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NUCLEAR REACTOR AND SAFETY
AN INTRODUCTORY COURSE
Module 02 Lecture 03
Basic Physics of Nuclear Fission

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So, good morning, everybody. Today, we move to the third lecture of this series. Here as I mentioned to you last time, I would like to expose you to the basic concepts of fission reaction; what is fission, how it is caused and things about that.

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INTRODUCTION

- It is essential to understand the different types of reactions including the fission reaction, which is at the base of nuclear reactor operation. In addition, the conditions needed for a sustained fission reaction is needed. Knowledge of the origin of radioactivity and behavior of radioactive atoms is of importance in understanding means of measurement and shielding methods for humans from the effects of radioactive environment.
- This lecture is therefore devoted to an overview of nuclear physics and radioactivity. It also gives a background of the neutron multiplication. This knowledge is very much essential to effectively control the nuclear fission chain reaction.

Now, it is very important to understand the different types of reactions which happen with these different atoms. Now basically, fission reaction, how a fission reaction happens. Next, how to sustain the fission reaction? Suppose, the reaction happens and then it stops. So what are the conditions that I need to sustain fission reaction and then also, I must know how this radioactivity is produced because I must take care of the fact that radioactivity can harm us. So I should know how the radioactive nucleates behave, do all atoms behave or only some atoms behave, so then I must be able to understand measure and also I must know how to shield, how to protect myself.

So in all these things you must really know how the whole thing happens. What are the properties of the atom and radioactive elements.

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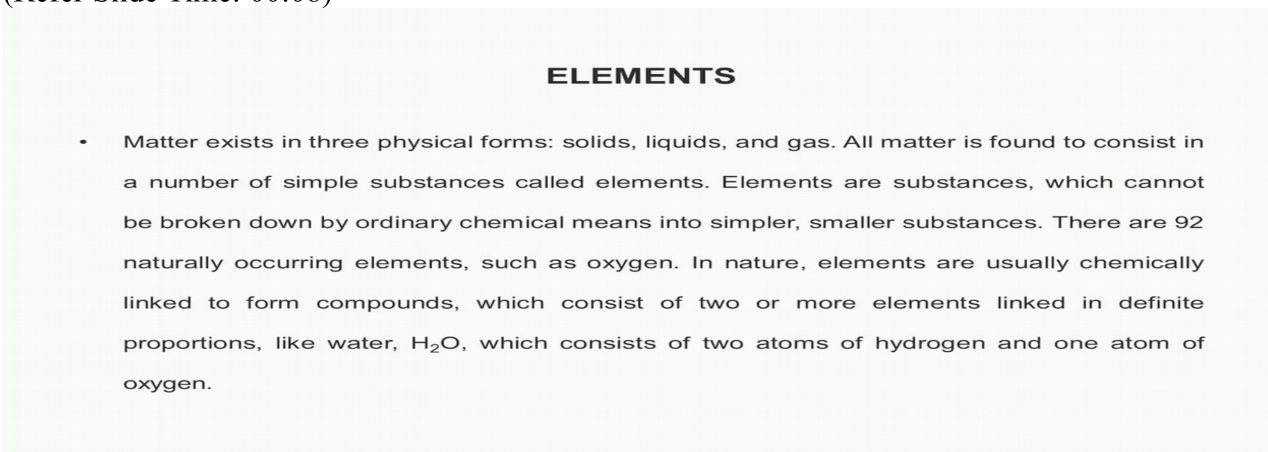

Now, all of us know that matter exists in three physical forms; one is solid, liquid, and gas. Now, all the matter whether it is a solid, liquid or a gas consists of different substances called elements. For example, your air contains oxygen and nitrogen. Nitrogen is an element, oxygen is an element. Then there are substances -- so basically elements are those substances which cannot be broken further into simple or smaller substances and there are about 92 elements which are naturally occurring, as I mentioned oxygen, nitrogen and etc. You can combine two elements to have compounds like hydrogen and oxygen gives you water, carbon and oxygen gives you carbon dioxide and things like that.

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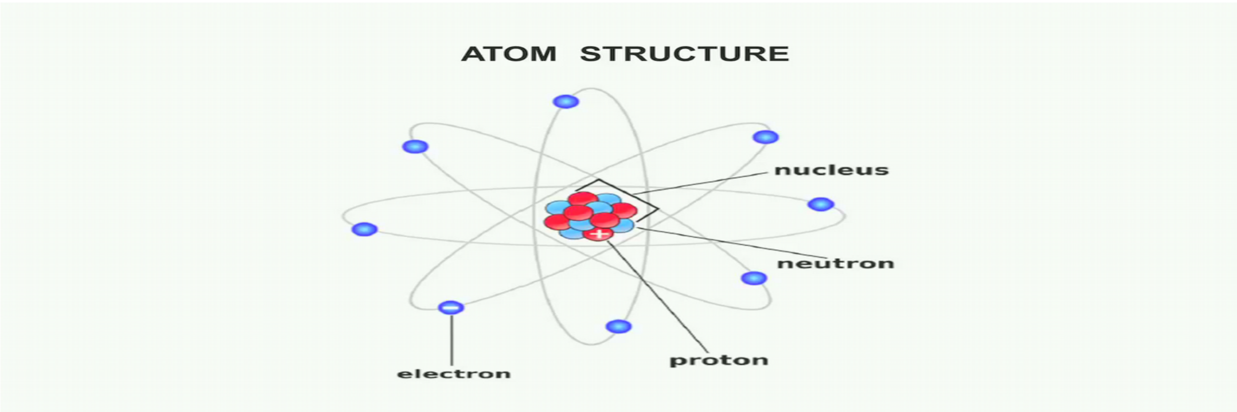

But then each element itself consists of lot of smaller particles called atoms. At the heart of the atom are the neutrons which really provide mass and also the protons, the red ones are the protons and the blue ones are the neutrons and you have electrons which are orbiting around these protons and neutrons. The combination of the proton and neutron is generally referred to as nucleus. This is where the reaction of the nucleus with neutrons produces as fission.

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ELEMENTS-Atoms

- Elements are made up of atoms. The atom is made up of neutrons and protons tightly clustered in a nucleus and surrounded by electrons spinning around in a variety of orbits. The protons are positively charged particles each having a mass of unit charge exactly opposite that of an electron. The mass of the proton is 1836 times that of the electron. Neutrons have no electrical charge and a mass just slightly larger than that of a proton.
- A particular atom is designated by its atomic number, *Z,* which represents the number of protons present, and by its mass number, *A*, which is equal to the number of neutrons, *N*, plus the number of protons: $A = N + Z$

So what is happening? The protons which we saw are they are positively charged particles while the electrons are negatively charges particles. So if you take atom as a whole it is having equal number of protons and equal number of electrons. So the charge is null.

Now the mass of the proton is about 1836 that of an electron. Electron is very little mass, neutrons do not have an electrical charge. Yes, electrons have negative charge, protons have positive charge, neutrons have no charge. The mass is slightly higher than that of a proton. Now then how do designate an element or an atom or I should say atom of an element? So we have what is called as the atomic number which refers to the number of protons or electrons but generally we refer by definition, the number of protons present, we call it as the atomic number and what is a mass number?

Mass number is, mass is due to the protons and the neutrons. So the total mass will be equivalent to the number of neutrons and the number of protons. So here I put it as A = N+Z.

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ISOTOPES

- Chemical property of an element is a function of the electrons which are orbiting around the nucleus. Atoms with same number of electrons/protons behave identically in a chemical reaction but exhibit marked differences in the nuclear characteristic.
- Elements having same atomic number but different mass numbers are referred to as Isotopes. Oxygen has three isotopes O^{16}, O^{17}, O^{18}. Common oxygen is O^{16}, which has 8 protons and 8 neutrons, while O^{17} has 8 protons and 9 neutrons. Hydrogen has three isotopes H^1, H^2 and H^3. H^2 referred to as Deutrium (D) and H^3 tritium (T). While ordinary water has the form H_2O, Heavy water has the form D_2O.

Now if you take elements, there are atoms of same elements. They may have same number of electrons and protons but they may be behaving different nuclear characteristics. For example, you take oxygen, in oxygen, we have heard about atomic number 16 but we have oxygen with atomic mass 20 and atomic mass 18 also. Commonly found oxygen is Oxygen-16 (O^{16}) which has eight protons, eight neutrons. So total is 16, whereas if you go for 17, it will have nine protons.

Again, coming to hydrogen, you have hydrogen with Hydrogen-1 (H^1), Hydrogen-2 (H^2) and Hydrogen-3 (H^3). So H^1 is our normal hydrogen we find, the H^2 is called as the deuterium, and third one is called tritium. With hydrogen and oxygen you get, you get ordinary water. With deuterium and oxygen you get heavy water and this heavy water is a very important material that we use in the nuclear reactors.

So here you get an idea of that there are isotopes of an element which have behaved identically in a chemical reaction but nuclear characteristics are different.

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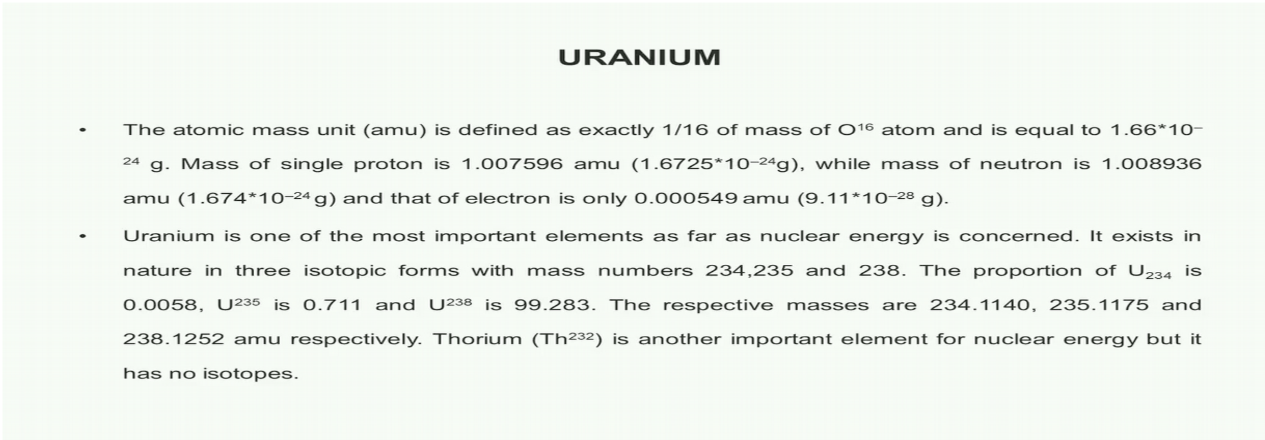

Let us now come to the mass. The mass in an atom, as I said, we have units called as atomic mass unit which refers to the 1/16th of the mass of an oxygen atom and it is equal to about $1.66x10^{-24}$ grams. If you take a proton, the mass is around $1.6725x10^{-24}$ grams and the mass of a neutron is slightly more, $1.674x10^{-24}$ grams, and electron is only $9.11x10^{-28}$ grams.

Now let us come a bit forward to uranium which we have been telling that it is a very useful element in the nuclear field. Again, this exists in three isotopic forms; U^{234}, U^{235}, and U^{238}. If you take the proportion of these in the natural uranium it is about 0.0058% of U^{234} and about 0.711% of U^{235} and about 99.283% of U^{238}. You see the major content is U^{238}. Thorium is again another important element which is can be used in nuclear but it has no isotopes.

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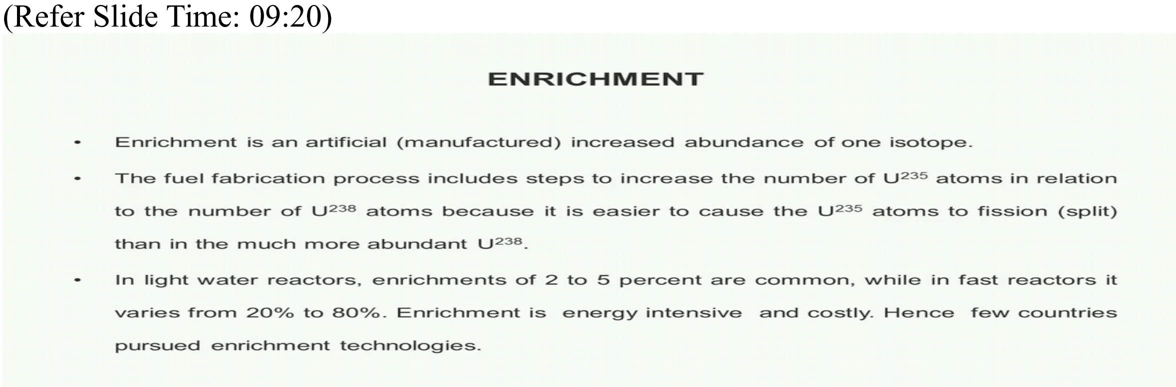

Now enrichment we talked about earlier. This is a process to increase the amount of one isotope. In natural uranium, 0.7% U^{235}, but for some reactors I want to make it to 2-3% or 5% and in some cases higher to 80%, I have to enrich it. So in the fuel fabrication process as I showed in the last lecture, you have the enrichment also, so enrichment is what we call. So many times we call, we are importing enriched fuel from outside for our Tarapur reactors. They use enriched uranium. For example, our Kudankulam reactors which are again a pressurized water reactor, they use enriched uranium, but our heavy water reactors, we use natural uranium.

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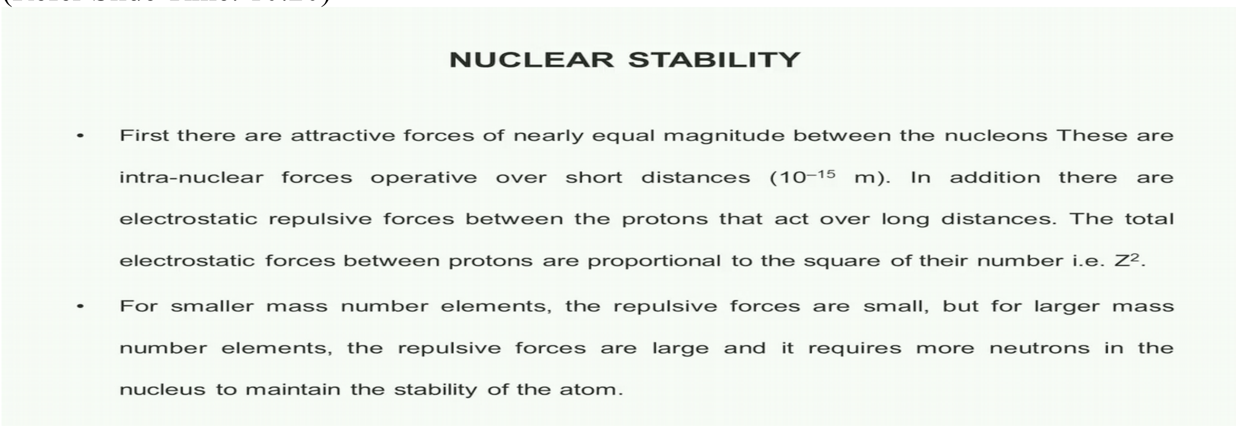

Now we come to the concept of what is nuclear stability. What is an atom which is stable from a nuclear point of view? Now, there are attractive forces and repulsive forces. Now these forces operate over short distances because atom itself is very small. So you have attractive forces between the nucleons, the protons, the neutrons, etc. and then there are also repulsive forces between the protons because all protons are positively charged.

Now it so happens that the attractive forces are over a shorter distance while the repulsive forces act over long distances. The total force, electrostatic force, between the protons is proportional to the square of their number, let us say, Z^2. Now if you take an element of small mass number, repulsive forces are small. So they are not able to break but for large mass numbers, the repulsive forces are large and then because the repulsive forces are large, if an atom has to be stable, it requires more neutrons in the nucleus to retain the stability.

So in other words, if my atoms are having a large mass number, I must have more and more neutrons so that the atom is stable.

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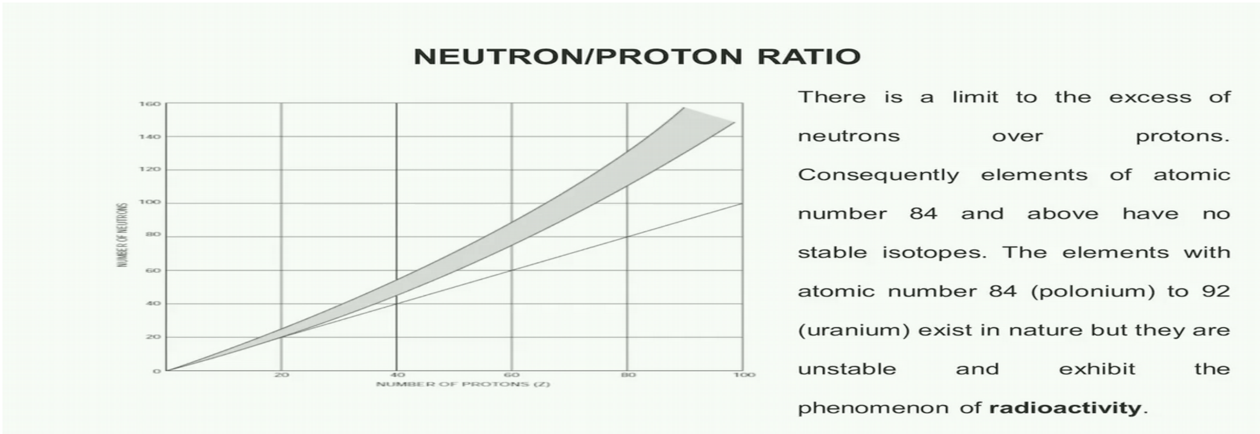

So let us have a look on the number of protons and the number of neutrons in the different elements. X-axis you see protons and if number of neutrons should be equal to the protons, you'll follow the straight line graph. But in reality, the number of neutrons as you go for high mass number, somewhere beyond 84, 84 atomic number is polonium and further to uranium which is about 92. These elements are unstable because they are moved away from the stable. If you say, if number of neutrons is equal to number of protons then they have a better stability; which are away, they don't process.

So what happens, these try to become stable because everything in the world would like to become stable and that stability to achieve that they emit some particles which are referred to as alpha, beta, gamma, and this is called as the phenomenon of radioactivity.

So basically unstable nucleates emit the particle or sometime called as radiation and that transforms them into a nuclei which will be better stable. It has been seen that nucleates which are unstable due to high mass numbers they emit either positively charged alpha particles and what do you mean by alpha particle, it is just like helium nuclei that is two protons and two neutrons, or negatively charged beta particles. Beta particle is nothing but an electron because after all what you have in the atom is protons, neutrons and electrons. If something has to go, the proton or the electron has to go or the neutron.

So the nucleus you might say that it doesn't contain an electron but then how the beta decay happens? In a beta decay, the neutron gets converted to a proton and an electron plus a neutrino which is a very small particle.

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Alpha rays/Particles

- When the ratio of neutrons to protons in the nucleus is too low, certain atoms restore the balance by emitting alpha particles. For example: Polonium-210 has 126 neutrons and 84 protons, a ratio of 1.50 to 1. Following radioactive decay by the emission of an alpha particle, the ratio becomes 124 neutrons to 82 protons, or 1.51 to 1. Alpha emitting atoms tend to have high Atomic Number.
- It is the most energetic (densely ionizing), but the least penetrating type of radiation. Alpha particles can be stopped by a sheet of paper.

Now let us get an idea of what this alpha rays, beta rays and gamma rays and then we'll also have a look at the, compare their effects or properties. Then the ratio of the neutrons to protons in the nucleus is low, then the atoms give out or emit alpha particles. Now you take Polonium-210, it has got 126 neutrons and 84 protons. And after a radioactive decay by emission of an alpha particle, it will have 124 neutrons and 82 protons. So this is how alpha emitting atoms are generally from high atomic number elements.

One thing about alpha, it is energetic, I would say not very deeply ionizing, it is the least penetrative of all the radiation. It could be stopped even by a sheet of paper but it is having large amount of energy.

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BETA PARTICLE

- Beta particle emission occurs when the ratio of neutrons to protons in the nucleus is too high. In this case, an excess neutron transforms into a proton and an electron. The proton stays in the nucleus and the electron is ejected energetically.
- This process decreases the number of neutrons by one and increases the number of protons by one. Since the number of protons in the nucleus of an atom determines the element, the conversion of a neutron to a proton actually changes the radionuclide to a different element

Then coming to the beta particle, this occurs when the ratio of the neutrons and protons in the nucleus is too high. So in that case, what happens? The excess neutron transforms as I mentioned into a proton and an electron. The proton stays in the nucleus and the electron is ejected out. So this process what happens, the number of neutrons is less by one, the number of protons increase by one. So here, this really changes, once the number of protons have changed, it becomes a different element.

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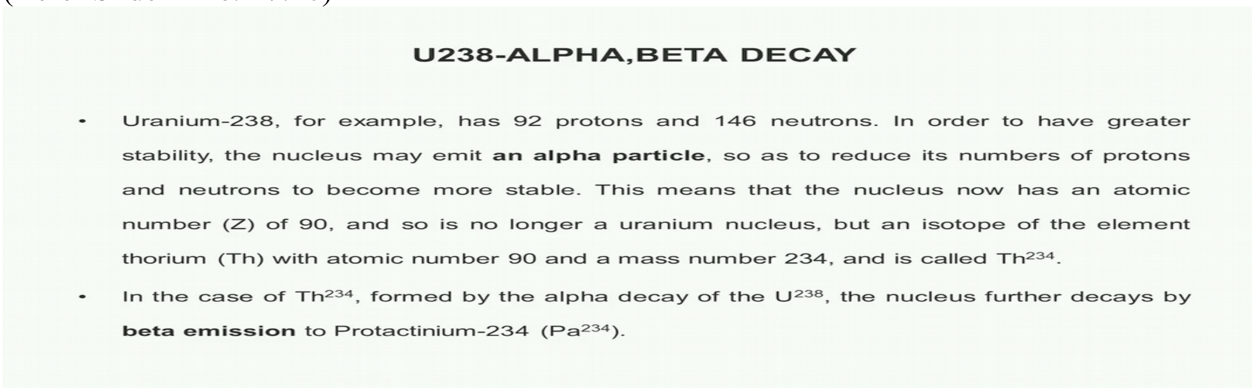

Let us take a look at Uranium-238 which is about 99.3% of our natural uranium. It has got 92 protons and 146 neutrons. What it does in order to have a good stability, it emits alpha particle. Then in that process, it reduces the number of protons as well as neutrons. Now, let us take with 92 protons we had in shell and two are gone, so now we have only 90. So the atomic number is 90. It is no more a uranium nucleus but it could be something similar to thorium because it has got an atomic number of 90 and a mass number of 234. We could call it as Thorium-234. Then this Thorium-234 which is formed by the alpha decay of Uranium-238 further decays by beta emission to Protactinium-234. So this is how the decays are continuously happening in the earth.

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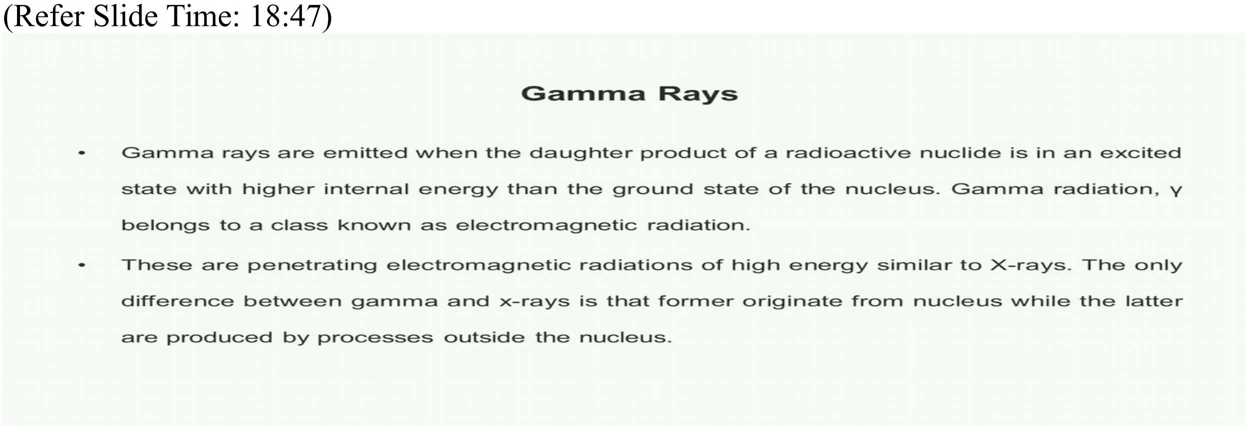

So these things are referred to as the alpha decay and beta decay. Then last but not the least, gamma rays because gamma rays are used very effectively in all applications which we have discussed in the first lecture; medicine, it has been used in sterilization, food preservation, everywhere we use gamma rays. These gamma rays are emitted when a radioactive nuclide is in an excited state with a high amount of internal energy, then it tries to come to a ground state of the nucleus, at that time it emits a gamma. It also belongs to the range of electromagnetic radiation. These gammas, they are penetrating. They are high energy; they just are similar to x-rays which you normally go through. The only difference is where they originate, in the case of gamma rays, they originate from a nucleus, whereas in the case of x-rays you produce it through some other means. So the production means are different.

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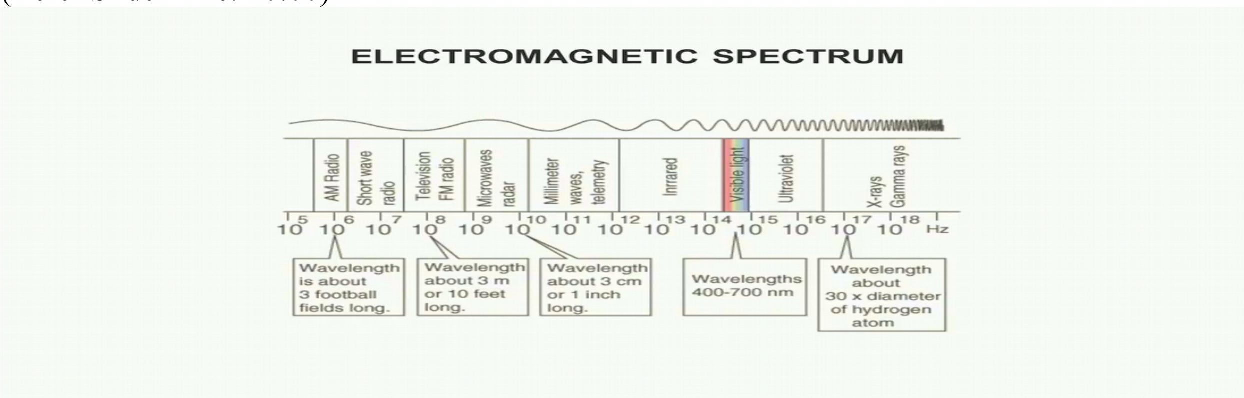

This is to give you an idea about the electromagnetic spectrum. Basically, you can see the visible light is there. To the left, you have the infrared, then microwaves, etc. All these things are also non-ionizing radiation. They don't ionize the material that is suppose you pass microwave through air or something, it doesn't get ionized whereas to the right of the visible light, on the right, you have x-rays, gamma rays. These are ionizing. So the difference is these ionize, they don't ionize.

So to an extent, ionizing is not good because they can affect our skin, our body, tissues, they can ionize. So it can cause harm. So that is why we feel that ionizing radiations we should be careful; non-ionizing, not that much, but it doesn't mean that non-ionizing don't have any effects.

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PROPERTIES –ALPHA,BETA,GAMMA

Property	Alpha	Beta	Gamma	Neutron
Nature	Particle	particle	Electromagnetic radiation	Particle
Electric Charge	Positive	Negative	None	None
Speed	Varies with energy	Varies with energy	Constant and equal to that of light	Varies with energy
Penetrating power	Poor: Can be stopped by a sheet of paper	Poor; can be stopped by a thin metal sheet	Good: Highly penetrating at relatively high energies	Good: Highly penetrating at relatively high energies

Now let us just compare the properties of the alpha, beta, gamma and neutron very aptly put in the table. I told about the charges, positive, alpha, it's an electric charge; beta is negative; gamma has no charge; neutron also has no charge.

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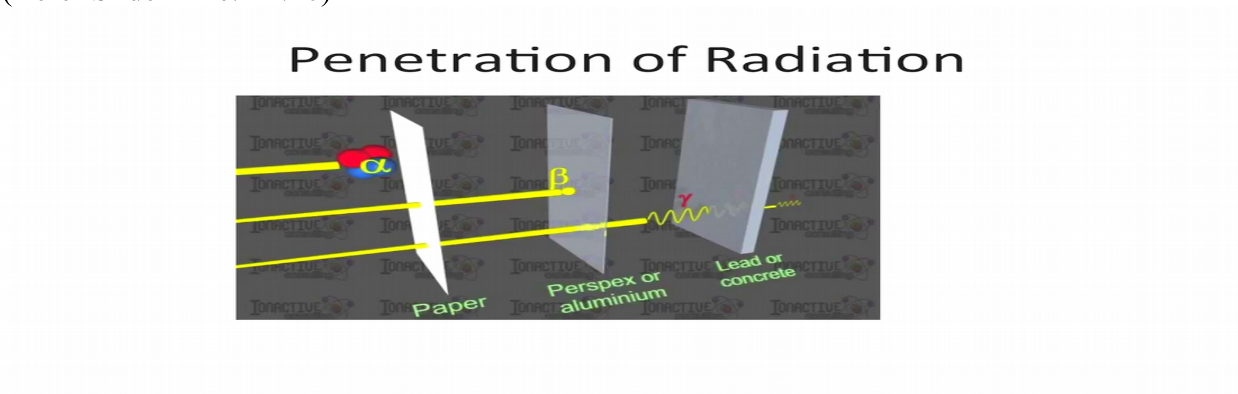

The penetrating power is most important. Very poor penetrating power with alpha as I said; a sheet of paper can stop. When you go to beta, again, it's not much penetrating, maybe a metal sheet could stop. But gamma, it is highly penetrating and really requires a very good shield, maybe lead is one of the very good shielding materials. Even neutrons, they are also highly penetrating. So you would really take protection from neutrons also again through lead or concrete.

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Radioactive Decay Law

- The nucleus of a radioisotope emits radiation of a specific type and energy. The radioactive half life is the time period in which half of the nuclei initially present undergo radioactive transformation. Some radioisotopes have a very short half life of the order of fraction of a second, while there are others that are long lived with a half life that runs into millions of years.
- The number of disintegrations occurring in unit time is proportional to the number of radioactive atoms present. From either approach the mathematical expression for the rate of decay is $dN/dt = -\lambda N$, where N is the number of radioactive atoms at a given time λ is the "decay constant," which is a measure of the decay probability.

If you look at these radioactive elements, I said elements which are unstable elements are radioactive; they emit alpha, beta, gamma radiation and they try to become more stable. So these as they keep on emitting radiation, they are coming down, they get transformed into another element and then goes on. But how this continues? Maybe let us say, in the beginning, we had some 100 radioactive atoms, well, 100 radioactive atoms will decay. Finally, at a stage, let us say we have come down to 50 radioactive atoms still left. Then this time period which takes from

100 to 50 is what we refer to as half-life. Half-life of the nucleus is a measure of how long you are going to get the radiation. So we would prefer a very short life, half-life means okay, the effect will go fast. If it is a long half-life you have to take care, you have to really store that material properly.

Now there are materials, radioactive elements which have a fraction of a second of half-life, some running into millions of years. Now in a mathematical way we can always say that the rate of decay of an element is proportional to the number of elements. So we can represent mathematically by saying $dN/dt = -\lambda N$ where you can refer to λ as the decay constant.

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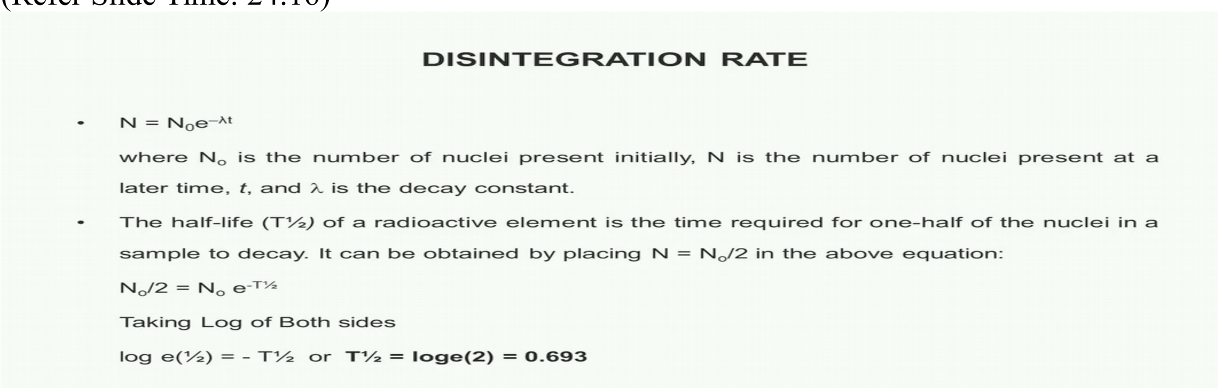

This when you integrate you'll get a solution as $N = N_0e^{-\lambda t}$ where your N_0 was the initially present number of nuclei and N will be after a time t how much is present and your λ is your decay constant.

If suppose I want to find out the half-life, that means N will become $N_0/2$. So I can find out the time. Time is about 0.693. So in other words, the 0.693 it reaches the time. Now we'll look at the rate at which radioactive element disintegrates. As I mentioned it is $dN/dt = -\lambda t$ which can be integrated as $N = N_0e^{-\lambda t}$ where N_0 is the number of nuclei which are present in shell and λ is a decay constant and N is the number of nuclei present at a later time.

If you go through the equation, if I substitute $N = N_0/2$ then I would be in a position to get the half-life. So half-life, let us see, how the half-life of different atoms are.

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HALF LIFE

In one half-life, the activity decays to one-half its initial value, or ½*Ao*. In two half lives it decays to ¼*Ao*, and so forth. This method can be applied to isotopes whose disintegration rates changes appreciably over a reasonable counting period.

This just gives a pictorial thing. In one half-life the activity decays by half. In two half-life, it decays by 1/4th and so on. So these are very easy way of knowing the half-life.

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Half Life Of Some Radioactive Elements

Radio nuclide	Half Life(approx)
RADON-210	4 s
IODINE-131	8days
COBALT-60	5 years
CAESIUM-137	30 years
CARBON-14	5730 years
URANIUM-235	0.7 billion years
POTTASSIUM-40	1.3 billion years

These are some of the important radioactive elements of concern and you just have a look at their half-life. You take Radon-210 which comes from radium. It has got half-life of only four seconds. Iodine-131, it has got about eight days. Iodine-131 is one of the important radioactive things which come in the gaseous form. Cobalt-60, five years half-life; Caesium-137, 30 years. Then look at Carbon-14, 5730 years. And our Uranium-235, 0.7 billion years, and Potassium-40, 1.3 billion years. So that means whatever Uranium-235 we are getting now must have existed billions and billions of years ago; it is not something man-made and Postassium-40 is much more. I can tell you, Postassium-40 is very much available in the soil everywhere. The footsteps which we take, we do get in Potassium-40, all of us have Potassium-40 inside our body. It is radioactive and okay, we are living with it. There’s nothing to be concerned about it.

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SUMMARY

- Structure of the atom
- Isotopes
- Nuclear Stability
- Alpha, Beta and Gamma rays
- Radioactive decay-Half life

Now this talk which I have gone through has exposed you to basically what is the structure of the atom, then I have talked about what are the constituents in the atoms; the neutrons, the electrons and the protons. Then why some elements are stable, some elements are unstable and we have looked at what these unstable elements do to become stable, that is what is called as the radioactivity, they release radioactivity in the form of alpha particles, the beta particles or the gamma particles or the gamma rays, and then we also went into the concept of radioactive decay half-life wherein we compared the half-life of different materials, nuclear materials.

Thank you.

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