

welcome all of you for the last lecture probably in this series on properties of a nucleus

so before we started describing the properties of a nucleus we also looked at atom the bohr model and before that we also studied photoelectric effect view particle duality and

so on

so in a sense as i told you in all probability we will be concluding this set of lectures today i cannot claim that i have covered all the topics in your syllabus but whatever is a matter of information or whatever you can easily pick up i have left it out but i will certainly indicate what is it that i have left out as i go along in the last lecture what we did was to look at great detail on the process of fusion

so we were able to understand the processes that are going in the stars especially our own star the sun as to how such an enormous energy is related and although we did not even attempt to describe qualitatively the theory underlying a fusion process it is way way beyond your 12th standard in fact it is way beyond even in your undergraduate studies just by making use of mass energy equivalence and energy conservation we were able to work out what we will call as energetics and argue how energy is produced and how is able to sustain itself that is only one part of the story because there is the other part of the story where the nucleus can actually decay in the first case that we have studied in about two or three lectures is the coming of later nuclei together to produce heavier nuclei and in that process there is a mass defect they lose some of their mass

so produce a daughter which has a higher value of a atomic number or atomic weight higher value of z but then it has lesser mass than the masses of the incoming particles and energy is liberated that is what we found and i described some cycles for you carbon cycle etcetera etcetera and i told you that eventually everything should end up with iron because iron is the most stable of the nuclei it has the maximum binding energy per nucleon therefore iron cannot go to anything by itself unless you are going to violently perturb that act on it you can always break iron for example if you send very highly energetic proton or a neutron another nucleus but by itself it is a very very stable nucleus that is the statement that we made today what i want to do is to look at the other side other side of iron nucleus which will give rise to fission and also the unstable isotopes of various nuclei it could be carbon it could be boron whatever whatever is that okay as to how they undergo dk there are essentially three decay mechanisms the so-called alpha beta and gamma alpha refers to helium nuclei beta refers to either electron or a positron and gamma of course is electromagnetic radiation what we call as the photon

so before i start discussing that i should actually round off my discussion something by telling you something about the age of the stars remember we told that as the mass of the new sun keeps earning star keeps on increasing its lifetime actually keeps on decreasing because there is more and more material and therefore there is more and more fusion that is taking place

so what we are interested in is actually showing you as to how the lifetime of a star depends on its mass

so that is the first thing that i am going to look at and this is a brief recall of the carbon cycle that i told you as to how you start with hydrogen you produce helium and then go via lithium and then produce a carbon which is a fairly stable isotope because it sits on the top in the among its neighbors in the binding energy per nucleon what we want to do is to show you the effect of this on the masses of the stars

so this is the picture that i have been repeatedly showing you

so if you look at it

so i am going to focus on carbon you see carbons binding energy per nucleon is larger than all its neighbors and of course oxygen is even larger

so that is the next cycle but at the top most in this whole spectrum of binding energy per nucleon is iron this is something that you have to remember that means if you look at nucleic molybdenum or tungsten or whatever or uranium they would all like to decay and come back to iron whereas these fellows would like to keep on fusing and come back to iron provided sufficient conditions like temperature or whatever are there for fusion processors and this is a figure or a graph which should hold very close to your heart it is an extraordinarily informative graph

so here is the lifetime which i have picked up from literature

so now you see our standard for the mass of the sun is of course sun

so when i say it is one it actually refers to one solar mass

so our sun would typically live for about 10 billion years and if you imagine that the solar system and the star the sun they were all formed roughly at the same time okay because of collision between two stars or whatever depending on the astrophysical model then our earth is about a few billion years old maybe two or two and a half billion years worth

so we need not really worry about what the fate of the sun will be for the next eight billion years it is an enormous enormous time now if i jack up the mass by let us say a factor of one and a half you see correspondingly the lifetime comes down to three billion it goes down by a factor of three it goes up by three factor of three it becomes three seventy million

so it is falling very very fast in a super exponential manner probably certainly in an exponential manner ok with a very very large value of the decay constant whatever that constant is and by the time the mass acquires something mass of a star is something like 60 times the mass of the sun it leaves would be to live only for a few million years three million years dinosaurs i think were there a few million years ago

so this is an extraordinary thing and this can be estimated simply by the know the amount of nuclei that are there the rate at which they are burning etcetera etcetera simple kinetics

so i would encourage all of you to see that if you come back to this graph of course i should also mention what would happen if there is a super light star let us say of  $\theta$ .

1 that would live for thousands and thousands of billions of years

so stay light live longer is not only the dictum given to us humans we should not become too obese at any age it seems to be also true of the stars ok

so i want to whatever i told you i would like to repeat because it certainly bears repetition it is a very important thing and this graph clearly shows you on the left hand side it is diffusion that generates energy on the right hand side it is the fission that generates energy okay iron is standing at the border line and you have all these things copper molybdenum strontium tin xenon etcetera etcetera

so whatever was shown in the previous graph is reiterated by showing the line explicitly ok this sort of concludes ah whatever i had to round off from my previous lectures what we are now going to do is to look at new phenomena namely fusion radioactivity gamma d k gamma dk of course is also a part of radioactivity but then i have written it separately because it is a slightly different phenomenon compared to the others i will tell you why in a minute and that is the reason why i have written it separately these are the things that we are going to look at

so let us start with nuclear fission and remember i have shown you the graph

the condition for a nucleus to break into smaller nuclei is  $Z^2$  must be greater than forty seven that is a very very important thing if you look at the lighter nuclei the most stable ones are those for which  $Z$  is equal to roughly  $A$  is equal to roughly equal to  $A$  equal number of sorry equal number of not a equal number of protons and equal number of neutrons will be there that is equal to  $A$  by two but as we keep on going to heavier and heavier nuclei the nucleus becomes bigger and bigger we know that  $r$  equal to  $r$  naught  $A$  to the power of one third that is what we are writing

so the nucleus becomes bigger and bigger when the nucleus becomes bigger and bigger the strong interaction the nuclear force between distant nucleons either protons or neutrons or protons and neutrons become weaker because i told you nuclear force is a very very short range force but on the other hand the repulsion between the protons and the neutrons keeps on increasing that becomes dominant because of the electromagnetic force therefore what you do is to actually tend to increase the number of neutrons to compensate and that is the reason why this is an important parameter that squared by  $A$  must be greater than 47

so here is a canonical example which i am showing the famous decay of the uranium 235 uranium its spontaneously undergoes a decay into 140 xenon plus 92 strontium and it emits three neutrons in that process

so you can add them up and you can see what you are going to get and the energy liberated is about 173 mm

so one might say we have an unlimited source of energy because all that we have to do is to collect some heavy nuclei put them together and then they will start producing energy by decay i do not have to do anything at all just as i am receiving the radiation or energy from the sun but the catch is that the probability per decay is  $10$  to the power of minus 11 per second

so on an average if you have  $10$  to the power of 11 nuclei maybe one of them would decay

so it does not do much for us is that ok and that is the reason why we are not interested in spontaneous fission but we are interested in what is called as an induced fission i am not going to get much into it

so this is something that you can remember

so there are certain thumb rules in that we have to follow and i am sure you people would have worked it out any number of times in your class

so what are we going to write there is a parent nucleus which is going to  $x_1$  plus  $x_2$  maybe some alpha particles actually that also i can write it as a nucleus but let me write it explicitly maybe some betas and maybe some gammas

so this is what i am going to write

so this is some kind of a generic process it split into two nuclei i am showing helium separately because we are interested in alpha dk in that process it may emit some beta and it may emit some gamma

so i will put an  $n_1$  beta and then  $n_2$  gamma it let us say it emitted  $n_1$  beta particles and  $n_2$  gamma now this beta itself can come in two species that we are going to see

so it can either be the electron and it can be the positron is it ok

so this will be let us say  $r_1$  and this will be  $r_2$   $r_1$  plus  $r_2$  is equal to  $n_1$  that is what we are writing the total number

so what is the statement that we want to make in this process there are two things that we have to check that is this product initial quantity  $A$  should be heavier than the sum of the masses of all these fellows the mass of  $A$  should be greater than the sum of the masses of all the outgoing particles including the energy of the gamma particles number one number two you should conserve total charge remember my protons carry a positive charge my positrons are the

so called beta plus carry a positive charge and electron carries a negative charge

so in all these processes the basic account keeping involves conservation of energy mass defect and conservation of total charge

so in your exam you will be asked any number of chains and you will be asked tell me how many protons decayed how many neutrons came out all that to do is to balance this is that okay but before i do that i should know a little bit more about beta tk and that is what i am going to come to in this so what are we going to do when we look at beta dk

so basically as i told you my beta minus is notation for electron beta plus is the notation for the positron this is a hangover from earlier days of nuclear radioactivity when people knew nothing about the electrons or the basic particles the electron was being just discovered

so all of them were called as radiations because they produce some kind of scintillation or whatever on the detector and then what people did was to actually put magnetic fields and actually ascertain that they were carrying a charge positron was of course discovered much much later but anyway

so these are the things that people have seen is that okay

so the notation is beta minus this electron beta plus is positron alpha is nothing but the nucleus the

so called helium nucleus and gamma is nothing but your photon that is what we have and let us see what is happening the first thing that we have to look at is the gamma dk because it is the simplest in the case of gamma dk actually a nucleus is not undergoing any dk we all the time speak of radioactive decay radioactive decay actually gamma is an example where there is no radioactivity ok it is a perfect analog of the atomic de-excitation

so let me remind you what we studied in the case of the atoms

so in the case of atoms for example hydrogen

so you have the ground state and you have the first excited state second excited states one and

so forth and if i remember correctly this gap is ten point four electron volts well this must be n equal to two this is equal to one this is n equal to 3

so basically 13.

6 divided by 4

so that gives me 4 3's are 12 3.

4 that is what i have

so 13.

6 to 10

so it is not 10.

4 but 10.

2 electron volts

so what do you do in the case of hydrogen atom for example you can heat the hydrogen atom to a very high temperature what would be the temperature be of the order of let us say 10 electron volts one electron volt is something like 10 to the power of 4 kelvin

so let us say 10 to the power of 5 kelvin is what you are going to do is that ok 0.

1 million 1 lakh kelvin is that ok at that temperature there will be enough energy to excite the hydrogen atom into the first excited state and then what will you do it will emit it will get de-excited and come to the ground state the atom is not doing it was in an excited state and then it simply comes down by what is called a spontaneous emission and it produces a gamma

so it produces a gamma in that particular process and that is what you study of course you can study the inverse process i can send radiation of the order of

10.

2 electron volts and then you will see that there will be an absorption and it will go and sit there and after a while it will come down whatever is given by the dynamics of electromagnetic interactions is that ok that lifetime and then what you see is a sharp plane with  $10$  to the power of whatever  $10$  point electron volts coming and this is a de-excitation process in a similar manner if i were to go to the nucleus

so far we have discussed only what the size of the nucleus the mass of the nucleus etcetera etcetera right  $r$  equal to  $r$  naught  $e$  to the power of one third how the volume depends on a

so on and

so forth actually it turns out just as atoms have excited states molecules have excited states okay in a similar manner nuclei also have excited states this was known when people started studying nuclear reactions

so in those reactions for example when if you excite it it has to come down to the original state the nucleus has not changed its identity or its nature at all except that it was sitting in an upper level it comes down as to what the energies of the excited states are that is a different matter altogether but when such a thing happens when it comes down it emits gamma rays just as my atom emits gamma rays that is what is happening

so i have given you two examples here here is  $10$  beryllium in its first excited state it comes to the ground state by emitting a photon is that ok in a similar manner here is a heavier nucleus  $13756$  barium is that ok everyone has heard of barium that again comes down it from its first excited state to the ground state now suppose somebody showed you the information on the photon emitted by an atom and the photon emitted by a nucleus how would you distinguish whether it came from there or not the answer is always in the length scale the time scale and the energy scale atomic phenomena are governed by energies of the orders of electron volt whereas nuclear phenomena are always governed by the orders of a million electron volt that is what you found in fusion right mass defect is of the order of  $mv$  in a similar manner if strong interactions are strong and have a sharp range of about a per  $me$   $10$  to the power of minus  $15$  meters from that we can infer that the corresponding energy scale is about a million electron volt

so this will be typically of the orders of million electron volts they are very very highly energy take gamma particles is that ok they have and that is what we see and the most important thing is that you see neither the atomic weight nor the atomic number changes of course the energy changes because you had supplied some internal energy to the system that is something that your people have studied in your thermodynamics course

so whatever energy you supplied that went as an inter energy of the atom and then it got de-excited and it comes

so this is about the grammatical the next one is what we call as alpha dk and here is a nice picture which is telling you how  $240$  i think it is plutonium is going to uranium and then alpha particle

so when we are looking at alpha t k and the gamma decay we have to make a fundamental discussion the distinction and that is why i am going to see showing you this specially

so you can see that initial value of a what is here the nuclear number the total number of protons and neutrons was  $240$  and the final one is  $236$  that means it has lost four nucleons that means the total number of protons and the total number of neutrons lost is equal to  $4$  but now if i look at the charge initially the total number of protons was  $94$  in the parent nucleus in the daughter nucleus it is  $92$  that means it has lost two protons that means the whatever has come out because of the decay the particle is carrying four nucleons and a charge of two

that means its helium nucleus  $4\text{He}$  that is what we have

so let me write down explicitly because that will be an example for us throughout because i am not going to work these problems anymore

so what we have is  $240\text{Pu}_{94}$  going to  $236\text{U}_{92}$  plus  $4\text{He}_2$

so what is the balancing that we have to do  $236 + 4 = 240$   $92 + 2 = 94$  but it does not end here what should you do you should look at the mass of plutonium you should look at the mass of uranium and you should look at the mass of helium

so what we shall do is to see that my  $240\text{Pu}_{94}$  has decayed into  $236\text{U}_{92}$  and  $4\text{He}_2$ .

so what is it that i was telling you  $236 + 4 = 240$   $92 + 2 = 94$  therefore we have taken care of the total number of protons and the neutrons but more important is that i have to look at the mass of the parent nucleus and the two daughter nuclei is that ok we call this as a particle although that is also a nuclei

so if i look at  $m_{\text{Pu}}$  and i look at  $m_{\text{U}}$  and i look at  $m_{\text{He}}$  i am looking at this what am i saying this has a rest energy associated given by  $m_{\text{Pu}}c^2$  this has a  $c^2$  and this is  $s^2$  and this is greater than this plus this

so this  $\Delta K$  was possible because the total energy contained in my original nucleus  $m_{\text{Pu}}c^2$  is greater than the rest energy is contained

so what is happening to the rest it will go as the kinetic energy remember my alpha particle is produced with a certain momentum

so it starts coming with a momentum if my nucleus is decaying at rest there is a recoil momentum

so that goes as the kinetic energy of the two particles and in any case there is a jargon which you people should know and that is  $m_{\text{parent}} - m_{\text{d1}} - m_{\text{d2}}$

so i am writing alpha  $\Delta K$  right

so let me call it as helium  $m_{\text{He}}$  this into  $c^2$  is called the  $Q$  factor basically it is the mass defect multiplied by the  $c^2$  and this is responsible for decay

so this is the same old mantra everywhere that is

so good what we are going to say energy conservation momentum conservation charge conservation these are the three accountants whom we should always respect and whom we can never violate

so that is an important statement that you have to note and that is what we are going to do now comes the beta decay process and the point that i want to make for you is that there is a fundamental difference between beta  $\Delta K$  and alpha decay

so maybe i made a comment in the previous slide

so if you look at the top there is a statement which i made there is called a compound nucleus

so in this process you can actually pretend as if my plutonium is a compound nucleus it is a compound just as you know elements forms atoms forms compounds molecules is that right that is what we are going to form in a similar manner we can to some extent in fact to a large extent assume that my plutonium itself is a compound of what uranium and alpha particle and it just turns out it is not a very stable compound it decays and when it is going to decay what is going to happen the one of the constituents from the compound comes out and then that is what we are going to see but then when i am starting looking at beta decay my beta decay is coming

so this is the universal feature let me first discuss the universal feature and

then go to the distinction you have a x z

so what do you mean by that a is my atomic number my set is my atomic weight that is my atomic number let us call a as the nucleon number

so when it decays my electron has negligible mass remember my proton is 2000 times heavier than an electron

so i do not worry about that small quantity here in any case the total number of protons and nucleons will remain the same but the total number of protons will increase because i produce an electron i produce an extra charge and the total charge should be conserved therefore what should happen initially if there were that protons there must be z plus one protons that means one of the neutrons actually emitted an electron and it became a proton that is something that we are going to look at and the other piece of information that you should be familiar with that is that although initially becquerel and curie and all these people could not see this it was actually initially proposed predicted by poli based on conservation of angular momentum

so on and

so forth it is accompanied by a particle called antineutrino which you denote by  $\bar{\nu}$  at this point you do not have to worry too much about what the properties of the antineutrino are what its nature is except that for all practical purposes it is something like photon that is it always it travels with the speed of light it has no rest mass is that ok and it is also something like an electron because just as electron carries spin half we discussed that intrinsic spin my anti-neutrino also carries a spin half now the other process is the beta plus dk remember i told you beta plus is the positron what happens in this particular case if i have emitted a positron that means the total charge in the protons plus neutrons must go down that means my one of my protons becomes a neutron the total number remains the same but the number of protons decreases and in that process it emits a neutrino neutrino and antineutrino they are both massless they don't have charge they don't have spin but still they are distinct particles they are distinct particles and how do you distinguish them it is like you know in your chemistry course you study about left-handed molecules and the right-handed molecules some molecules go like a right-handed spiral some molecules go like a left handed spiral there is a corresponding properties between neutrino and antineutrino you do not have to worry about that so they are distinct particles because of their chirality or the handedness nature is that ok

so this is the universal feature that is something that we have to know what then is the difference between alpha dka and a beta decay

so let us spend some time on that that is very very important i have already hinted at that for you in the case of alpha dk the four particles two neutrons plus two protons were inside the nucleus

so this is like an escape just as you know a person can escape from a prison or a confined area the person was already there it is thus that you were able to break open the barrier and come out what is happening is that the particles were already there and it simply break open the barrier and they come out because and for that reason we say there is no production as such in the sense that production is a production of something which was not there but when it comes to beta dk i told you that when i write a x z there are z protons and a minus that neutrons there are no beta minus or beta plus that is the most important thing

so what happens is that the particles undergo a transmutation that is the most important word is that ok they undergo a transmutation they undergo a change in the property

so what happens a neutron actually becomes a proton in fact that is going to come in the next example and then it produces an electron and then it produces a

anti-neutral now that is the most important thing in a similar manner my proton  
i will put a star here i will let you know why can become a neutron plus a  
positron or your beta particle plus a neutrino

so when a proton in a nucleus becomes a neutron we say that there is a beta  
plus decay when a neutron becomes a proton we say there is a beta minus dk you  
see the particles have changed initially the particle did not have any charge at  
all but now it has acquired a charge it is a strongly interacting particle  
initially my proton had a charge but after the decay it lost its charge but it  
continues to interact strongly and in that process it produced a particle which  
was not existing it gave birth to two particles actually in this case it  
produced an electron and an anti-neutrino here it produced a positron in the  
neutron that is what it did and therefore although in the initial days of  
nuclear radioactivity when pacquiao and the curie couple discovered they did not  
make any distinction they called all of them decays alpha beta gamma etcetera  
there are fundamental distinctions gamma is because of the de-excitation alpha  
is because of the escape of two protons and two neutrons and beta is because of  
the production of new particles that is something that we have to remember i  
have put a star on a proton and i will tell you why and for that what we shall  
do is to go to the next slide ok i think i will come back to this slide after  
looking at this particular example

so the first example that you see here is my neutron going to proton plus  
electron plus anti-neutrino remember there is always one person who is all the  
time looking behind us and saying to it that we do not cheat and what is the  
cheating that we should not do we shall not violate conservation of energy  
conservation of momentum and conservation of charge now if you therefore look at  
it you see my neutron is becoming a proton an electron and an antineutrino first  
thing is to conserve charge my neutron is a neutral particle i am sorry about  
that my neutron is a neutral particle it produced a positively charged particle  
namely the proton it produces a negatively charged particle electron the  
magnitude of the two are the same therefore the net charge is zero and  
anti-neutrino of course does not carry any charge

so it is perfectly fine now if you go to the other example this is what we are  
interested in 14 carbon is an isotope of carbon 12 carbon is a stable isotope 14  
carbon is not a stable isotope

so what 14 carbon does is to look at its surrounding nuclei with the same a is  
that ok and 14 new nitrogen actually turns out to have a lesser mass

so what does it do it says i will go and sit in the state with lesser energy  
and in that process it produces an electron

so what is happening one of the neutrons in the 14 carbon becomes a proton

so it goes to 14 nitrogen it emits an electron and it is a new bar and that is  
also perfectly consistent no problem at all but the most interesting case is 10  
carbon 10 carbon is again another isotope what have you done you still have 6  
protons but you have only 4 neutrons that is what you have done if you look at  
this it is producing 10 boron which is very good and it is oh ok thank you

so it is producing a neutrino and a positron that means what are we saying one  
of the protons converted into a neutron

so let me make a few statements on that

so basically we are saying that the fundamental process is proton going to  
neutron plus in a plus nu now we are in for trouble if you go back and look at  
the masses my mass of the proton is less than mass of the neutron that means we  
are not conserving energy and of course that must be correct because hydrogen is  
stable hydrogen atoms have been there for billions of years they are not going  
to decay into anything proton is a stable particle whereas neutron is not stable  
you all know that it has a half life about 13 minutes or

so so if that be the case if i come back to this picture how is it that my in this carbon decay my proton is able to go to a positron and the answer to that is in what i am going to write and that is what i have to explain i said p star goes to neutron plus e plus plus nu although a free proton cannot decay into your neutron a proton inside a nucleus can decay because there are other surrounding particles which can give the missing energy therefore what we have to do is to worry about the conservation of total energy is that okay and not of individual constituents that is something that you have to remember therefore what should we do when i come back and look at this i should look at the mass of 10 carbon i should look at the mass of 10 boron i should look at nu i should look at e plus then what will it give me it will immediately give me consistency with conservation of energy conservation of momentum conservation of charge and this process is therefore allowed

so in that sense we have looked at three particular processes the gamma dk the alpha tk and of course the beta dk and we have found out what the distinctions between them are all of them of course are coming from a nucleus in that sense they are common but they are also different from each other but then it is also true that they share one more common feature and that is in the law that governs their decay that is the famous law of radioactivity which i am going to come to so you see to club them all under radioactivity is not incorrect it is perfectly fine provided we understand the distinctions between these three processes that is something that we have to remember of course if you give me a nucleus it is not going to tell me i will only going to dk this way that way or anything

so here is an example probably it is there in your text book of what we call as a chain reaction what is a chain a goes to b b goes to c c goes to d etcetera etcetera

so it will trigger a chain of reactions that is what we have

so here my parent is thorium 232 90 what will it do it will first emit an alpha particle and produces 224 88 radium is that ok that is what it is going to produce now this radium is also unstable because of the i told you how the mass factors are

so that will produce actinium which is 228.

89 by a beta dk you see therefore they will look at which is the plus place for them to go that is what they are going to do actinium goes to thorium again do not confuse this thorium with this thorium there are two different isotopes here it was 232 here it was 228 that means there is an extra 4 neutrons in this then it produces a c minus and thorium again goes to another isotope of radium and 4 h2e

so in this process when i start with a heavy nucleus it will start looking all around its surroundings and it will keep on emitting particle going to the nearest neighbor which is favorable because of the proximity because of the energy difference because of charge conservation because of the rate at which processes go the rate at which gamma emission takes place is not the rate at which beta emission takes place is not the rate at which alpha particle takes place is that okay they are all governed by different dynamics

so i am not telling you anything about the time scale here

so if you look at this this is what is an example of a chain reaction

so this chain reaction is illustrated very nicely is that okay it is color coded

so even if you can't see what it is you don't have to worry is that okay basically you start with uranium 238

so this is what i am showing it keeps on coming

so whenever there is this pink color you call it as an alpha particle

so whenever there is a blue for example that means it has emitted a beta is that ok and of course this lead 206 is a stable nucleus and after that there is no further decay it is going to sit there is that okay when i say beta it may be either beta plus or beta minus again depending on the energetics is that ok there is a nuclear stability line you have to go either to the right or left depending on whichever is more favorable

so this is a very nice process that you have and of course you have to give the credit to the radioactive dot eu.

com who have carefully made this figure and compiled it this is a very very nice example this is another example of the same kind which is more involved and i wrote the first few fellows for you

so you do not have to worry about that

so let us stop there

so in other words we have fairly well understood the qualitative features of what is happening with what the radioactive processes alpha beta alpha dk beta decay and gamma dk now we have to go to the quantitative features as i told you in the quantitative features what is happening is that all of them are governed by a universal law however in stating this universal law i should be very very cautious and careful i should also try to be precise because otherwise it conveys an impre a completely different impression which happens many times when you read the book

so what are the things that we have to know the things that we have to know is to start with this slide actually i am going to look at the third line in radioactive decay what matters is probability that is the most important thing and maybe i should spend one or two minutes on that all of your classical mechanics is that ok newton's laws planetary motion etcetera etcetera were all completely governed by deterministic evolution that is there was no question of probability when you people solve you know you say my particle is an across the electric and magnetic field my charged particle it has an initial position and it has an initial momentum where will it be after a time t there is no question of probability you will predict it precisely in a similar manner a planet is in an orbit at this particular point it is at this particular position where will it be you know that that is how we are able to predict eclipses we are able to build machines we are able to do a whole lot of things with our technology because there is no question of probability of course you have probability in statistical mechanics but there are thermodynamics but there the probability is because we do not have the initial information the problem is not with the dynamics but with the lack of information but here when i come to law of radioactivity this probability is fundamental you give me all the information but you can never predict what the nucleus will do

so if there is a nucleus you cannot ask how long will a nucleus live you can only ask what is the probability that after a certain time it has survived or it has decayed that is the probability that we have to ask we have to write an equation for the probability

so that means when i speak of probability it is necessarily statistical in nature how do i verify laws of probability one sample is not going to be doing that you have to perform a large number of repeatable experiments keep on repeating them under identical conditions if you perform them then you will be able to extract probability that means you need law of large numbers

so for example you cannot ask a question there was one neutron and half of after about 13.

5 minutes what happened we do not know what happens it can either be there it cannot be there

so when we speak of half life or mean life or whatever you should understand it

is statistical in nature but unfortunately we frame questions like there were ten thousand nuclei radioactive nuclei at a certain time  $t$  given its  $\lambda$  how many nuclei are left after a certain time let us say  $t$  equal to 10 seconds strictly speaking it is not a very very good query to form when we say 10000 nuclei we are assuming that is a big enough number for us to realize probabilities but there are certainly bound to be some deviations that is something that we have to remember this feature should not be forgotten

so once we do that it is remarkable that people by looking at all these radioactive sources in fact mari curie succumbed to her experiments at those days people did not know that this hard radiation can actually cause cancer is that ok it did cause for her and she died because of that that obeys what is called as the law of radioactivity which i am going to come in a minute and i have written that

so if you give me the summaries here decay rate depends on the population at that instant

so what am i saying suppose at a given time  $t$  there are  $n$  of  $t$  number of parents let us call it as a nuclei then the decay rate depends on how many of them are there if there are very few of them then very few of them dk if there are very large number of them very large number of them decay that means underlying is probability that is what we are saying is that ok and this probability will get multiplied by the number of particles or number of nuclei that are there therefore number of decays is proportional to the number of participating nuclei there is nothing great about that therefore  $dn$  by  $dt$  is given by minus  $\lambda n$  of  $t$  that is the statement that we are making

so this rate depends on  $\lambda n$  of  $t$  that is what we have  $\lambda$  of course is a positive constant if  $\lambda$  is very very large lot of them decay if  $\lambda$  is very very small very few of them decay if  $\lambda$  equal to 0 of course none of them decays that is what we have

so if you look at  $r$  which is minus  $dn$  by  $dt$  that is called activity activity is nothing but the rate at which something decays is that ok therefore i have put a minus sign here

so  $r$  is  $\lambda$  into  $n$  of  $t$

so what is the equation that i am going to write let me write it for you my  $dn$  by  $dt$  minus  $\lambda n$  i should put a time here and i should put a time here that is what i am going to write and  $r$  by definition is  $\lambda n$  into  $t$  this is my activity

so if there is a decay process you see activity decreases with time this activity of course depends on time

so how are we going to write that  $r$  of  $t_1$  is  $\lambda n$  of  $t_1$  and  $n$  of  $t_1$  is  $n$  naught  $e$  to the power of  $-\lambda t_1$  ok we will come to that in a minute  $r$  of  $t_1$  is equal to  $\lambda n$  of  $t_1$   $r$  of  $t_2$  is  $\lambda n$  of  $t_2$   $t_2$  greater than  $t_1$  is what i am writing therefore  $r$  of  $t_2$  over  $r$  of  $t_1$  is  $n$  of  $t_2$  over  $n$  of  $t_1$  is less than 1 because as time passes number of nuclei which have not decayed become smaller and smaller there were many more at time  $t$  equal to one than  $t$  two

so with time my activity keep on decreasing if you look at the definition of my activity what did i write i wrote  $r$  of  $t$  is equal to  $\lambda n$  of  $t$  this is my number which is dimensionless and this is minus  $dn$  by  $dt$  therefore  $\lambda$  is dimension of  $\lambda$  is one over  $t$  that is the time scale its inverse is the time scale for the dk of a particle

so my dimension of  $r$  of  $t$  activity is one over  $t$  now when you speak of one over  $t$  which is something like the same dimension as the frequency you have to provide a units and there are two units one is  $s^{-1}$  in which it becomes second inverse and another is curi c i usual people should be familiar with that

so let me write it again here

so my lambda has two dimension units in s<sup>-1</sup> which is second inverse it is called becquerel is the person who discovered the radioactive phenomenon of radioactivity and another is curi it is denoted by Ci which is curi becquerel is not a practical unit like for example if you want to study atomic physics you are not going to use meter or centimeter it is not a practical unit or if i want to give the length of a table i am not going to give it to you nanometers it is not a practical unit in a similar manner if you want to study the activity for radioactive phenomena curie is a practical unit

so i have written it down here that is equal to three point seven into ten to the power of ten becquerel you get the point right i am not going to

so t in three into ten to the power of ten per second that is what you are going to write

so you wait for that long and normally all of activity is given for example if you go to a hospital where radiation is done or a nuclear reactor etcetera etcetera query is the unit that is being used and that is the first thing about the decay i have not written down one slide which is of course which can of course be worked out at this particular point and that is the solution and all of you are completely familiar that dk law equation

so if i write  $dN/dt$  is equal to minus lambda N of t i can integrate it dN by N minus lambda dt

so i am going to integrate it from 0 to t zero to t

so what will i get i will get log N of t by N of 0 is minus lambda t that is what i am going to get

so what is my solution my solution is simply given by N of t is equal to N naught e to the power of minus lambda t all of you are thoroughly familiar with this and this is what is called as an exponential decay this is what is called as an exponential dk it is not a linear decay in a linear decay the rate or the velocity would be independent of time particle is moving with a uniform velocity the particle has having a uniform deceleration that does not depend on time whereas here it depends it is an exponential decay it falls off very very rapidly

so once you realize that there are two important physical concepts and that is contained in this particular slide okay and those two concepts are half life and mean life

so half life is given by  $\log_2$  by lambda mean life is given by  $1/\lambda$  let me explain that to you and leave you

so what do we have half life

so what does half life mean N of t is equal to N naught e to the power of minus lambda t at t equal to zero N equal to N naught at t equal to t half that is the notation right t half N equal to N naught by two

so roughly half of them will survive at some particular time and this is called half life and this is a very important concept because this half life is how we characterize the decay of most of the things and obviously there is only one time scale lambda therefore it should depend on that

so let us calculate that

so what would that quantity be

so we are interested in N of t half is equal to N naught e to the power of minus lambda t half is equal to N naught by 2 that is what we are writing therefore e to the power of minus lambda t half is equal to half that is what we have and i will leave it as an exercise therefore my t half is nothing but  $\log_2$  by lambda one minor point to which you should pay attention is that this is in the natural logarithm and we are not treating the common logarithm anyway its value is known 0.

693 this is what you have now there is something called the mean time which is

an average time and that is a pretension why is it a pretension because we say that suppose the rate were the same but now the question comes how can the rate be the same the rate is keep on changing the rate depends on the total number so now i what i ask is in order to discuss the mean life when would all the particles decay if the rate were the same at  $t$  equal to zero that is a question that we ask the answer to that is very very easy to find out in that case we would have written  $n$  of  $t$  is equal to  $n$  naught minus  $\lambda n$  naught into  $t$  and this is not the real  $n$  naught i will put an  $n$  bar is that ok and  $n$  bar equal to  $\theta$  when  $t$  equal to  $1$  over  $\lambda$  identically equal to  $\tau$  that is what we write therefore  $\tau$  is my mean time and  $\log 2$  by  $\lambda$

so they differ by a factor of  $\log 2$  is my half life obviously mean lifetime is not a very very important concept but certainly the half life is an extraordinarily important concept and this figure tells you what it is

so we have plotted  $n$  as a function of time  $t$  half is the time at which the number of nuclei becomes half its original value whereas  $\tau$  is an extrapolated value at this point i will calculate the tangent to the curve and extrapolate i will get  $\tau$  this is  $1$  over  $\lambda$  this is  $t$  half is that okay  $r^2$  over  $\lambda$  and this picture should illustrate for you whatever is happening there are two more things that i should tell you i don't have to write in general there are going to be sequential processes i told you the chain

so let us look at the sequential processes a 1 d case to a 2 by a constant  $\lambda_1$  at a rate  $\lambda_1$  given by the constant  $\lambda_1$  a 2 goes to a 3 given by  $\lambda_2$  unless it hits this table a  $n$  how will we write the equation first we will write  $d_1$  by  $d t$  is minus  $\lambda_1 n_1 t$  but when i do  $dn_2$  by  $dt$  of course that depends on how fast it decays therefore  $\lambda_1 n_1 t$  minus  $\lambda_2$  into  $t$  so on and

so forth

so you know how to write a chain of equations and you know how to solve them you do not have to get into that in a similar manner if there are multiple decays suppose the same particle can go to multiple tks then you add them up

so that will give the relativity case and in this sense this essentially concludes whatever i had to tell you about the radioactive processes of diffusion and diffusion controlled fission i have not told you but you can read them up

so in some sense we have covered all of modern physics through this set of lectures and i hope that you will be benefiting from them ok have a great day you