Nuclear Physics
Fundamentals and Application

Prof. H.C. Verma
Department of Physics
Indian Institute of Technology, Kanpur

Lecture - 26
Beta decay

So, we discussed alpha decay; the key points I can summarize once again. All nuclei with mass number capital A greater than certain value somewhere around, say, 150 or so. Energetically they can decay through this alpha decay thing because that product nucleus the daughter nucleus and alpha particle rest mass energy of that is lower than the rest mass energy of the parent once this capital A is more than 150 or so. So, energetically it is favorable, but then there are many stable nuclei or very nearly stable nuclei beyond 150.

And we saw that the key feature is that alpha particle forms inside this bigger nucleus; of course, that preformation probability is also there, not that all heavy nuclei already have alpha particle. All the theory developed by gamma assumed something like that that preformation is also something which will depend on the nucleus, but it is an overall lowering of this total probability of decay as far as the variations are concerned it does not have much effect. And this alpha particle when it tries to come out of the nucleus, it encounters the coulomb potential barriers. So, that is the key feature that is the central feature.

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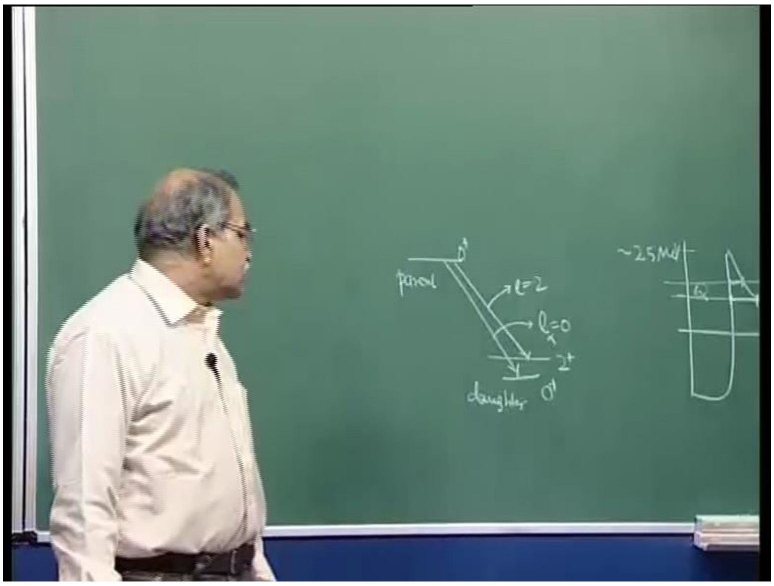

This alpha particle when it tries to come out, it encounters this coulomb barrier. The barrier height is around say 25 M e V or so, and the energy of the alpha particle which one can obtain experimentally once it comes out that energy somewhere around say 4 to 9 M e V. We manage the q value, and this is that barrier. And this barrier tunneling probability which is a purely quantum mechanics effect is almost solely responsible for this alpha decay. And this probability is very very sensitive with this q value; if q value is raised slightly, the width of the barrier to be crossed reduces considerably and the probability and harnesses.

So, about one mega electron volt raised in this q value will lead to hundred thousand times greater probability of this channeling. So, that explains how the variation of q from say 4 M e V to 9 M e V leads to some 25 orders of magnitude variation in the lifetime from say giga years to microseconds or so. We also saw that for even even nuclei, the ground state of the parent is 0 plus, and the ground state of the daughter is also 0 plus. And so, the alpha decay when it takes place from ground state to ground state that alpha is l equal to 0.

Angular momentum of that alpha particle is l equal to 0, but if it decays to higher states then you have l which is more than this will correspond to l equal to 0; this will correspond to l equal 2 and so on. So, if a alpha particle comes out with a nonzero angular momentum, then this potential barriers is raised because of that centrifugal term l l plus 1 h crosses square by 2 m r square. So, that will reduce the probability of tunneling, and that will increase the lifetime. So, the branching; what is the probability of going to ground state and what is the probability going to the excited state? That probability will be guided by this barrier tunneling probability with raised potential because of this angular momentum.

This alpha particle when it forms normally this paired neutron and paired proton take part information of this alpha particle. And therefore, for odd a nuclei it will be slightly energy less energy efficient, because when pairs are combined to form alpha particle that last unpaired nucleon that is left in higher energy state. So, total q value available decreases or this daughter nucleus will have that raised energy because of that unpaired nucleon. So, that probability is less. So, all these things we discussed; the parity should also be conserved. So, 0 plus to 2 plus is alright because plus 2 plus parity change and l equal to 2 is positive parity so that is perfectly alright.

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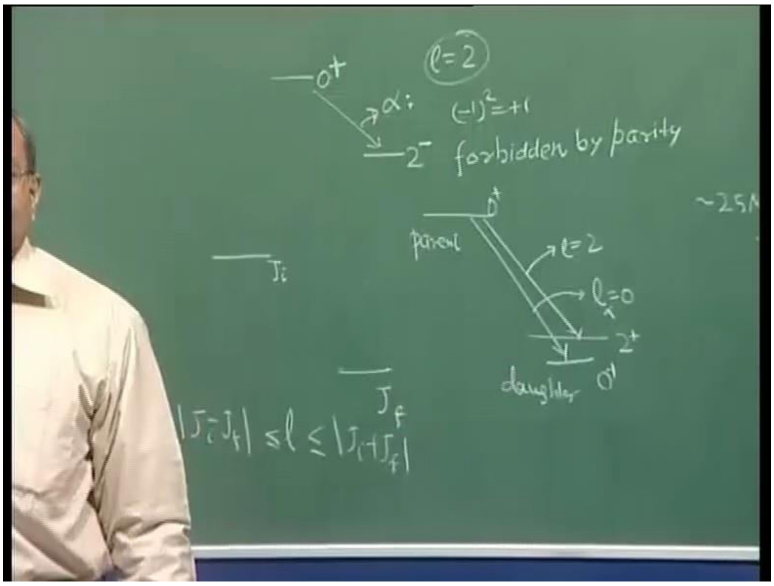

But suppose you have some state where this is j I, and this is j f daughter is j f daughter state where it is decaying is j f and the parent state from where it is coming is j I, then the l which has to come that must be between this j i minus j f to j i plus j f. And it has to also conserve the parity; in strong interactions the parity is conserved. So, this has to be satisfied as well as parity has to be satisfied. So, for example, if you have, say, from 0 plus you are looking at transition to 2 minus; suppose this daughter has a state 2 minus and the parent is in 0 plus.

And you are looking for this transition of alpha particle that will be forbidden, because 0 to 2 if we use this inequality, this l must be two. And if l is equal to two and this parity is plus here and parity is minus here, so that is not possible 1 minus 1 to the power 2 is plus. So, this transition is forbidden, absolutely forbidden. So, these are some of the things that are interesting in alpha decay. So, now I move on to the next type of decay radioactive decay that is beta decay. So, the basics of beta decay you know from your schooldays and also we have discussed a lot in the beginning about the basic processes which lead to this beta decay.

So, once again that stability ZN curve you can in your mind, and there are some specific combinations of neutron number n and proton number z for which you have those stable dots black dots in that ZN diagram. And if you create a nucleus or a nucleus is created somehow with neutron number slightly more than that, then it is possible that one neutron of that nucleus converts itself into a proton giving an electron.

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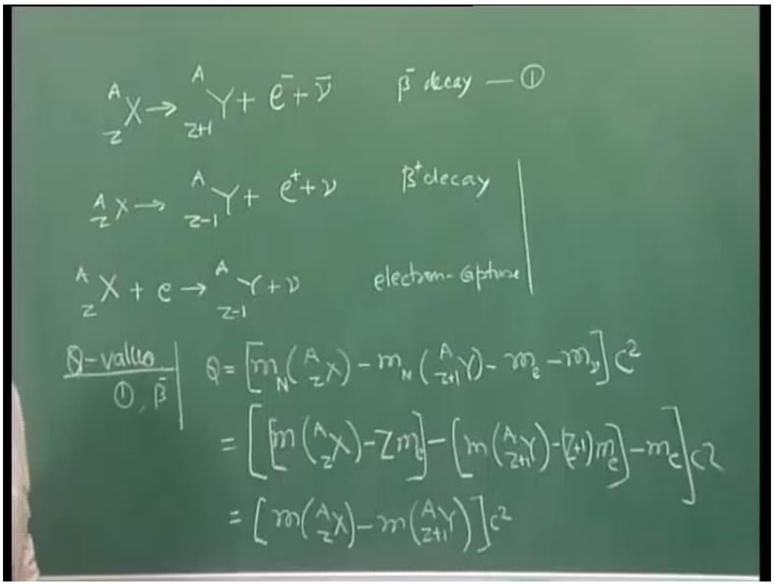

So, in that case this x a z, so if a neutron is converted into proton, the proton number is increased by one, and if neutron converts into proton it also creates an electron and a particles called antineutrino plus energy. So, that is one type of decay which we call beta minus decay. Another possibility is if proton number is more than what is required for the stability, then one proton of that nucleus can decay can convert itself into a neutron. In that case a x z will become y z minus 1 a, and if that happens if a proton converts into neutron, then you have e plus positron, and this neutrino this is known as beta plus decay.

And then the nucleus in any real experiment or phenomena, nucleus is part of the atom and you have atomic electrons. So, neutron this nucleus can capture one of these electrons from the orbits; in that case this a z x will take up an electron, and that will make z minus 1 A and plus neutrino. This is known as electron capture. Both of these will occur if you have more protons than what is required for stability. So, one proton is trying to convert itself into neutron. So, here proton is converting into neutron emitting or creating a positron here proton is converting into neutron by combining with this already existing electron. So, these are the processes.

So, most of the time when proton number is more than what is required, both these channels are open, and depending on the situation certain probability for this type of decay and certain probability for this type of decay. Now let us take the q values. So, for this equation beta minus decay, take this beta minus decay first, alright. Beta minus decay for this how do I get the q values from the known masses? The q value will be mass of the initial parent nucleus here; that is mass of a x z. Let me write it n here; this n is for nuclear mass. We are talking of not atomic mass, nuclear mass. So, q value of this reaction is mass of this parent and minus mass of the product.

So, minus mass of nuclear mass of this a y z plus 1 and then minus mass of this electron and minus mass of neutrino times c square. A neutrino mass is something very very interesting and lots of recent experiments have enhanced our knowledge about neutrino mass. We will talk about that later in somewhat more detail, but for the time being this neutrino mass is going to be extremely small. This m nu c square will be, say, hardly few tens of electron volts. This is rest mass energy of electron 511 kilo electron volts which is 0.511 mega electron volts, and this is only some ten electron volt or twenty electron volts or seven electron volts like that. So, we will just neglect this part.

Now if I write in terms of an atomic masses because atomic masses are which are readily available which are measured which are tabulated, we can get the values of those atomic masses from those tables. So, convert it into atomic masses, this will be once again forgetting that atomic binding energy this will be atomic mass; if nothing is written it is atomic. So, a x z and minus z times mass of electron, alright. This is nucleus, and this is atom. So, atom is nucleus plus electrons; there are z electrons. So, z times mass of electron; that if I subtract from the atomic mass, I get this nuclear mass neglecting the atomic binding energies which are again few electron volts. Then here it is minus.

So, this is one part and then minus here it is other part mass atomic mass of a y z plus 1 n minus z plus 1 times mass of electron. And then this is mass of electron, and I neglect this mass of neutrino c square. So, now we can look at this electron masses minus z m e here and minus m e here. So, that makes it minus z plus 1 m e, and here you have plus z plus 1 m e. So, all these electron masses will cancel out, and you have only the difference between this parent nucleus mass atom atomic mass and then minus m a y z plus 1.

Now it is atomic masses that we are talking of time c square. So, to calculate that q value in a beta minus decay scheme, you only have to look at the atomic mass of the parent and atomic mass of the daughter and subtract to get this q value. Now the second equation beta plus decay we can do similar analysis q value of.

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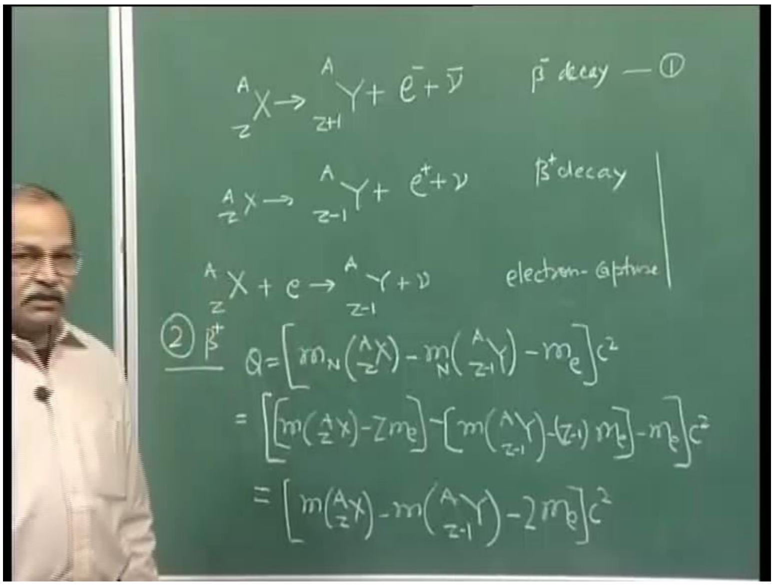

So, equation two which is beta plus decay; so, q value will be similarly nuclear mass of this parent a x z minus nuclear mass of the product. So, rest mass of the products, so, m of this a y z minus 1. So, that is it minus mass of positron with its same as mass of electron and neutrino mass we neglect. So, this into c square, and if I convert it into atomic masses this will be atomic mass of this a x z and minus z times m e. So, this is this one, then minus this one will be atomic mass a y z minus 1 and minus z minus 1 times m e. So, it is this one and then minus m e c square.

Now look at the electron masses. You have minus z coming from here and plus z minus 1 coming from here. So, this plus z minus 1 and minus z will be minus m e; this term and this term is minus m e and here also you have another minus m e. So, it is twice electron mass. So, that electron mass has to be carefully seen, and the rest is difference between the parent and daughter atomic masses. So, it is m times a x z and minus m times a y z minus 1. So, this is parent atomic mass minus daughter atomic mass; in case of beta minus decay we just had to stop here and into c square, but for beta plus you have two times m e c square.

So, be careful if you have to calculate the q value of this beta decay. The expressions are different for beta minus decay and beta plus decay. In beta minus decay you only look at the atomic masses of the parent and daughter and subtract, but for beta plus decay you also have to subtract this double of electron mass. And it is quite significant, because the beta decay q values are again typically in mega electron fuel mega electron volt range one M e V, two M e V, three M e V type and twice of m e c square will be more than one mega electron volts. So, it is quite sizable this q value, and for electron capture if you do similar thing.

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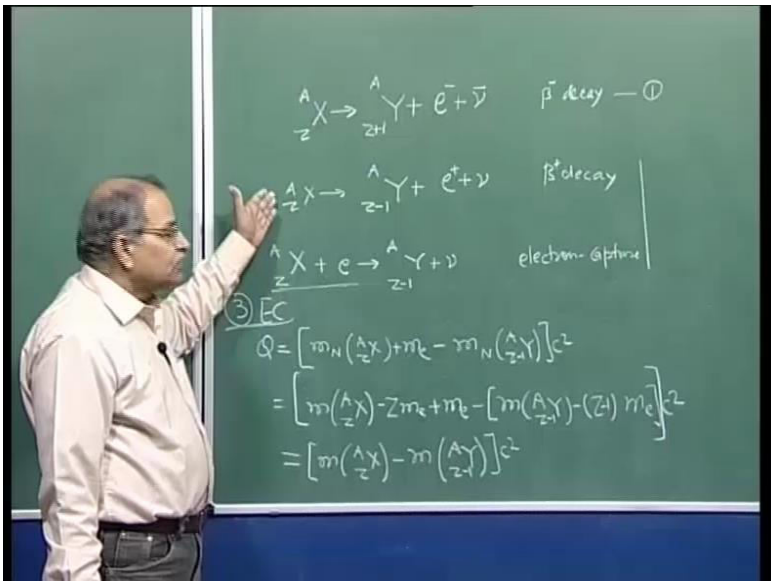

Third equation electron capture; so, here the q value will be mass of the initial constituents. So, it is nuclear mass of a x z and plus m e; that is the mass of this part left inside and minus the rest mass of the product side. So, it is minus nuclear mass of a y z minus 1 neglect neutrino mass, this into c square. Convert to atomic masses, it will be atomic mass a x z and minus z times m e; that is this part. Then plus m e and then minus atomic mass a y z minus 1 and minus z minus 1 m e times c square, one more bracket somewhere . So, now if I look at the electron masses I have minus z and plus 1 from here, and here this minus and this minus product is one. So, z minus 1 m e; so, z minus 1 m e from here and negative of that minus z plus 1 m e here.

So, they will all cancel out, and you will only have difference between the atomic masses of parent and daughter. So, if we compare these two, same nucleus can decay through beta plus and electron capture because in both of these cases proton is converting into neutron. But then the q value of electron capture will be larger by this two times m e c square than the q value of this beta plus. So, you can find in many cases that this electron capture is energetically possible but beta plus is not because q becomes negative there; in electron capture q is positive. So, those nuclei will only go through electron capture and not through beta plus. So, these are the energy considerations.

Now the most interesting observation about these beta decay process which puzzled physicists for two decades or so is the energy distribution of these beta particles. So, if I consider some beta decay then q values we have calculated. So, this q is the available energy, and this available energy this extra energy reduction in the rest mass energy, this appears as the kinetic energy of the products as usual. And here the products are the daughter nucleus, the beta particle itself and the neutrino. Now these neutrino and antineutrino when I say neutrino here, it could be antineutrino it could be neutron; we will talk more about neutrinos separately as I said.

So, consider for sample beta minus decay. So, you have this daughter nucleus and the electron and antineutrino. These three particles share this energy. Now this daughter nucleus recoil that energy take up due to this is very very small, because the daughter nucleus is much heavier, mass is very high as compared to the mass of electron or mass of neutrino. So, with that part you can safely approximate to 0 and neglect that. So, this is now shared by electron and this antineutrino. Now how in what proportion it should be shared? For that you need to go into quantum mechanics and we will be doing that right in this lecture itself, but during 1911 when this beta spectrum was measured by some physicists in twenties or so; that time this neutrino thing was absolutely not known.

So, experimentally what people absorbed was only these electrons, not these neutrinos or antineutrino. And these electron kinetic energies were measured, and it was found that this kinetic energy has a distribution. So, if I do not know about neutrino antineutrino, what I will expect is that q value is almost entirely taken up by the electron. And therefore, electron kinetic energy should be very definite, should have very definite value depending on the decay scheme, the rest mass of parent, the rest mass of daughter and so on. And if the daughter nucleus is not in ground state it is in excited states, then the q values will be different, the kinetic energies will be different. But then they will take some discrete values as we saw in alpha particles alpha decay, but the experimental result which I am trying to show you qualitatively this is from 64 copper.

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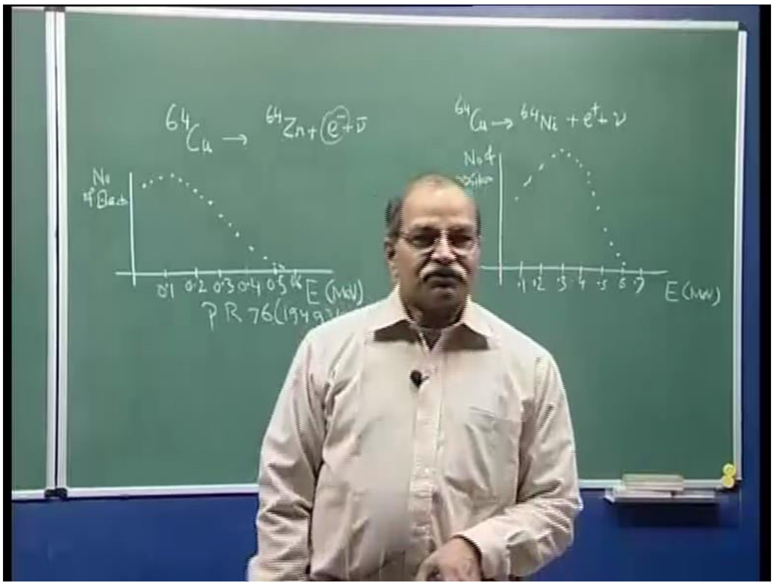

Now 64 copper is a very interesting nucleus. So, it can go through positrons emission, and it can also go through electron emission. So, here is energy spectrum. What do I mean? This is the measured kinetic energy of electron, and this is the number of electrons. So, it is decaying to 64 zinc and plus beta minus and plus of course, antineutrino. So, these electron these beta particles which are measured in nuclear detectors, energies are measured. So, one can count at this energy take a very small interval whatever is allowed by that detection system; in that channel in that energy range d e at this e, how many beta particles are detected in a given time? And in the same time how many these beta particles are detected in some other d e centered at some other e.

So, that is how this distribution is plotted number of electrons as a function of energy and that turns out to be of this type. I am just trying to reproduce this as nicely as possible. So, this is the scale in M e V's and this side the points are going like this somewhere here, here, here, here, like this and then decaying; the last value is somewhere here. So, these are the kinds of points obtained in the experiment, alright. The experiment is in physical review 76 1949 1725. And for this beta plus decay where it goes to 64 nickel and neutrino, here also one can measure the energy in M e V and this side is number of these positrons, and here once again you have that scale.

So, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 scale energy; it is the kinetic energy of these beta particles in mega electron volts, and this side you have these numbers. And here it goes like so it is somewhere maximizes here, and then on this side it falls and it goes up to here. So, something of this sort; so, if you do not know about neutrino and you try to understand what should be the kinetic energy of this beta plus or beta minus from these decays, you only have to calculate the rest mass energy of this parent and daughter. And perhaps if it is positron if it is beta plus decay minus twice of the electron energy and you can calculate this should q value.

And neglecting the kinetic energy taken by the recoil of the daughter nucleus, this whole thing should come with this beta particle, and you should have mono energetic type of spectrum or if there are excited states maybe a discrete spectrum. So, this kind of continuous distribution in energy or in momentum was a great puzzle that time and where is the missing energy; if electron is coming with energy much is less than capital Q, many of the electrons are doing that or many of the positrons are doing that, where is that missing energy and similarly.