Nuclear Physics Fundamentals and Application
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Lecture - 29
Gamma Decay

So, after alpha decay and beta decay, the next topic will be gamma decay all this 3 you have done during your school days college days. In alpha and beta decay nucleus changes whereas, in gamma decay if the same nucleus which deexcites from some excited state to either ground state or a lower excited state. So, it is the nucleus is same and you have the energy levels of the nucleus depending on. What nucleus it is? So, if the nucleus is somehow placed in 1 of this excited state it just deexcites and emits photon and that is called gamma ray and this whole process is gamma decay. Now, placing nucleus in excited state normally that is through beta decay or sometimes alpha decay when a nucleus decays through beta process or alpha process quite often the brothel nucleus is created in the excited state to start with and from there it decays to lower states emitting these gamma photons.

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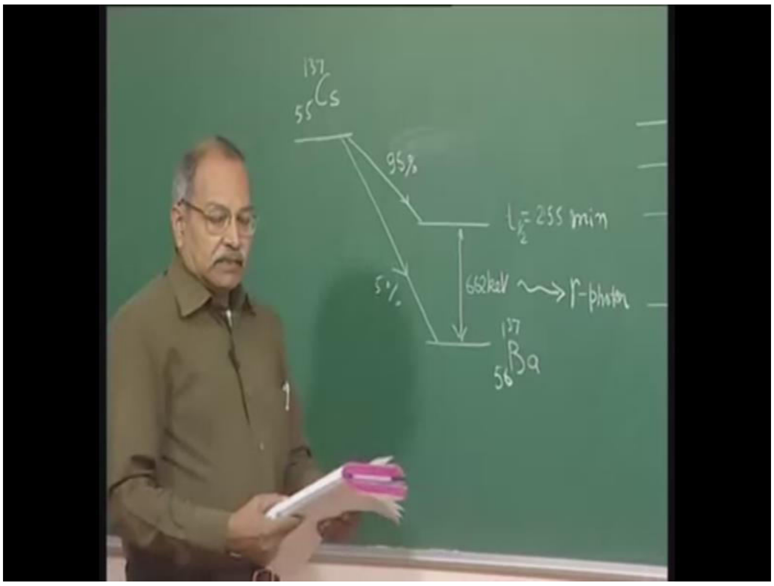

So, I give u some examples, 1 is see this is 137 cesium z is 55 this decays to barium, excited state barium. This is barium 137 and this is 56. So, from 55 it becomes 56 it is beta decay a neutron is converted into proton. So, 95 percent of times when this decay the cesium decays 95 percent of the time it decays to this excited state. And 5 percent of times it decays to the ground. This excited state has a half life of 2.55 seconds and energy here energy difference here the first excited state here is at 662 k e V. So, through this beta decay when it comes the cesium 55, 137. When this nucleus is converted into barium 137, 56 here that is in excited state and when it decays to ground state with this half life of 2.55 minutes your gamma photon is emitted.

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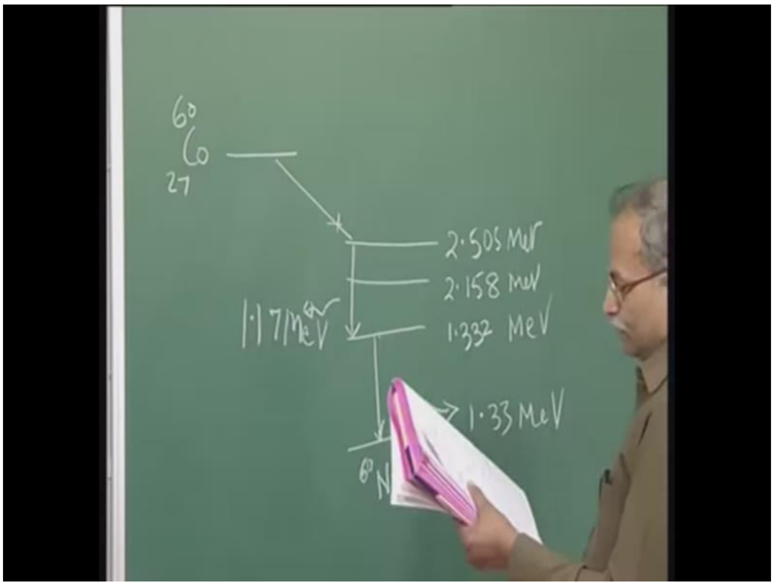

Similarly, another example you can take from this cobalt 60. If you have cobalt 60 cobalt z value is 27. This goes to nickel and you have nickel energy levels this is the nickel and you have nickel energy levels. These are the nickel energy levels and 99.88 percent times it goes to this state. This state is at 2.50 M e V then this 1 is at 2.158 M e V, this 1 is at 1.332 M e V and this is the ground state. So, the main transitions are from here to here and from here to here and this energy differences this is of course, 1.33 M e V. So, you get a gamma photon from this transition at 1.33 M e V and this transition from here this transition gives you 1.17 M e V. So, these gamma photons come out. You can take another example from beta plus decay.

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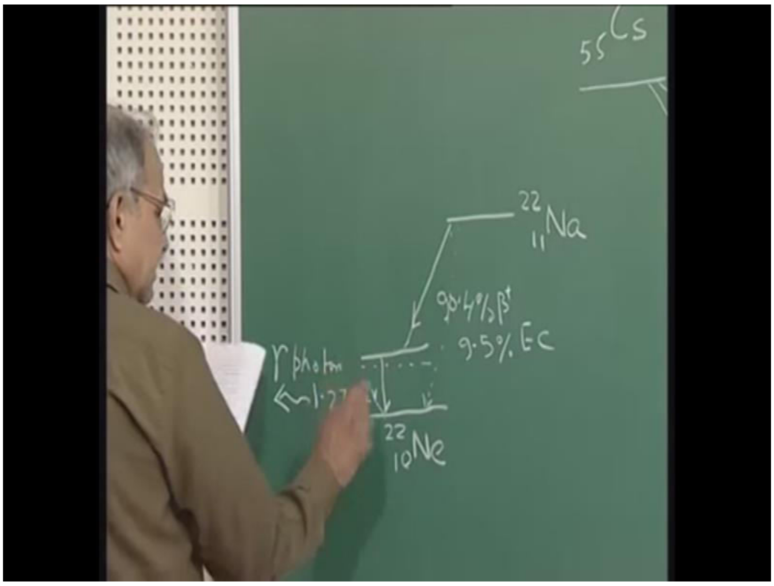

And the example I am telling is sodium 22. So, you have sodium 22 22 sodium, sodium is a 11 z is a 11 and then it decays to 22 neon. So, this time a proton number has decreased from 11 it has gone to 10 and so, it is a beta plus decay or electron capture. So, this goes here mostly this is 90.4 percent of beta plus and 9.5 percent of electron capture and the remaining 0.05 percent or so that, goes direct to the ground state. And this difference here is another state here but, the main transition is this 1 and this difference is 1.27 M e V. So, you get a gamma photon of this energy you can this deexcites from here to. So, this way following beta decay most of the time and sometimes alpha decay also the nucleus is created in excited states and this comes out as gamma photon. So, it is a similar thing where the electron makes a transition from higher energy orbits to lower energy orbits and emits a photon that you are well familiar with similar is the case with x rays where inner electron makes a transition.

And depending on the value of z that x ray k x ray that comes out when electron makes a transition from say capital L energy shell to capital K energy shell so that, k alpha x ray that is order of that can be few kilo electron volt to say 100 kilo electron volt or so and this gamma ray energy are also say 662 k e V 1 M e V 1.27 M e V. For cobalt 57 from cobalt 57 it goes to iron 57 and from there it goes to ground state that energy is 126 k e V or from the first excited state is only 14 k e V. So, quite often you will find that the x ray energies and the gamma ray energies are comparable, low energy gamma rays and high energy x rays that energy will be comparable. So, once it comes out a is just a photon and if the energies are same you just do not distinguish anything from that but, 1 is called x ray 1 is called gamma ray because of the origin x rays in x rays this are the electronic transitions from the inner shells and in gamma rays it is the nucleus which deexcites so that, is the difference in the origin.

Now, these gamma photons which come out they are electromagnetic radiation and electromagnetic radiation can be classified in different groups. So, the charge distributions electromagnetic radiation comes when you have oscillating charges are currents which are changing with time. So, charge let us first take a charge distribution the charge distribution itself can be classified as multiple distribution, dipole distribution, quadrupole distribution and so on. A pure multiple pure monopole distribution is spherically symmetric charge distribution where you do not have any dipole moment or any higher pole moments only the total charge. So, far outside the charge distribution the field or potential is from this spherically symmetric distribution is same as if it the whole thing is placed at the origin, so that 1 monopole type of distribution but, if that monopole vanishes that means the total charge vanishes then comes dipole moment if the dipole moment is not 0.

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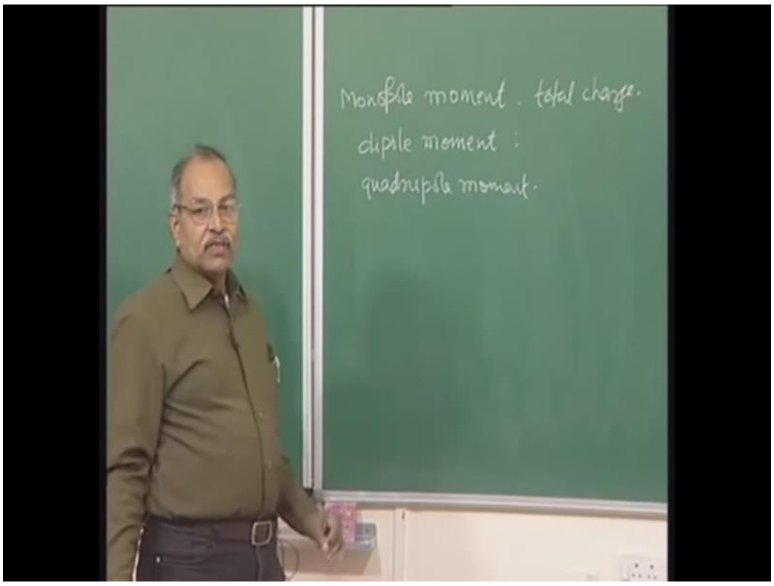

The monopole moment is just the total charge in the distribution then you define dipole moment and quadrupole moment and all those things. There are specific equations formulae for all these you know that this is vector quantity integration rho r vector d toe.

And this is tenser quantity of rank 2. So, you will have 9 components and so on. Now, the electric field of these distributions has a characteristic angular distribution for example, a if it is only monopole moment spherically symmetric charge distribution then the field is also radian, but when if it is monopole moment is 0 at a dipole moment which survives then you have a totally different type of a field distribution.

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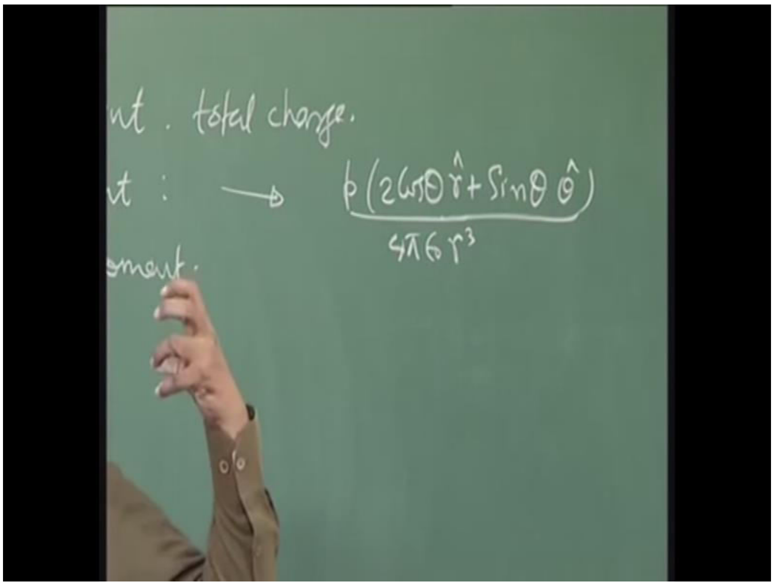

So, for dipole moment charge distribution having non zero dipole moment but, 0 monopole moment. It as something like p 2 cos theta r cap plus sin theta cap over 4 pi epsilon naught r. There is a characteristic angular distribution similarly, if the dipole moment is 0, monopole moment is 0, dipole moment is also 0, quadrupole moment is not 0 then you will have a characteristic different angular distribution of the field. Now, if these charges oscillate then they can create radiation at large distances dipole moment. If the dipole moment oscillates in time then you get electromagnetic radiation from that which will term as electric dipole radiation. So, a charge distribution which has dipole moment if that oscillates in time, the dipole moment oscillates in time then the radiation that it gives at large distances is termed as electric dipole transition radiation.

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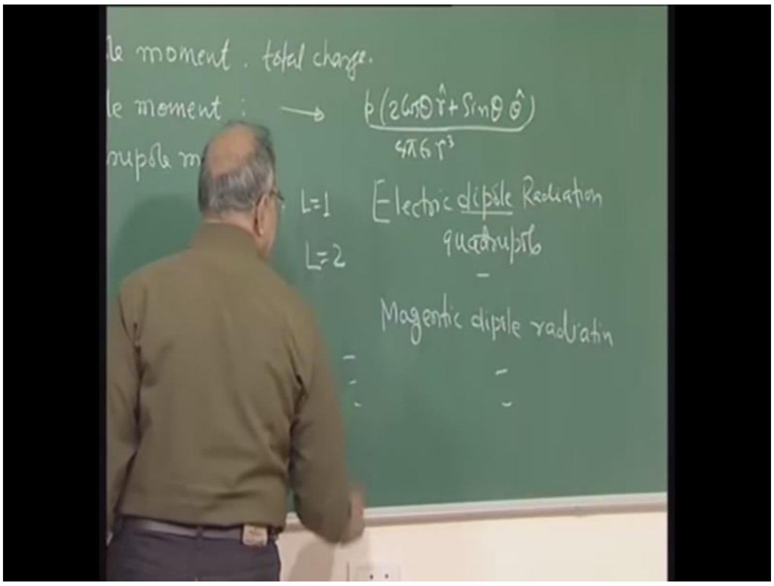

So, electric dipole radiation similarly, you can have electric quadrupole radiation octupole radiation and so on. Similar is the case, with the current distribution if you have a current distribution in a volume that current distribution can also be regarded as having magnetic dipole moment or magnetic quadrupole moment or octupole moment or higher order moments. Essentially, it is an expansion of vector potential if it is a current distribution you can write the magnetic field at large distances using this current distribution and that vector potential you can expand as a in terms of 1 by distance in power of 1 by distance, and from there you get all those magnetic multipole moments. So, monopole moment is anyway 0 magnetic moment monopole moments would be in a particular volume it is 0. So, you do not have that magnetic monopole moment you have magnetic dipole moment and magnetic quadrupole moment and so on.

And when these moments oscillate then they give of radiation and those radiations will also have characteristic distributions depending on which multipole moment in the characteristics distribution dominated. So, therefore you have magnetic dipole radiation and similarly, magnetic quadrupole radiation, magnetic octupole radiation and so on. These are all electromagnetic radiations but, having characteristic angular distributions depending on their source. Now, in nuclear gamma decay the photons which come out gamma photons which come out they are they are also electromagnetic radiations and they are also classified like electric dipole radiation or magnetic dipole radiation and so on. Although you have electric monopole moment but, you do not have electric monopole radiation because monopole moments and if there is no dipole moment and no quadrupole moment it is spherically symmetric.

And this is spherically symmetric charge even if it oscillates for outside the field its same as that of the whole charge placed at the center so that does not give of radiation and so, it all starts with dipole relation electric dipole radiation magnetic dipole radiation and then you go up. And these photons with are emitted they will carry angular momentum and that angular momentum will be related to what kind of radiation it is? So, we talked of electric dipole radiation dipole is L is equal to 1 then quadrupole is quadrupole radiation is L equal to 2 octupole will be L equal to 3 and so on and similarly, for the magnetic radiation type.

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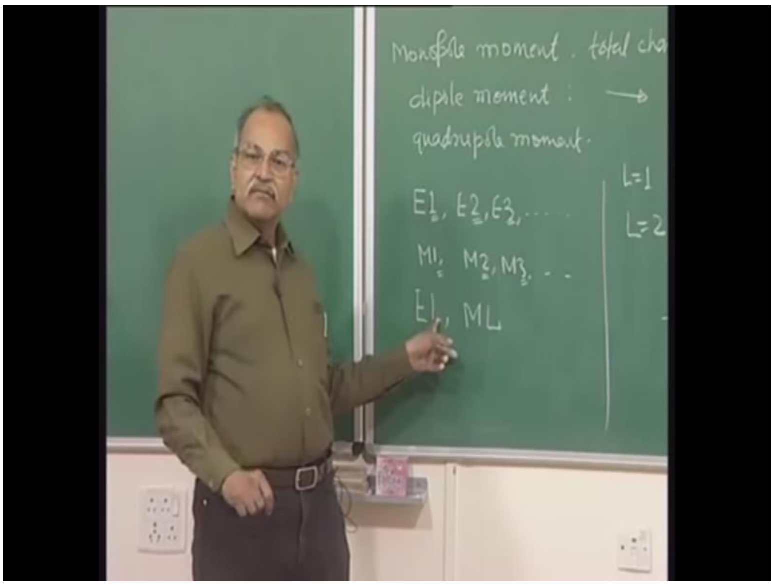

So, we have we write it as E and E 1 E 2 E 3 and so on. This is electric dipole moment, this is electric quadrupole moment, this is electric radiation dipole radiation, this is quadrupole radiation, this is octupole radiation electric variety. And the magnetic variety is written as M 1 M 2 M 3 and so on. So, u have 2 thing 1 is either E or L E or M and this numbers this are written as L capital L. So, E L or M L, and this gamma photon that comes out that carries angular momentum and that angular momentum is also characterized by this quantum number. This is also the quantum number for the angular momentum of the of that photon. So, if it is E 1 transition E 1 radiation gamma photons corresponds to electric dipole variety of radiation then you have the photon carrying angular momentum l is equal to 1. If it is a quadrupole type radiation electric or magnetic then the angular momentum carried by the photon will be characterized by this L is equal to 2. So, that gives us selection rules for angular momentum.

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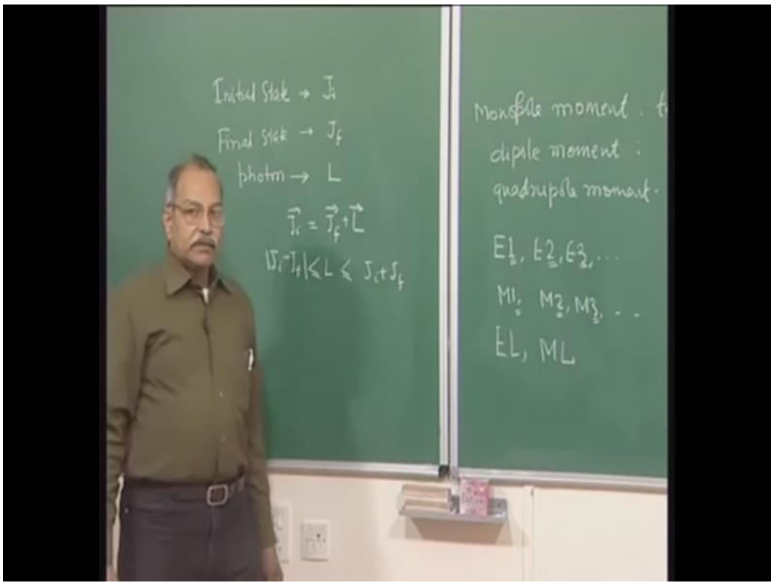

The angular momentum selection rule will be if the initial state has a angular momentum given or spin nuclear spin given by J i and the final state the angular momentum is J f. And then the photon angular momentum is L this L. Then the angular momentum conservation or the addition rule should apply J i J f and L, they should be able to form the triangle in equality and therefore, you can write it as J i is the initial 1, J f is the final spin of the nucleus and this L is here. So, this should be satisfied and therefore, the value of L should be greater than J i minus J f mod value or should be less than or equal to J i plus J f.

So, depending on what kind of excited state nucleus is in? What is the nuclear spin there? And where it is decaying? What is the nuclear spin there? Is that will decide what are the possible values of l? Where it can emit a dipole type of radiation or it can emit a quadrupole type of radiation and so on. So, if you know the nuclear spins of the 2 states in with the transition is taking place. Then you can work out that which kinds of radiation it will be which kind of transition it will be. So, that is on angular momentum.

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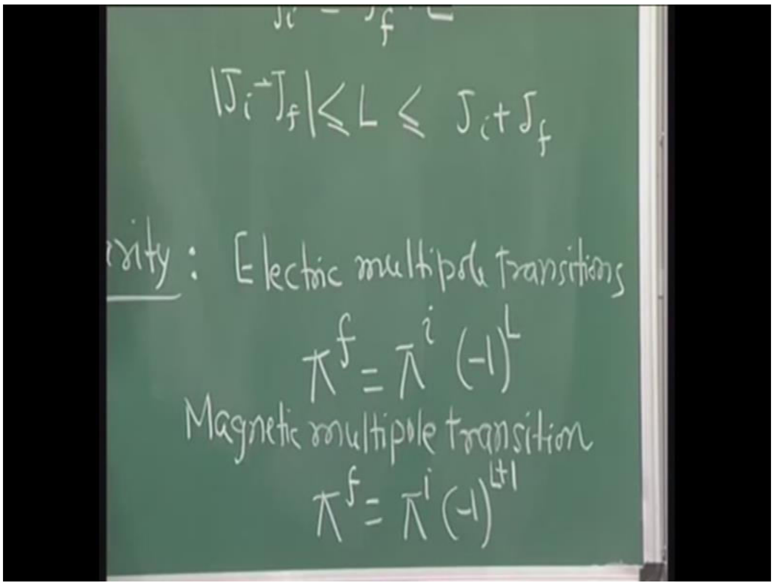

And you also have parity consideration the parity of that photon that is coming out or the radiation that is coming out, which will cause a change a possible change in the parity of the nuclear state that depends 1 on L, and in second on whether it is electric transition type or it is magnetic transition type.

And the rule goes that for electric multipole transitions the final parity pi f is pi i initial parity times minus 1 to the power L, where l is the order of that multipole transition. If it is E 1 transition electric dipole transition gamma photon giving electric dipole type radiation then l is equal to 1 and you just put l is equal to 1 for E 2 type it is l equal to 2, for E 3 type it is L is equal to 3 so that, is this L. But, if it is a magnetic multipole transition the gamma photon which is coming out is giving you a multipole magnetic multipole type of radiation in that case this final parity is initial parity and minus 1 to the power L plus 1. So, these are the rules for angular momentum and parity. Now, let me take some examples once again.

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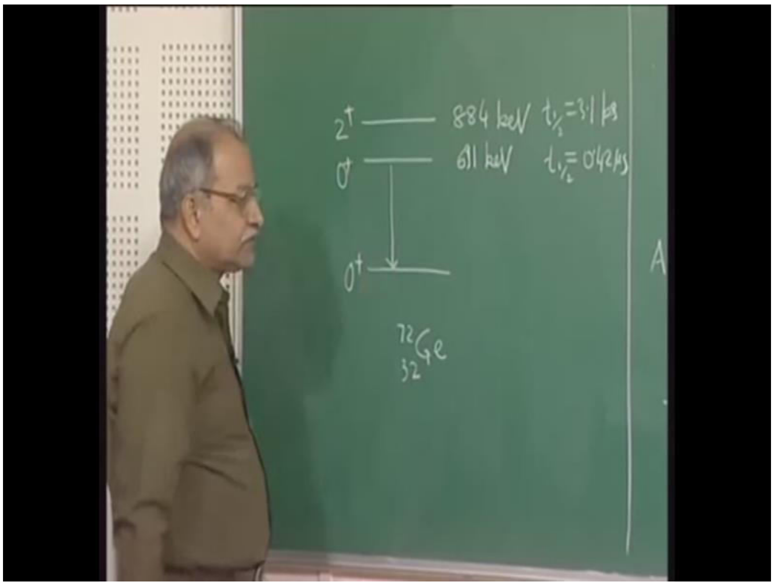

You have nuclear transition this is 72 germanium 32 and this is at 691k e V this exited state and another exited state is here this is 884 k e V. The ground state is 0 plus this first exited state is also 0 plus and then this is 2 plus. This half life here is t half equal to 0.42 microseconds and this 1 is 3.1 picoseconds. Now, you have first look at this 0 plus exited state and this 0 plus ground state, if the nucleus happens to be here in this first exited state and it decays giving that 691k e V. What kind of transition it can be 0 plus to 0 plus?

If I look at this in equality here, if this J i is 0 and J f is also 0. Then this L has to be 0 fine because it is 0 minus 0 and 0 plus 0 this L has to b between these and therefore, the multipolarity should be 0 but, there are no radiations with multipolarity 0 and therefore, 0 plus to 0 plus transition through gamma decay is not allowed is not possible because of this angular momentum conservation so but, the transition does take place with a half life of 0.42 microsecond. So, what kind of transition is this? This is a different totally different variety where the nucleus deexcites and the energy that is decreased comes out not has a photon not has electromagnetic radiation but, this energy is internally given to an atomic orbital electron. This nucleus is part of the atom in any given material and the s electrons they spend some time inside the nucleus.

So, the nucleus interacts with the electrons atomic electrons mostly 1 s electron where the wave function overlaps with the nucleus in a significant way. So, this interaction of electron with the nucleus in excited the state that interaction makes the electron receiving that extra energy and the nucleus going to the ground state. So, no gamma photon is created no electromagnetic radiation is created as the nucleus comes down but, nucleus does come down and that extra energy is taken up by this electron. And if that energy is more than the binding energy of the electron in that orbit, usually it is 1 s orbit inner innermost orbit and the binding energy will be few 10's of k e V or may be 100 k e V or so, if that nuclear transition energy is more than that and if the electron has received that much of energy from the nucleus as it deexcites then the electron is not out of the atom binding energy. How much is whatever the binding energy of the electron with the atom so that, much will be reduced and remaining will come out has the kinetic energy of this electron and will be requital of the a nucleus and so on.

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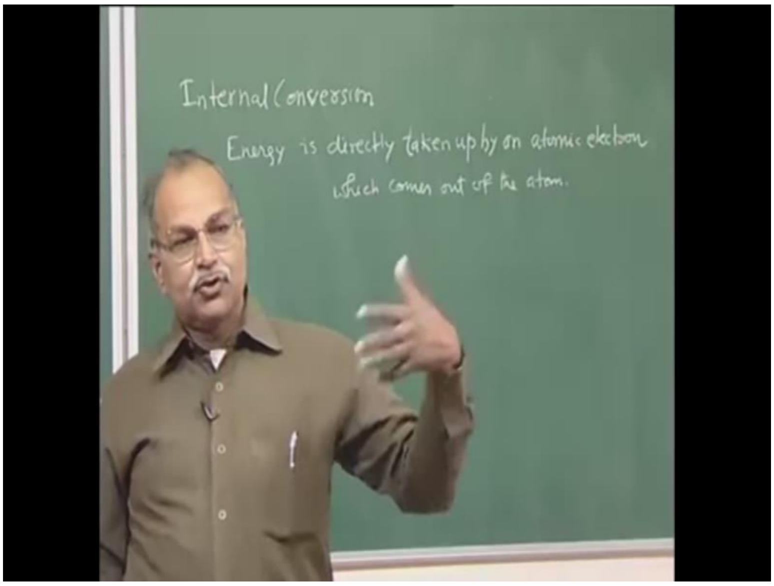

So, this process is known as internal conversion. So, in internal conversion the energy is directly taken up by an atomic electron which comes out of the atom. So, this internal conversion process can take a nucleus from the excited state to ground state or lower excited state for 0 plus to 0 plus if the excited state is at or the initial state is having spin parity 0 plus. And the ground state or the lower excited state final state also has a this spin parity 0 plus or angular momentum in fact 0 and 0 in a initial and final stages the only possibility for the excitation of the nucleus is this internal conversion because gamma photon will not be created will not come out.

Even for other cases where gamma photon is allowed gamma photon can be created even in those cases this internal conversion is possible right. If it is 0 positive 0 plus has is the case with this 72 germanium first excited state to ground state this is the only possibility.

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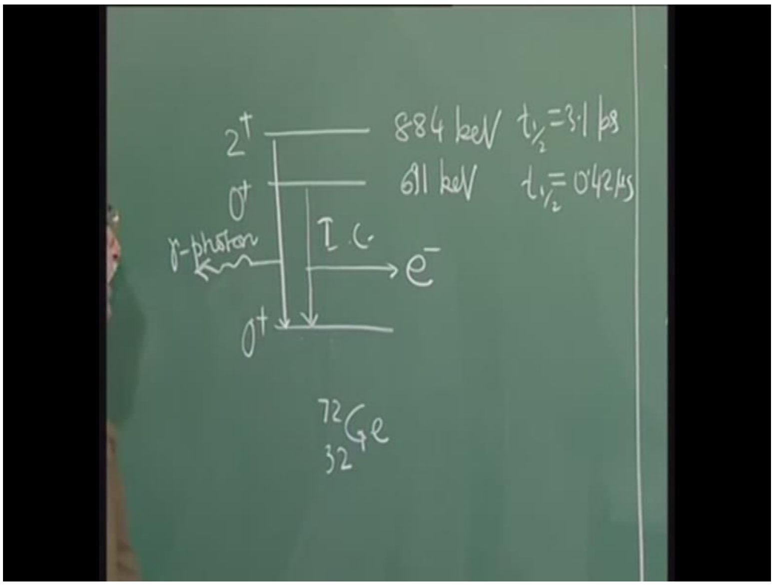

So, what will come out here will be electron right. So, this is the only possibility internal conversion but, even for other cases where the gamma is allowed see this 2 plus to 0 plus this can give a gamma photon, this can give say a gamma photon, if it is gamma photon J i is 2 plus.

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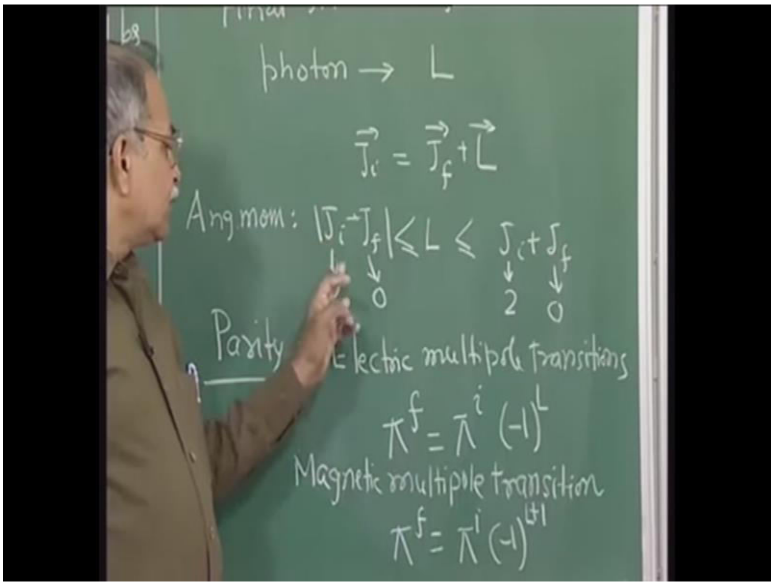

So, this J i is 2 and J f is 0. This is 2 J i is 2 and J f is 0. So, if I look at this in equality here this equation here this J i is 2 J f is 0. So, this 2 this is also 2 L is 2 it has to be a quadrupole transition. And then the parity is not changing here this is 2 plus and this is 0 plus. So, both parties are same and L is 2 from here L has to be 2 and then the parity does not change so that, means it is this kind of case the final parity is same as initial parity with L equal to 2. So, it is not this kind of case it is this kind of case and therefore, it is pure E 2 transition. This is pure e two transition but, then even if the gamma decay is possible even if you have this multipolarity eligible to for gamma photon always there will be a chance of internal conversion 0 plus to 0 plus it is the only root but, even for others together with gamma photons you will also have a chance of internal conversion. So, internal conversion competes with gamma decay and normally it is termed as conversion coefficient the ratio of probability of internal conversion to the probability of gamma decay that is known as conversion coefficient.

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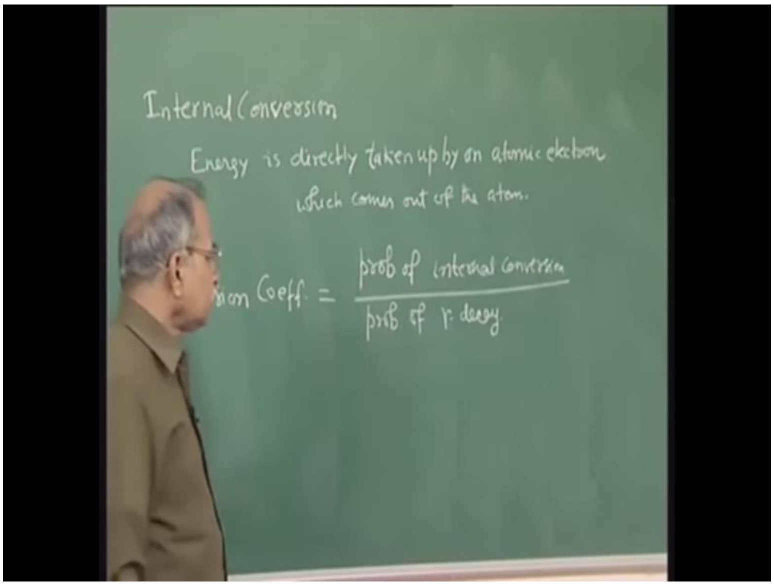

Probability of internal conversion and divided by probability of gamma decay alright. So, that is some part could be through this internal conversion some part could be through gamma decay. So, these are the, let me take some more example.

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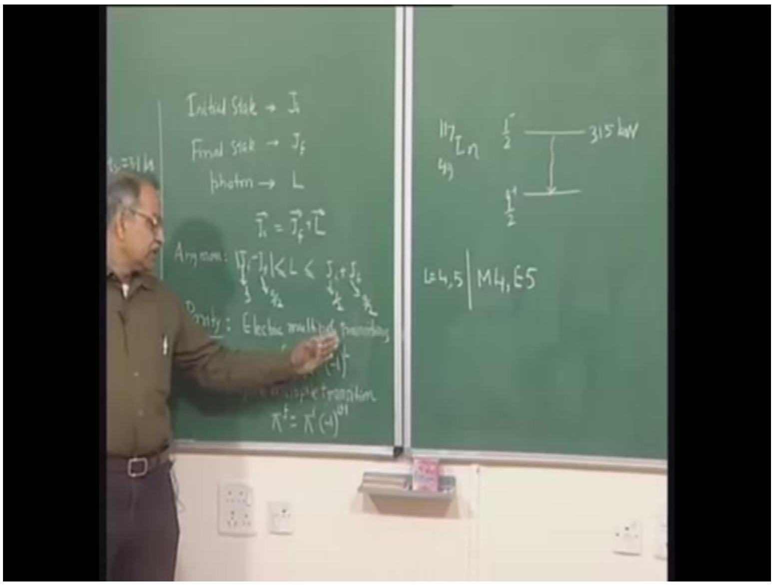

One more example and that example is 100 and 17 indium in 100 and 17 indium z value is 49. You have excited state at half minus and ground state at nine-second plus. And the excited state at is at 315 k e V. What kind of transition it could be? So, the initial state has spin half. So, J i is half. This is half and the final state is nine-second. So, J f is 9 second. So, 9 second here and 9 second here. So, this is 1 second plus 5 9 second is 10 second 5 and this is plus. So, this is 5 and this is 9 minus 1 is 8-second 4. So, L can be 4 or 5 and there is a parity change. This parity minus and this is parity plus. So, L can be 4 or 5 according to the angular momentum selection rule. So, it can be E 4 M 4 E 5 M 5 and then there is a parity change. So, this part should be minus 1. So, if L is equal to 4 it has to be M type magnetic multipole transition. If L is equal to 4 because then it will be 4 plus 1, 5 and minus 1 to the power 5 will be minus 1. So, that pi final is negative of pi initial.

So, parity change will take place. So, M 4 is possible and E 5 is possible because if its electric multipole type then this rule will apply and with L is equal to 5 you will have a parity change. So, looking at the spin parity of the initial state and final state you can find what kind of multipolarity can be there and whether it is an electric multipole type or ah magnetic multipole type. So, in this case it is M 4 E 5. Now, in general if such is the case that different L values are possible different multipolarity are possible for gamma decay. Then the probability of lower multipole will be higher the probability of decay through lower multipole transition will be higher and that of higher multipole will be smaller.

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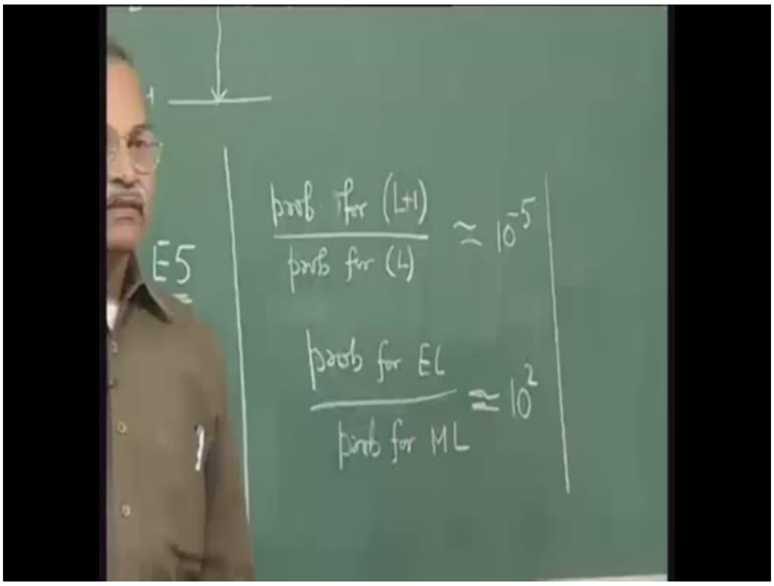

As a rule of them that means very roughly approximately the probability for say L plus 1 type transition divided by probability for L type transition. That means if I go 1 order higher than the probability decreases by let us say 10 to the power minus 5 or so, if it is a same type electric type or magnetic type. In the same electric type and magnetic type the effect of increasing L by 1 unit that decreases the transition probability by factor of 10 to the power 5. And in the electric and magnetic type so that, means probability for let us say E L and divided by probability for M L. So, is a same L the value of L is same we are comparing.

Now, electric and magnetic type, so if this probability it is in the electric transition has larger probability and this is of the order of say 10 to the power 2. So, this are to be kept in mind that if 2 are more kinds of transitions are allowed. What is the relative probability? If M 4 and E 5 are both allowed what will be the probability ratio of these 2. So, this rule can be worked out and you find that the of these E M 4 and M 5 this M 4 will have the dominant role so this decays through this magnetic multipole with L equal to 4 that type of transition. So, the probability is very small because from L equal to 1 to 2 to 3 to 4. The total probability since the transition can only take through M 4 or possibly E 5 which is yet less probable. So, M 4 L is equal to 4 the lifetime will be large and these type of states where you have very high value of l as the dominating mode. The lifetimes are quite large sometimes in minutes and sometimes in hours where is typically the gamma decays go through a lifetime of picosecond nanosecond of type this are known as isomeric state.

Where the lifetime is large and large means what do not compare with beta decay lifetime and alpha decay lifetime. Here it is in minutes if it is in minutes is very large. Normally, the lifetimes are in picoseconds or nanoseconds. So, these are the terminology of gamma decays and when you do some kind of gamma rays spectroscopy and from that you try to get the structure the energy levels of the nuclei this things become important. Now, another topic that I wanted to take up in this is the recoil of nucleus.

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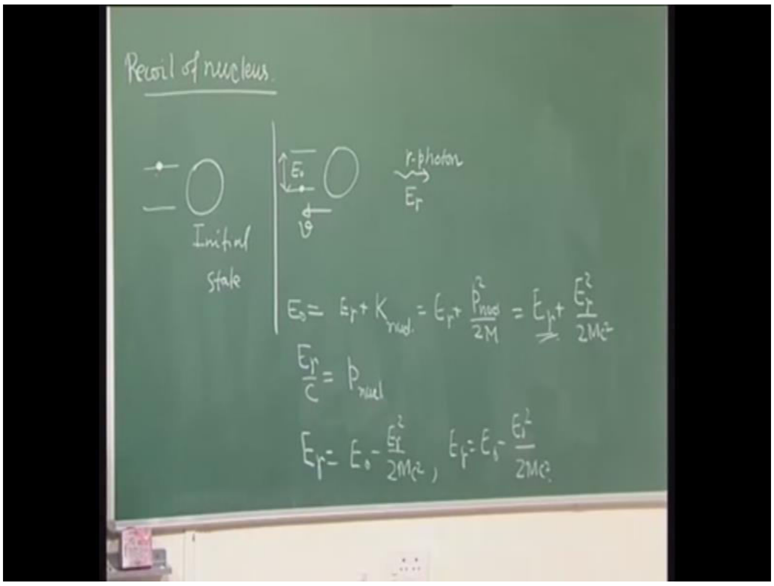

Since no new particles are created apart from the gamma photon the q value or the difference in and rest mass energy of the nucleus in the initial state and in the final state. That whole thing is available as the kinetic energy, and the gamma photon energy. So, if you have a nucleus in excited state, this is that nucleus in the initial state. So, it is in the excited state the higher energy level state that is the initial condition and then it deexcites. So, you have that nucleus and it deexcites. Now, it is here the gamma photon is going this way and then this nucleus has to recoil some kinetic energy so that, the momentum conservation and energy conservation both are satisfied.

So, momentum conservation if this energy is E gamma let us say and this energy level difference is let us say E naught. So, here this is E naught should be equal to here the energy is E naught and plus the rest mass energy here. So, this e naught will be equal to

E gamma and plus this recoil energy kinetic energy of this recoiling nucleus so that, is the energy conservation and then you have momentum conservation. Initially, the assuming that we are in that frame where the nucleus is at rest the 1 excited in the first energy level this initial state that is at rest than this momentum is 0 and therefore, these 2 momentum should have the same magnitude. So, you have you should have E gamma by C that the momentum of the gamma photon that should be equal to the momentum of the nucleus so that, the total momentum is 0.

So, from here you can work out how much is this you can write as E gamma plus p nucleus square over 2 times mass. The required velocity will be very small as compared to the speed of light. So, you can use all classical expressions kinetic energy is half m v square which is p square by 2 M and for p nucleus you can put it from here. So, this will be E gamma and plus E gamma square over 2 M C square. So, E gamma is equal to from here I am writing this E gamma is equal to E naught and minus E gamma square by 2 M C square. One can work out what is the E gamma? The gamma photon energy is less than the level difference by this amount and one can work out that this is going to be quite small.

The difference between E gamma and E naught is quite small and therefore, you can write this as E gamma equal to E naught minus square over 2 M C square. So, the gamma photon which comes out has energy less than slightly less than the energy level difference. How much it is depends on what is the energy of gamma ray? And what is the mass of the nucleus? So, from there one can work out and could be few electron volts are so or even less? But, it has got very important role once you have this what you call resonant absorption. So, what does that mean? That means suppose you have some kind of nucleus species some material which has that and that is in excited state.

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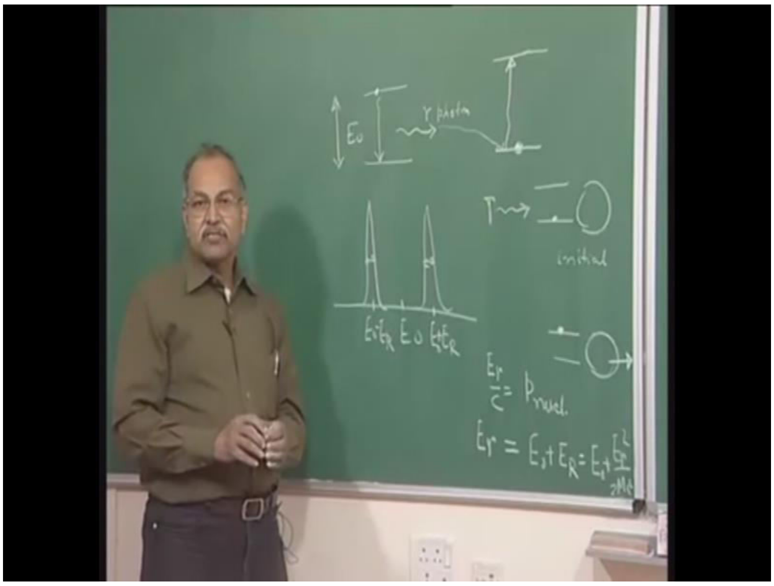

So, your nucleus is here and then it comes down giving you a gamma photon and we have a similar nucleus here in ground state another nucleus different nucleus this is 1 nucleus and this is another nucleus. This is in ground state what we are trying to do in the resonant absorption this gamma photon is absorbed here and this goes up to this excited state. Since the same nuclear specie the level difference is same. So, the expectation is that the gamma ray that comes out from one nucleus in that excited state is absorbed by that similar other nucleus in ground state. And then this goes to that excited state because the energy differences are same.

So, if that be the case then if I look at that fact that the energy which has come out with gamma photon is less than E naught. If this difference is E naught what I have is? If this is E naught here and this is the recoil this much is the recoil energy the gamma ray which is coming out is having energy less than that. E naught minus E R that will be some distribution it is not exactly E naught minus E R that you know like all excited states are defused due to Heisenberg Uncertainty Principle, and therefore you have some distribution but, centered at this. On the other side you can do a similar momentum energy analyses for this absorption process. If you have a nucleus here this nucleus in ground state and a gamma photon is coming. So, gamma photon is coming this way this is a initial this is a initial condition initial state and finally, you expect this gamma photon to get absorbed here so finally, this goes here if that is the case we are looking for then again momentum.

So, you have some momentum in this forward direction initially therefore, there must be some momentum in the forward direction in the final state al therefore, nucleus should recoil in the forward direction and if I look at the momentum equation this will be E gamma by C that the original momentum that should be equal to p of this nucleus final moment gamma ray is all ready absorbed here. So, it is only that nucleus in excited state. So, it is momentum of this and energy consideration if I see this E gamma this is at in ground state. So, this should be equal to this is E naught level differences is E naught and then plus E R and E R is once again E gamma square by 2 m c square which is close to E naught square by 2 M C square. So, the gamma if such absorption should take place then gamma energy should be more then e naught by this amount. So, the absorption profile if you think gamma ray energy needed so that it can get absorbed will be this.

So, the energy needed is this much and energy available is this much this is the energy available this gamma, this is the energy available is this much where as the energy needed for this resonant absorption is this much. And there is a difference of this 2 times E R. So, depending on what is that E naught? What is that capital M? And what is this width? If it so, happens that this E R is less than this width then you still have chance that this will go and get absorbed there. And this width is 1 is natural line width, because of that Heisenberg uncertainty principle there may be other reasons by which this width can be large 1 is that this nucleus is in some kind of material there is some thermal energy broadening thermal.

The velocities of these nuclei are there inside the material because of that some Doppler shift is there and because of that some broadening their. So, if there is some overlap between these 2 profiles this resonant absorption is possible. If this nucleus is embedded in a big crystal crystalline lattice, then the energy taken up is not just by that 1 nucleus but, by the whole lattice. The calculation that I am showing is if the nucleus is free to require but, if this nucleus is part of a big lattice crystalline lattice. Then the momentum is taken up by the whole lattice and then the lattice vibrations or lattice dynamics that comes into picture and there the energy is quantized. So, the energy of the lattice can be increased in only quantum.

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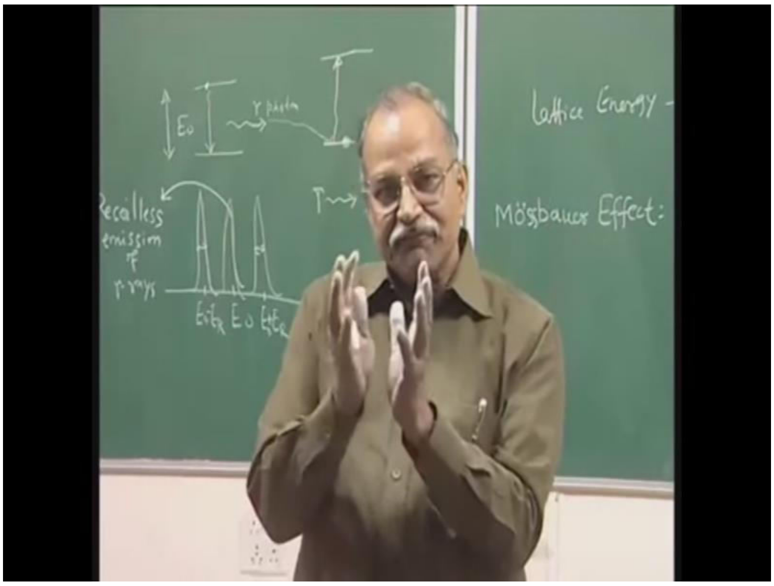

So, if that minimum quantum is that energy is is called phonons; 1 phonon vibration and 2 phonon vibration and so on. That lattice energy if the minimum quantum, a minimum quantum if the frequency is omega minimum quantum will be h cross omega. So, some minimum quantum can call it just E min. And if this recoil energy is less than that then, the lattice will not take up that energy. The gamma ray energy is reduced because some energy is taken up by this recoiling nucleus. Now, if the lattice is not ready to accept that energy because it is less than that lowest quantum. Then the chance is that gamma ray will come out with full energy difference E naught. So, this is a completely quantum mechanical phenomena. So, in real case this is a fraction of gamma photons if you have this excited source nucleus in embedded in a good crystalline lattice firmly bound there. Then a fraction of gamma photons come out with full energy difference E naught naught E naugth minus E R. So, this is a fraction which is emitted just with this energy. So, these are called recoilless emission of gamma ray.

And similar case for absorption when it is getting absorbed there also very similar case and there is a fraction they some kind some of if you are sending gamma rays of energy E naught to that material where the nuclei are in the ground state. In the lower excite in the lower state and this gamma ray is to be absorbed. So, in general classically if I think if a free nucleus than a nucleus has to recoil in the forward direction but, now the whole lattice has to take up that energy and if that energy is smaller than the quantum lowest quantum than these lattice is not going to take that energy, and in that case even if it is not E naught plus E R but, E naught that we get absorbed. So, this also can be here and you can have a very significant number of absorption resonant absorption taking place. So, this is what is called Mossbauer Effect?

Recoilless emission and recoilless absorption so, that is known as Mossbauer Effective, which is a very versatile way of finding the intermediate environment of this crystalline environment of this nucleus this is because the crystalline environment changes joules the energy levels of the nucleus by very minute amount hyperfine between the nucleus and the remaining lattice the electrons and everything the whole lattice. So, that very small energy difference shifts this e naught little bit this side that side and that changes in energy can be probed through proper experimentation proper instrumentations using these recoilless absorption and recoilless emission the resonant absorption phenomena, so that, is the basis of Mossbauer Spectroscopy and Mossbauer Effect.