



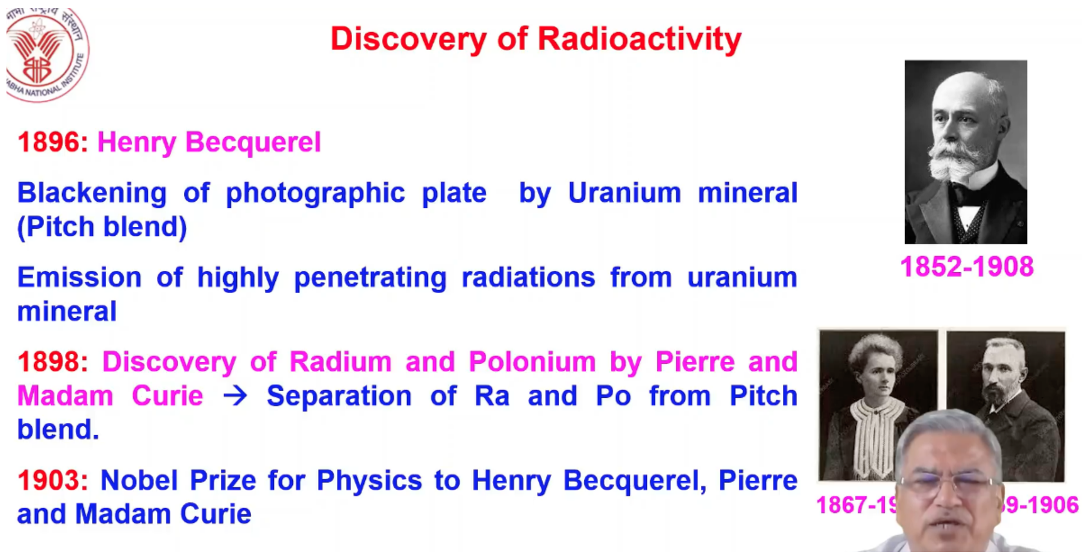
So radioactivity essentially involves the spontaneous emission of ionizing radiations like alpha, beta, gamma from the nucleus of the atom. So it's a nuclear phenomenon. So you can say radioactivity is an atomic phenomenon.

And it is independent of the chemical state of an atom. Whether you take a metal, whether you take an oxide, whether you take in liquid form or gaseous form, it is independent of the chemical state. Like for example, the parameters of radioactivity decay are the half-life. So the half-life is the constant of a radioisotope. It does not depend upon chemical state of the atom.

Before we go to the next part, other aspects of radioactivity, I thought it would be good to introduce some of the nomenclatures we will be discussing in these lectures. Like we have isotopes. So isotopes are atoms of an element having the same atomic number, which we will call as Z, but different mass numbers. So mass number is denoted by A, capital A, atomic number by capital Z. And mass number is nothing but the sum of the proton number and neutron number of the nucleus. For example, carbon-12 and carbon-13 are the two isotopes of carbon. Carbon-12 has six protons and six neutrons. So mass number is 12. Carbon-13 has six protons and seven neutrons. So the mass number is 13.

So these are the isotopes of carbon. Now radioisotopes are those isotopes which are radioactive. For example, tritium and carbon-14, these are radioactive and they are the, like tritium is isotope of hydrogen, carbon-14 is isotope of carbon. Another term that we will be frequently using is isobars. Isobars are atoms which have same mass number, but different atomic number.

For example, carbon-14 and nitrogen-14 have the same mass number 14. So they are the isobars and they have different atomic numbers, 6 and 7 respectively for carbon-14 and nitrogen-14. Now before we go further, let us discuss some of the initial history of this subject of radioactivity, namely the discovery of radioactivity.

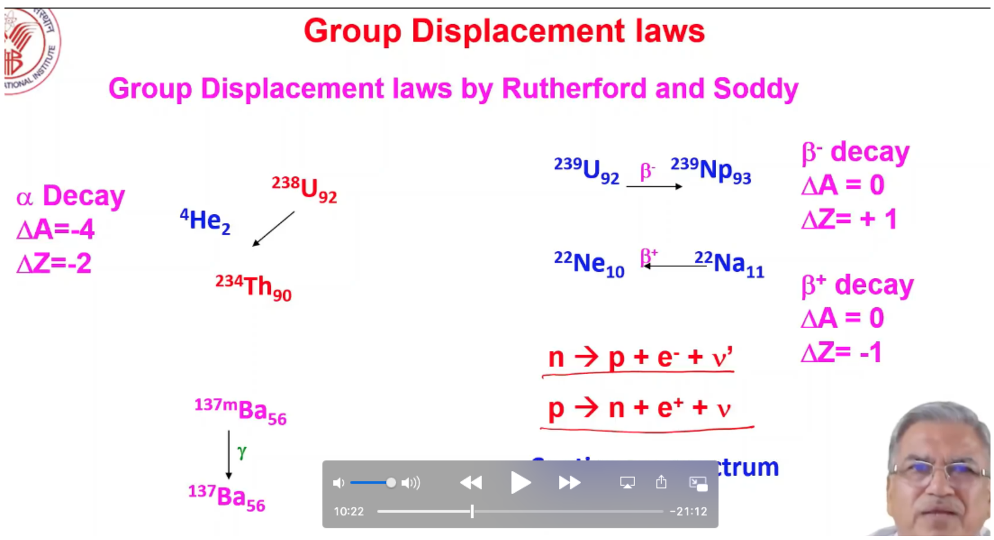


Most of you probably know already that the phenomenon of radioactivity was discovered by Henri Becquerel in France in 1896. Rongen discovered X-rays in 1895 and inspired by this discovery, Henri Becquerel started understanding the fluorescence emitted by uranium compounds when the light falls on them.

Now you know the fluorescence phenomena, when a fluorescent substance is exposed to light, it emits its own characteristic luminescence, we call it fluorescence. So while studying the fluorescence of uranium compounds, Henri Becquerel observed that even the photographic plate, which was kept in the drawer nearby a uranium mineral called pitchblende and so there is no light coming from outside. But he found that the photographic plate was blackened, which was kept in the neighborhood of a uranium mineral pitchblende and so he came to the conclusion that uranium mineral is emitting highly penetrating radiations which is coming out of the packing etc., and affecting the photographic plate. But the name radioactivity in fact was coined by Madame Curie who was responsible for the discovery of two more radioactive elements like radium and polonium along with Pierre Curie. So Pierre Curie and Madame Curie discovered two elements radium and polonium which were present in the pitchblende.

In fact, what they found based on the half-life of uranium-238 which is of the order of 10^9 years, the specific activity that means the activity per gram was found to be much more than what you expect from the half-life of uranium and so Madame Curie predicted that this uranium pitchblende contains some more elements which are more radioactive means they have higher specific activity than uranium. And so when they did the chemistry, separated elements which are responsible for high radio activity, she found that these are the daughter products of uranium and they were named as radium, atomic number 88 and polonium, atomic number 84. So the term radioactivity actually was coined by Madame Curie and the Nobel prize for this particular discovery of radioactivity was shared by Henry Becquerel, Pierre and Madame Curie in 1903. So the subject of nuclear science and technology began in the end of 19th century and there have been many more such discoveries subsequently in the 20th century. We will discuss them later.

Immediately after the discovery of radioactivity, Rutherford's group at Manchester also became very active and he along with Soddy formulated the laws that govern the different types of radioactivity.



You know that the prominent ones are the alpha decay, the beta decay. Gamma decay actually is not the decay of a nucleus from its ground state. I will discuss that more in details. But the alpha decay essentially involves the emission of a doubly charged helium atom from the nucleus of the parent isotope like 238 uranium.

When it is undergoing alpha decay, the mass number is decreased by 4 and the atomic number is decreased by 2. That is the configuration of the helium. So uranium-238 becomes thorium-234.

^{238}U □ ^{234Th} + ^{4}He

In the case of beta decay, now beta decay can be beta minus or beta plus. Like for example, uranium-239 undergoes beta minus decay to become neptunium-239.

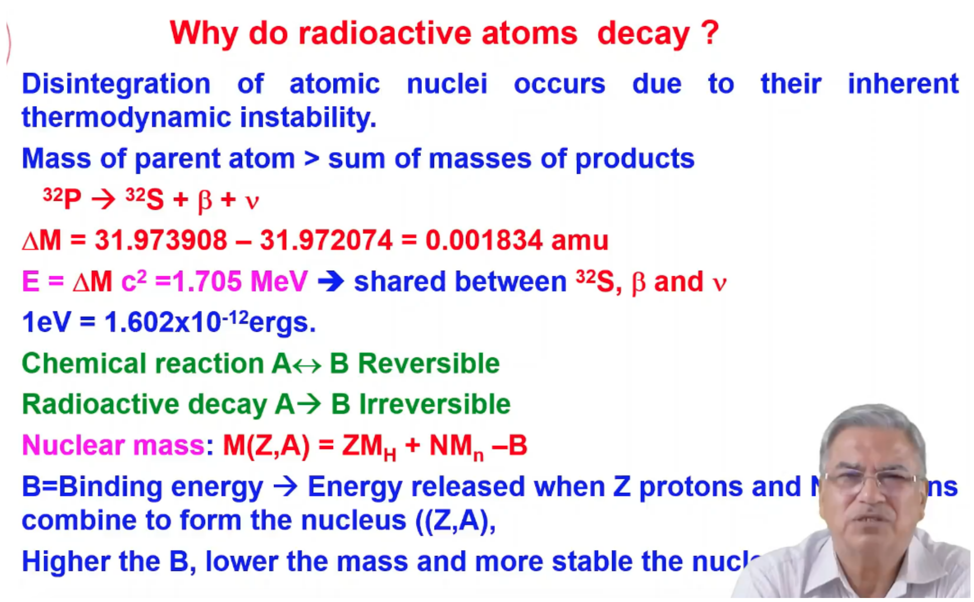
So in the case of beta minus decay, the mass number remains the same, but atomic number is increased by 1. On the other hand, in beta plus decay, the mass number remains the same, but atomic number is decreased by 1. You can see here ΔA is 0, ΔZ is minus 1. The fundamental equations representing the beta minus and beta plus decay are given below. The neutron going to proton and in the process an electron is emitted and also an anti-neutrino.

$n \rightarrow p + e^- + \nu'$

$p \rightarrow n + e^+ + \nu$

Whereas for the positron decay, the beta plus decay, proton is converted into a neutron and in the process, a positron and a neutrino is emitted. We'll discuss that in details in the beta decay theory because of the three body interactions, beta spectra are continuous unlike the alpha spectrum. The gamma decay, essentially you can see here, the excited state of a nucleus emits gamma rays. Like excited atom emits x-rays, excited molecules emit UV-visible radiations, excited nuclei emit gamma rays. So gamma decay is not essentially the decay of the ground state of the nucleus, it is the decay of an excited state.

Now let's come to the fundamental questions like why do radioactive atoms decay?



So the decay of a radioactive atom is essentially because of the thermodynamic instability of the atom. So the disintegration of the atomic nucleus occurs due to their inherent thermodynamic instability. What do you mean by thermodynamic instability? That means if the mass of the parent atom is more than the sum of the masses of the products, so it is like a potential. Potential means like when the water from a dam, if you open the floodgates, the water gushes down the stream because the water in the dam has a high potential. And so the moment there is a channel, there is a pathway for the decay, water will rush down.

Similarly, if a nucleus has higher mass than some other nucleus and there is a pathway, what is the pathway? Alpha, beta. So these are the pathways for decay of an atom. Then because of the thermodynamically instability of the atom, the nucleus having higher mass will decay to that with the lower mass. Just for example, phosphorus-32 emits a beta decay to sulfur-32. Now if you calculate the masses of these isotopes, so the mass of the phosphorus-32 in atomic mass unit is 31.973908. I will discuss later on why we use such a precise number for the mass because when you convert the mass into energy using the formula $E=mc^2$, we are multiplying the ΔM by 931. One atomic mass unit is equivalent to 931 MeV. So to have the precise atomic masses in terms of MeV, the multiplication factor should have large significant units.

The mass of sulfur 32 is 31.972074. And so the difference between the two, you can see the difference lies in the third decimal point in the atomic masses. So that is 0.001834. When you multiply by 931, then you get the energy of beta decay as 1.
705. That is the Q beta for decay of phosphorus-32 into sulfur-32. And this energy is shared between the three particles, sulfur-32, β^- and neutrino. Just to give you a feel, we will be using the energy in electron volts, kilo electron volts and million electron volts. One electron volt is the energy acquired by an electron when it is accelerated to a potential of one volt. That is the one electron volt and then you can have kilo electron volt, million electron volt and so on.

One electron volt corresponds to $1.602x\ 10^{-12}$ ergs or $1.602x\ 10^{-19}$ joules. Now, you must have read already that the chemical reactions like A □ B, they are mostly, they can be reversible. Some of them are irreversible also like burning of carbon $C + O_2 = CO_2$ is irreversible. But by and large, you can say that majority of the chemical reactions are reversible. So when you go from A to B, you can also come back from B to A. But the radioactive decay, if you call it such a reaction, then they are irreversible. You can go from A to B, you cannot come back from B to A because the mass of B is less than that of A.

Now, the mass and energy of nuclei are interconvertible, we have interchanged the mass and energy. So the mass of a nucleus we call in terms of M(Z,A), where Z is the atomic number, A is the mass number and this is equal to mass of the proton M_H into number of protons (Z) plus mass of neutron (Mn) into number of neutrons (N) minus the binding energy. So this concept of binding energy has come from when you combine Z protons and N neutrons to form a nucleus having mass M(Z,A) then the energy equivalent to B is released. So when the protons and neutrons combine to form a nucleus, energy is released and that energy released is called binding energy. So the energy released when Z protons and N neutrons combine to form the nucleus is called, it's binding energy. In other words, binding energy is the energy required to break a nucleus into its constituent nucleons.

I'm using the term nucleons. We will see later that protons and neutrons are together called nucleons. So higher the binding energy of a nucleus, lower the mass and it is more stable. You can see from the equation of nuclear mass, if B is more then M, mass of the nucleus will be small. So that will give you an idea that those nuclei which have high binding energy, they are more stable.

Now the next question is, why are some isotopes radioactive while others are not?

Why are some isotopes radioactive while some are not?

$^{11}B \leftarrow {}^{11}C_5$	$^{12}C_6$	$^{13}C_7$	$^{14}C_8 \rightarrow {}^{14}N$
Radioactive	Stable	Stable	Radioactive
$^{58}Fe \leftarrow {}^{58}Co_{31}$	$^{59}Co_{32}$	$^{60}Co_{33} \rightarrow {}^{60}Ni$	
Radioactive	Stable	Radioactive	

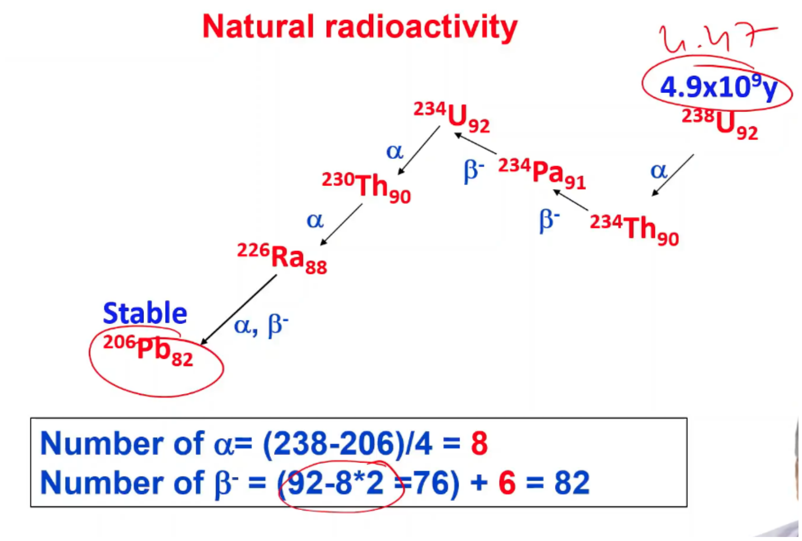
Atoms are stable if their N/Z ratio is in a particular range.

What decides if a particular isotope is radioactive or not? So I illustrate in the following section. I just give you an example of different isotopes of carbon, carbon 11, 12, 13, 14. You can see here, the atomic number of carbon is 6 and the neutron number from carbon 11 to carbon-14 goes from 5, 6, 7 and 8. Carbon-12 and carbon-13 are stable. You add one more neutron to carbon-13, form carbon-14 and it is unstable. It undergoes beta minus decay to nitrogen-14. So it is undergoing β- decay. Carbon-11 which is having one neutron less than carbon-12 undergoes β+ decay to boron-11. So you can see here that if you alter the neutron to proton ratio of the stable isotope, you have a high chance that next isotope will be radioactive.

Another example I give, cobalt has only one isotope that is stable. That is cobalt-59 having 27 protons and 32 neutrons. You add one neutron to cobalt-59 and you form cobalt-60 and this becomes radioactive. You remove one neutron from cobalt-59, you form cobalt-58 and it becomes radioactive. So cobalt-58 is undergoing electron capture decay. We will discuss that later on. So you can see here if I alter the neutron to proton ratio, the nucleus becomes radioactive.

So the atoms are stable if their neutron to proton ratio is in a particular range. That means when you have certain number of protons, you require certain number of neutrons to stabilize the nucleus and anything beyond that range on both sides, neutron rich side or neutron deficient side, nucleus becomes unstable. So I hope this explains that why are some isotopes radioactive while some are not.

Now I come to what is natural radioactivity.



So natural radioactivity means a radioactive isotope is present in nature in earth's crust. Now you know that the age of the earth, the earth was formed few billion years ago, around five billions years ago. And therefore, when the earth was formed, if there were some radioactive isotopes formed at that time in the earth, then they are decaying but they are still present because of their long half. For example, uranium-238 has got a half life of 4.47 billion years and it undergoes alpha decay to thorium-234. Now you can use the group displacement law to determine the daughter product's proton number, neutron number and so on. So it undergoes alpha decay to thorium 234 which has half life of 24 days, then goes to protactinium-234 by β- decay and then to uranium-234 by β- and again a series of alpha decay take place and finally it ends up with lead-206.

Now one common thing you will find in this series called natural radioactivity series that the mass numbers 238, 234, 230, 226 and so on. So many isotopes are formed in this series. All of them have a particular formula. You can write this in terms of 4n +2, n is an integer. For example, 206 you can write as 4 into 51+2. So all of them are 4 into some integer plus 2. That is why it is called as a 4n+2 series. All members of this natural series belong to the family of 4n+2. Now how to calculate the number of alpha and beta emitted in this radioactivity series? So I have given you a simple formulation below.

You know that the mass number is decreased by 4 in alpha decay whereas in beta decay there is no change in mass number. So from 238 to 206 the mass number decreased by 32. So 32 by 4 is 8. That means in this radioactive series from uranium-238 to lead-206, 8 alphas are emitted. So how to calculate the number of betas? The 8 alphas will decrease the atomic number by 8 into 2, 16. So from 92 we get 76 by alpha decay. If there were no beta decay then we should have got atomic number 76, but we get 82. That means there have been 6 β- decay because in β- decay atomic number increases by 1. So 6 β- decay will give you 82. So 92 minus 16 is 76, 76 plus 6 is 82. So in this natural radioactive series there are emission of 8 alphas and 6 betas.

That is how we can calculate in any natural series what is the number of alphas and betas. I give you another examples 4n+3, uranium-235 leading to lead-207. You can see all of them follow 4n+3 formula where n is an integer. And there is another series 4n, thorium-232 going to lead-208, 4n all of them are multiples of 4.

So these are the isotopes I have given with the half-lives on the right hand side. Uranium-238, 4.7×10^{9} years, uranium-235, 7.04×10^{8} years, thorium-232, 1.4×10^{10} years. Now you can see their half-lives are either comparable or more than the age of earth. And that is the reason why these isotopes are still present in the earth. Another explanation you can see here uranium-235 which is the fissile isotope that content is much less, it is only 0.7% now in the natural uranium because its half-life is one order of magnitude less than uranium-238. So it has decreased much more than uranium-238 and it is decreasing faster. When the earth was formed uranium-235 content must have been quite high, this may be of the order of uranium-238. There are other isotopes like potassium-40 going to argon 40 by β- decay, again because of its long half-life 1.25×10^{9} years, again of the order of age of the earth.

In addition to these naturally occurring radioisotopes there are two more isotopes which have short half life but they are present in nature. These are carbon-14 and tritium. Carbon-14 has a half life of 5,730 years whereas tritium has a half life of 12.3 years. So how is it that they are present even now? The reason is that they are being continuously formed in the atmosphere by interaction of cosmic neutrons with the nitrogen.

So atmosphere contains nitrogen, 78% is nitrogen and nuclear reaction of neutron with nitrogen-14 gives carbon-14 plus proton whereas neutron interacting with nitrogen-14 gives tritium plus carbon 12.

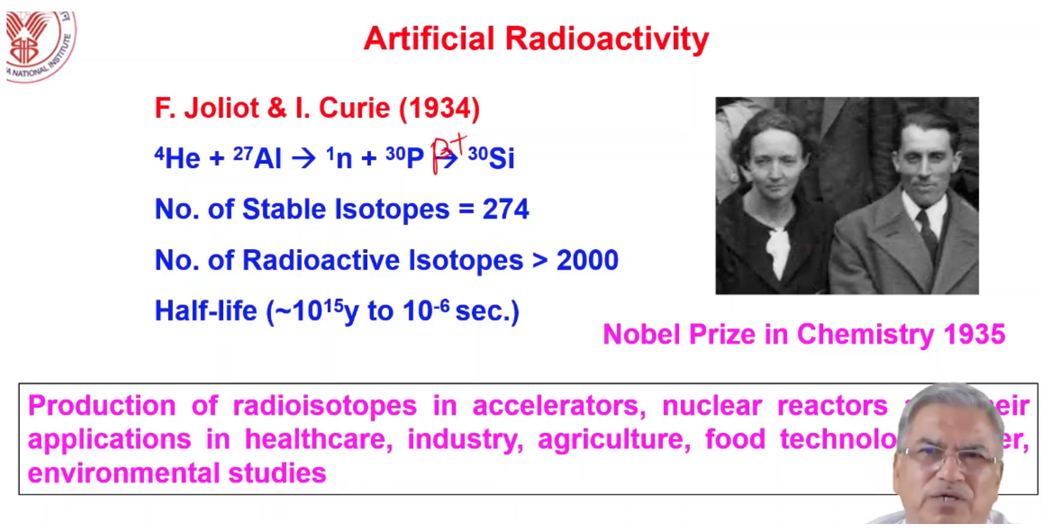
$n + {}^{14}N \rightarrow {}^{14}C + {}^{1}H$

$n + {}^{14}N \rightarrow {}^{12}C + {}^{3}H$

Because of these two reactions continuously occurring in atmosphere and the atmospheric carbon and tritium can get into the water bodies by rains and you will see here that all the water bodies will have tritium. So natural water contains tritium and even our body, living organisms, any living organism will contain carbon-14. So while we say radioactivity is harmful if we measure our body radioactivity you will have potassium-40, our body contains potassium, carbon, hydrogen and therefore these three isotopes are present in our body also. But we don't have any harm due to these radiations.

But the important point I wanted to highlight here is that these isotopes, the long lived ones which have the half-life of the order of age of the earth as well as carbon-14 and tritium are very much useful in many studies. For example, we want to determine the age of the rocks by determining the content of uranium-238 and lead-206, you can in fact find out when was the time this rock was formed. Similarly, the fossils, fossils contain carbon. So carbon-14 is decaying. You can use the activity of carbon-14 to find out the age of a fossil. Similarly, water bodies contain hydrogen and therefore tritium. From the measurement of activity of tritium in a water body you can find out if it has got disconnected from the normal water, rain water and if it is not being equilibrated by the normal water. So these are the way you can find out when was this particular water body or the fossils or the rocks formed.

Now I come to the last part of my today's this module that is artificial radioactivity.



Just now we saw several isotopes which are naturally occurring. But the number of isotopes which are formed by artificial means is now much more than the natural ones. And this phenomenon of artificial radioactivity was discovered in 1934 by Irene Curie and Frederick Joliot. Irene Curie was the daughter of Madame Curie. Now the reaction that they used was bombardment of aluminum-27 with alpha particles giving rise to a neutron and phosphorus-30. This phosphorus-30 undergoes β+ decay to silicon-30. Now I will tell you the story, very interesting story here is that the same reaction was used by Chadwick for the discovery of neutrons. So this group also had actually seen neutrons, but they were unable to interpret the results. And in 1932, Chadwick discovered neutron. This group were also studying the same reaction, but they missed the discovery. But then they were in for another discovery that is by artificial means you can produce radioisotopes.

So today, while there are only 274 stable isotopes, the number of radioactive isotopes is more than 2000. And the half-life of these radioisotopes can be as high as 10^{15} to as low as microseconds. So the artificial radioactivity has provided us with a tool to have different applications. So these isotopes can be produced by different means like in accelerators, where we accelerate charged particles like alpha particles, protons or heavy ions or in nuclear reactors where we have neutrons and produce them and use them in different fields like healthcare, industry, agriculture, food technology, water, environmental studies, etc. So this particular field of nuclear science and technology opened up once we knew that we can induce radioactivity in stable isotopes.

Thus, a new era began in the early 20th century. Subsequently, of course, the nuclear fission was discovered. That is another way of producing radioisotopes. But this phenomenon of a artificial radioactivity gave rise to a tool to produce isotopes of our interest. Think of an isotope, you can produce it in different facilities like accelerators or reactors.

I will stop here. And in the next lecture, I will talk about the radioactivity decay law and so on. Thank you very much.