Nuclear and Particle Physics
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Module – 02
Nuclear Force
Lecture – 01
Properties Dueteron

So we have been discussing the properties of the nuclear in the last class and in this lecture we will look at the force that is holding the nucleus together, which is basically the strong nuclear force, we look at some of the properties of this force and then consider some simple nucleon system, like the deuteron before we further go into the other interactions like nucleus scatterings.

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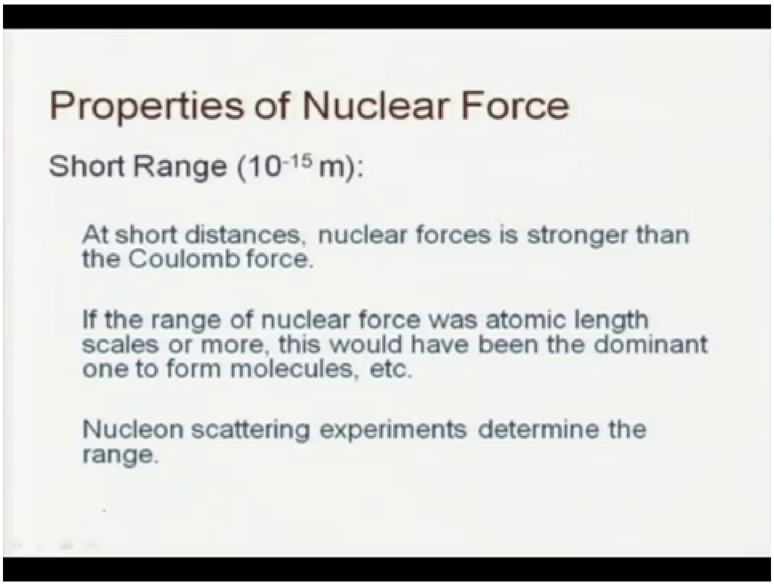

So, as mentioned earlier the nuclear force is a very short range force, it is its influence is limited to something like 10 power minus 15 meters in range.

So, if you take an atom only within the nucleus the nuclear force is effective, and the electrons which are moving around will not see this force. So, this is short range and it is stronger than the electromagnetic force, that is again evident because the strong nuclear force is holding like electrically like charged protons together against the repulsive columbic force; therefore, certainly it is much stronger than the electromagnetic force.

And how do we know that it is note going beyond a certain these nuclear length scales, otherwise its influence will be visible; say for example, in molecular formations when atoms come together if the new we know that strong nuclear force is stronger than the electromagnetic force and if that can influence the at long ranges then molecular formation will be dominated by the it would have been dominated by the strong nuclear force not by the columbic force, but we know that we can explain the chemical bonds or molecular formation coming together of the atoms to form molecules, by using a electromagnetic force.

And then there are also the nuclear scattering experiments, which can determine the range of this nuclear force and then from all these experiments we know now that it is a very short range force and as I said a little above this nuclear force is not there between electrons.

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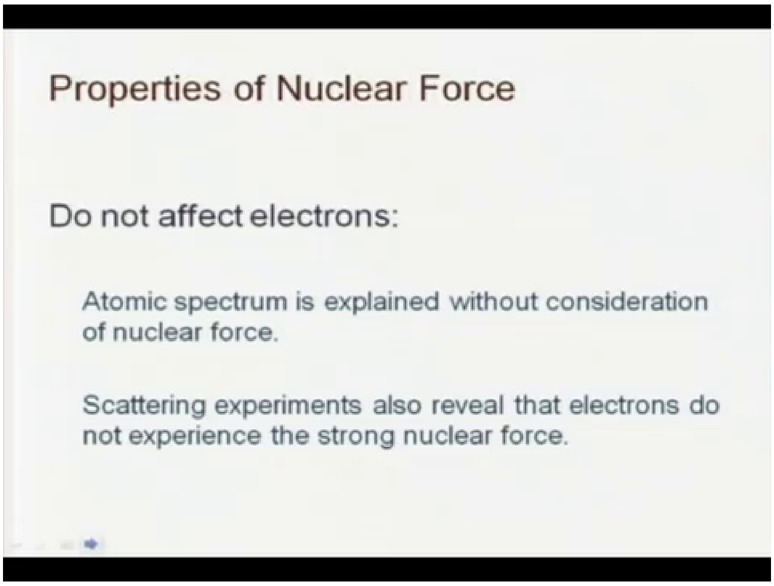

So, electrons are completely blind to this nuclear force, again we know this from the atomic spectra for example, because otherwise there are lot of electrons in the atom and they could have interacted strongly, they could have interacted between each other strongly or with the nuclear strongly; so, but we do not see those and because of this we now come to the conclusion that electrons have no strong nuclear interaction. It is also true from the other experimental results like a electron scattering etc that we do not see the strong nuclear force between the electrons.

Actually when we come to the next topic the particle physics, we will see that there are other particles like electrons called neon, for example or tau electron which is basically similar these 2 neon and tau electron are similar to electron, but slightly different. In the mass and also there are some other small differences, but for by enlarge they are similar to the electrons, they are collectively called leptons and then none of these leptons take part in the nuclear strong interactions.

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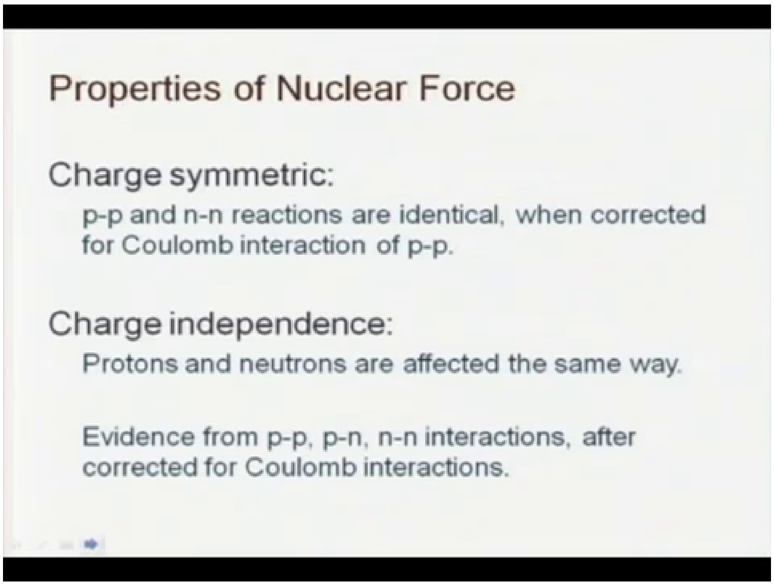

The another property is that it is charged symmetric by that we mean if I take proton and neutron, these are the 2 different nucleons that we know of and that they are there in the nucleus and they are both influenced by the strong interactions.

Now, you can ask the question like if proton and neutron was different how do they see these nuclear force is there any difference, that the nuclear force strong force which the proton and proton see together and neutron and neutron see together or when I actually change the species from neutron to proton is there any difference in the nuclear interaction. Answer is no that it is the same which is symmetry under the np exchange and this loosely we can call this the nuclear charge in at that level. So, here the charge actually means whether it is proton or neutron.

So, there is a symmetry as the local strong interaction is symmetric under such an interaction exchange or the between the proton and proton pair and neutron pair and there is also and its actually we can take this slightly, beyond this charge symmetry, we can actually say that its completely independent of the charge. It does not care about whether it is proton and proton interacting or proton and neutron interacting or neutron and neutron interacting, it is all expected to be the same. In fact, it is experimentally you know prove that it is the same.

But if you take a proton and proton and they also have in addition to the nuclear force, it also has the electromagnetic force and therefore there will certainly be difference in the total interaction of the proton and neutron proton system or the neutron and proton system, but since we know what exactly is the coulomb interaction, we can compute that and then once we make the correction for that, it is found that the strong interaction part of proton, neutron and neutron interactions the same. So, it is actually completely independent of this charge independent of the fact weather it is a neutron or whether it is a proton.

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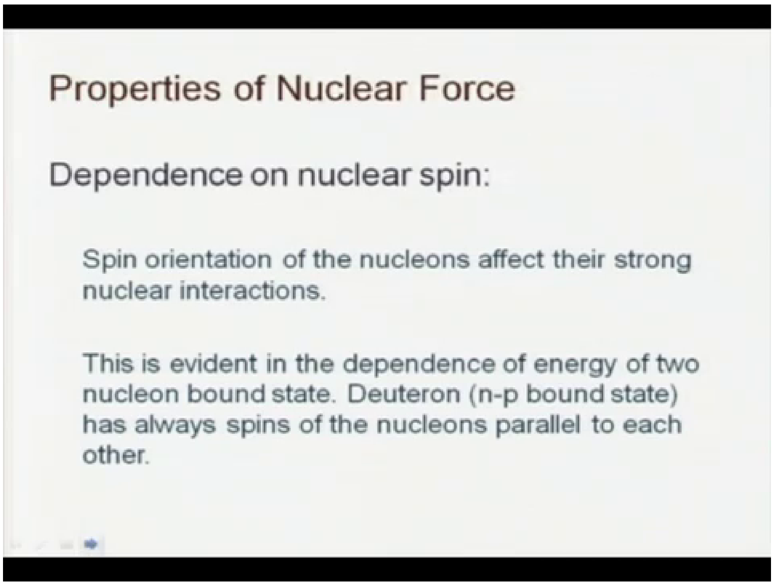

And another property is that actually it depends on the nuclear spin; I mean nucleon has a particular spin, but when it comes together or when they interact it is the relative orientation of the spin that will matter.

So, for example the spin orientation in the of the neutron and proton in deuteron is found to be parallel to each other; that means, that total spin of the neutron is equal to 1 and the individual the nucleons like neutron and proton will have the spins aligned parallel to each other not opposite to each other. And inverter if you compute the energy of different systems nuclear systems, with different orientations of the spin, you will see that the energy of the system bound system depends on whether the spins are parallelly aligned or oppositely aligned or if you have more than 1 then different combinations of these spin orientations.

So, energy will depend on that and it so happens that if you take a nucleus a proton and the neutron then the lowest energy state is found with parallel spin arrangement. And if you take anti parallel neutron and proton system anti parallel spins for this then, the energies are beyond larger and therefore, you cannot actually even form a bound state we have not seen any such bound state in nature.

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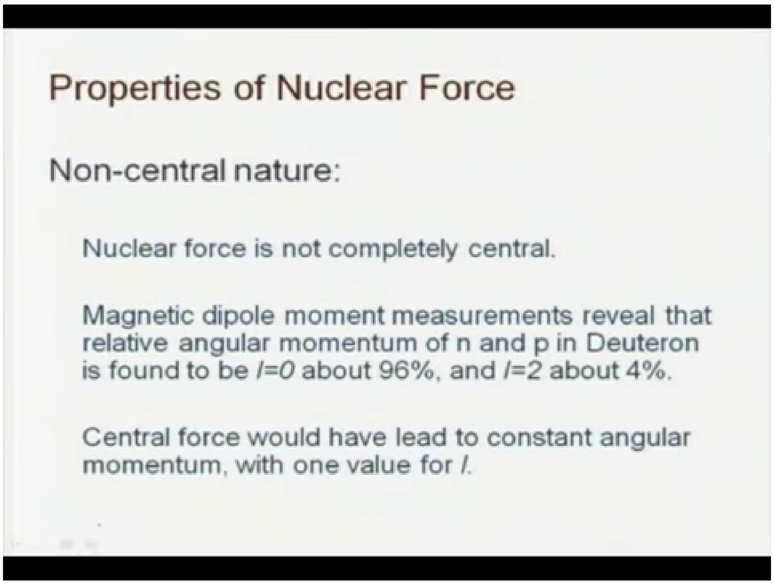

So the next thing is another very important aspect of this nuclear force which is that it deviates from its central nature, what you mean by a central force? If you have a force in between 2 particles which depends only on the distance between these 2 particles and not any other orientations then it actually is called center.

For example the gravitational force is central because, if you consider sun earth system the gravitational interaction of the sun and system depends only on the relative position or how far is the earth from sun is that is what matters not at in a particular coordinate system, what angle or what polar angle or what a smoother angle, it does not depend on that it only depends on the r coordinate in the spherical polar coordinate system.

So, that is the central force which is spherically symmetric; and I of the consequences of this as you must have already learned in classical gravitation, classical mechanism in under the central forces or in the case of a coulomb forces that central force lead to angular momentum conservation or the angular momentum of the system is then constant for a particular, once you found the system, then angular momentum remains there it is a constant thing and it has a particular value; therefore.

You can always ask the question like what is the angular momentum of the system relative angular momentum of the system, and then you will get an answer some number which is a concern vanity. But in the case of nucleon system it is not strictly central and for example, in the case of a deuteron you will see that there is an admixture of 2 different angular momentum values or the wave function which actually speaks about the state of the system physical state of the neutron can be either in a l equal to 0 or the 0 angular moment angular momentum between n n p can be 0 or it can be 2 or it can be a combination of these 2.

In fact, it is found that a 96 percent of the time this is actually l equal to 0 state and then a 4 percent it is actually in a l equal to 2 state, that is how the wave function of the angle I mean deuteron is and this can be actually experimentally determined using various methods for example, using a measurement of the magnetic dipole momen, which depends on what the relative angular momentum is.

We will actually come to this a little this magnetic dipole moment of the neutron, a little more details of this will be discussed when we actually discuss the deuteron system all right. So, another property is that the nuclear strong force, though attractive it is not attractive all the way down to small distances.

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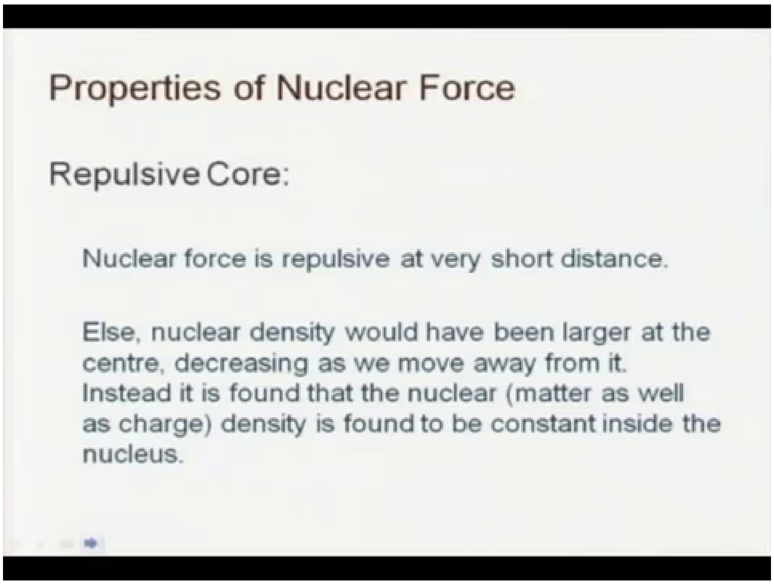

So, if you take say proton and the proton brings them together nearer and nearer and nearer the force will actually increase, it will be you will see that there is a attractive force between these 2, which is actually even stronger than the electromagnetic force.

But you will see that a beyond the distance these nucleons repel otherwise say for example, you take a large collection of these protons like a big uranium nucleus, protons and neutrons, in that nucleus there are many of them and if you have stronger forces; this force the nucleus strong force attractive all the way down to very small distances, towards the center of the nucleus you will see that this has large density because, the force is stronger they and then none of these nucleons are there and then they are all attracting each other and then coming together and towards the and when you go away from the center there should be a decrease in the nuclear density.

But this is unlike the case that we found experimentally, experimentally we have found something constant density matter and charge density for the nuclear; this actually tells us that we have as the nucleons come too close to each other, they actually do not allow each other to come any further nearer to them to each other. This is actually kind of a repulsive nature of the strong interaction when you go to very small length scales. So, this actually prevents the collapse of the nuclei also nucleus and nucleons being smashing into each other ok.

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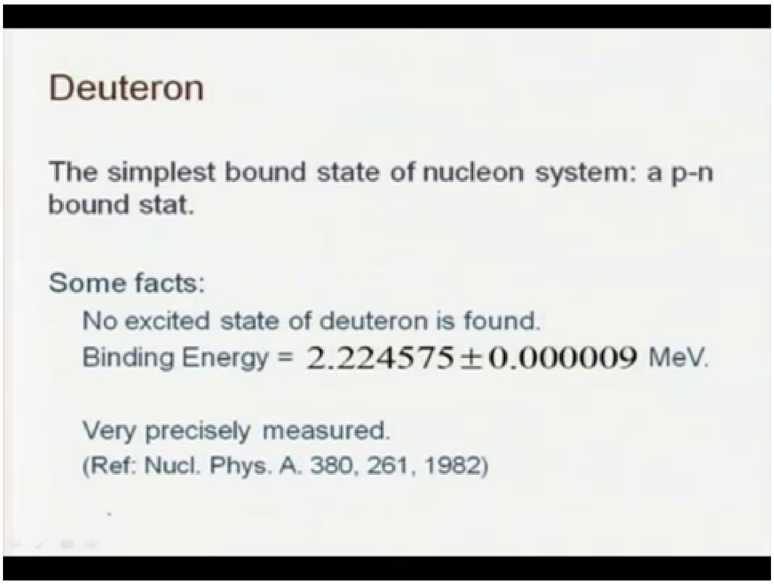

So, these are some of the properties that by enlarge we can associate to nucleus for any general nuclear force in general, between any system of nucleons and we will study some of these in a little more detail by considering some nuclear systems, we will first consider bound state of the nuclear which is basically the simplest one that we can think about is deuteron, it consists of a proton and a neutron and when they are bound to each other suddenly they should have energy smaller than the energy of the neutron and proton free neutron and proton put together.

We already discussed in the last class the binding energy of a nucleus or bound nucleon system. So, the binding energy of deuteron is and extremely or a very precisely measure the quantity we can measure that very precisely, and this leads to a value of say 2.224575 plus or minus point naught naught naught naught naught; 5 0's and a 9 MeV. So, this in this 2.224575 only the last digit is not ah certain.

So, if this is a, but this is actually a encoding a particular result, which is published in nuclear physics A 380 volume 380 and in 1982 page number 261 of the journal, and you can also look at other results and then kind of that will all be similar kind of this 1 and then with similar positions. So, it is actually a very high very precisely measured quantity.

Now, another property of this nucleon system the deuteron is its spin.

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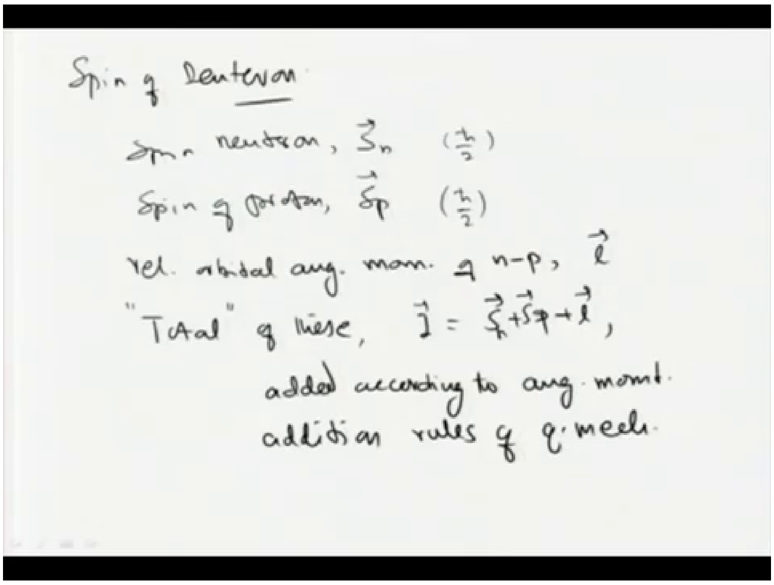

So, let us look at the spin of the deuteron. Deuteron has neutron in it and the spin of the neutron is let me denote it by S n its actual value is h cross by 2, and spin of proton is let me denote it by S p its again a spin half particle. So, these 2 are the constituents of this deuteron. So, suddenly when we talk about the total spin of deuteron the spins of the neutron and proton will contribute to it, not only this we can also think about relative angular momentum orbital angular momentum of this relative orbital angular momentum of neutron and proton.

So, let me denote it by l, and then the total as total of these when I say a total I mean the you have to add these angular moment according to the angular momentum addition rules of quantum mechanics and then the total of this let me denote it by I which is s plus oh s n plus S p plus l add that, according to angular momentum addition rules of quantum mechanics. So, let us look at the spin part of this.

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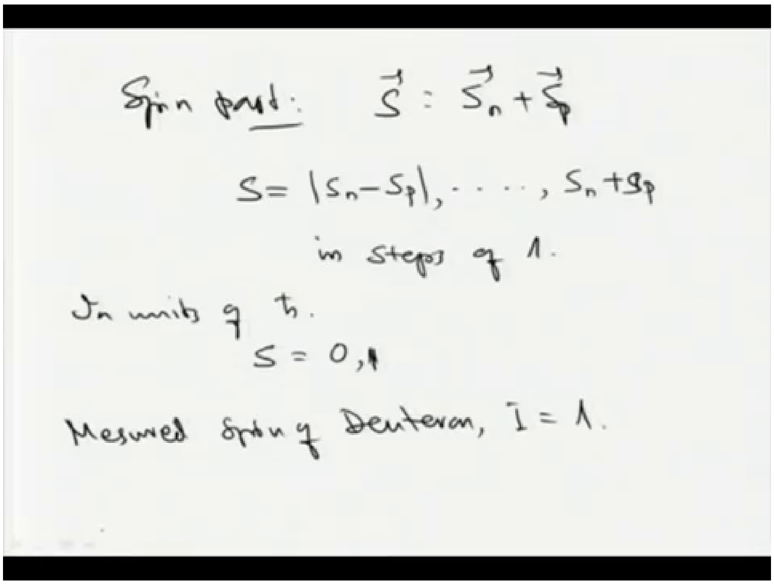

So, spin part which I by which I mean in the contribution to the deuteron spin due to the spins of the neutron and proton.

So, S is equal to S n plus S p added again according to the angular momentum addition rules of quantum mechanics which says that if S n and S p have values S n and S p without the vector sign now the magnitude of that then the total spin can have values ranging from S n minus S p the magnitude of this or the absolute value of this, and then increase it in steps of 1 and go up to S n plus S p. So, this are the values of s that are allowed according to the rule of quantum mechanics a angular momentum additions of the quantum mechanics.

So, in steps of one. So, in units of, we will be working in units of h cross actually. So, we will not put h cross everywhere you assume that that is there and then we will write everything in its in the unit where h cross is equal to 1. So, s can be S n and S p are half each. So, S n minus S p is equal to 0 and S n plus S p is half plus half equal to 1.

Since there is nothing in between which differs by 1 unit. So, we have s either equal to 0 or equal to 1 then you can ask the question what is the measured spin of deuteron the value of it, and answer is 1 it is x it is experimentally found that it is equal to 1.

So, as I said there is spin part and there is also the angle relative orbital angular momentum part of this, and since I is equal to 1 as measured.

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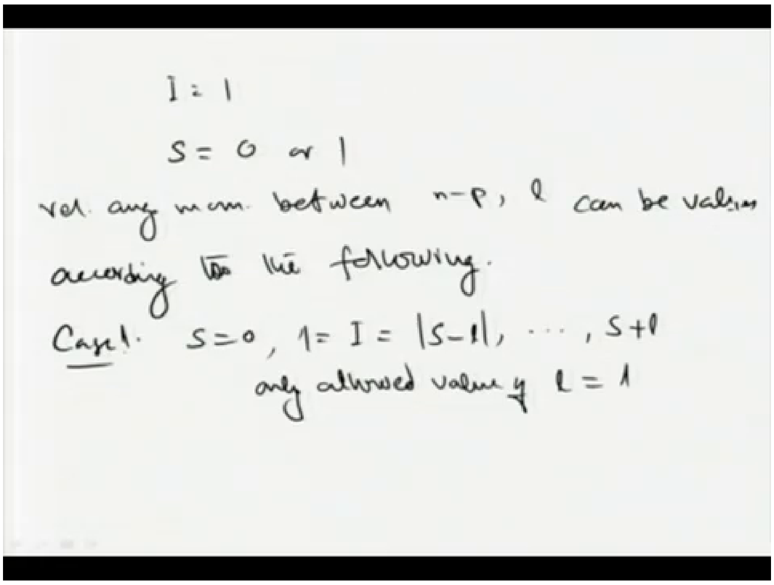

And since s is equal to 0 or 1 relative angular momentum between n and p say l can be different values according to the following. Again we will look at the angular momentum nominations.

So. Firstly, l can actually have values 0 1 2 3 etcetera now case 1 let us take S is equal to 0 case, we want I which is equal to S minus l to S plus l to be equal to 1, 1equal to I equal to this. So, since S is equal to 0 the only allowed value of l is equal to 1 now let us take the next case

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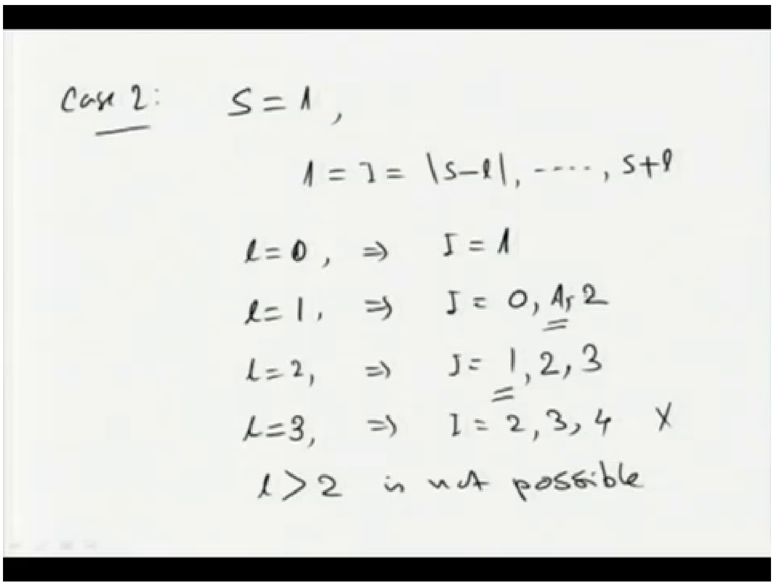

So, case 2 where we have now S is equal to 1 then again 1 equal to I equal to S minus l up to S plus l and I can have l equal to 1 0 in that case I is equal to 1 because l equal to 0 plus S is equal to 1, will give me I equal to 1 and l equal to 1 will give me it could be I equal to s minus l which is equal to 0.

And then steps of 1. So, 0 plus 1 is 1 0. So, 1 plus 1 is 2 which is equal to S plus l. So, I can have values 0 1 2. So, 1 which is experimentally measured value is there in this combination of l and S as well. If you take l equal to 2 then that will give I possible I values as 1 which is l minus s and then plus 1 which is 2 and then 3 which is l plus S 2 plus 1 these are the alert I mean possible I values and then I equal to 1 is again there. So, that is possible, but if you go anything beyond this say l equal to 3 this will actually give you I value starting from 2 3 4 etcetera.

So, this is not possible or any other l larger than 2 is not possible.

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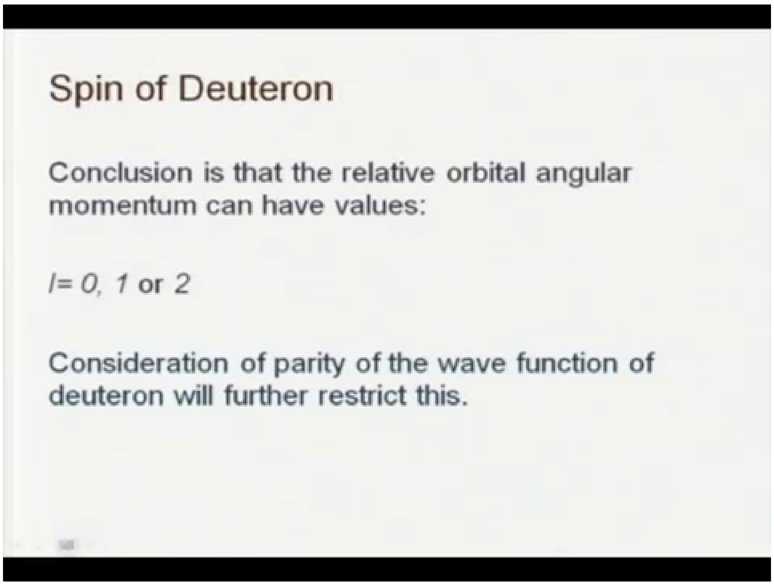

So, we can have system where l is equal to. So, conclusion from all these whatever we discussed just now is that, we can have forbidden angular momentum of the neutron proton in the deuteron to be either 0 or 0, 1 or 2 it cannot be larger than 2. So, that is the conclusion, but now there are further other considerations. So, which will tell us that we can restrict this further and then we will see that parity consideration for example, will restrict this.

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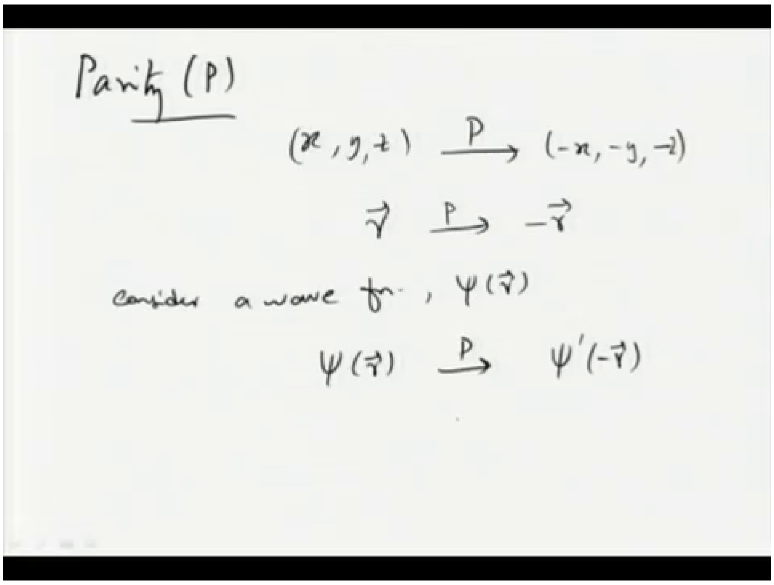

So, let us consider that parity what is parity? You must have come across with parity operation in your quantum mechanics class or other places. Basically it is inversion of space coordinates. So, if you take a xyz as your coordinate system, x y z as your coordinates of a particular point or a particular object anything, under parity operation let me denote it by P capital P, x will go to minus x, y will go to minus y, z will go to minus z or if you are considering r theta phi when r vector will go to minus r, the position vector of a point will go to minus r.

So, you can ask the question like what happens to deuteron and parity transformation. So, for deuteron we have the wave function says psi denote it by psi. So, let us consider oh deuteron or any other system considers the wave function psi r. So, under parity transformation under parity, this will go to some psi prime and r will go to minus r and we can ask the question specifically what happens to the wave function of the deuteron right just before that and let us look at this a little more a detail.

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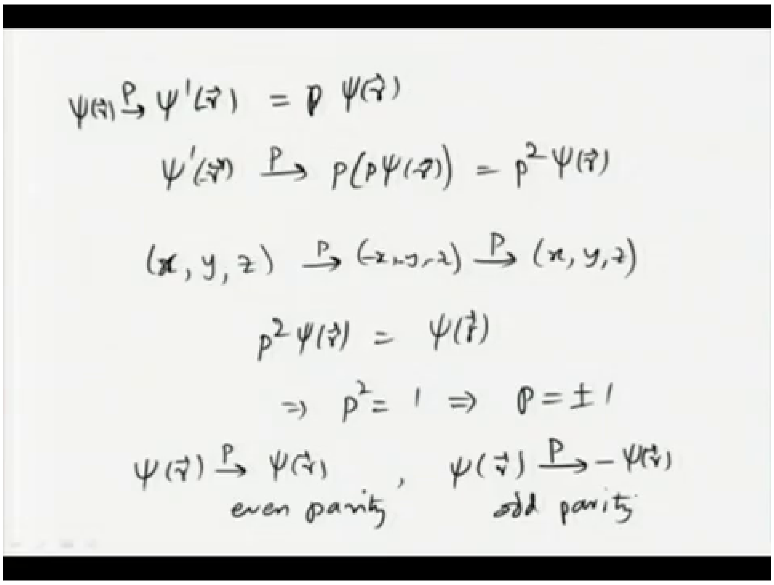

So, psi prime psi r goes to psi prime minus r under parity and if p is if the wave function is an even as an Eigen state of the parity operation, then you know that the wave function itself will not be changed in its form, that it will just be multiplied by the Eigen value of the operator. So, let us denote that by some p. So, if I do it once again. So, I will actually take the psi pi minus r and apply parity operation on this, and that will take me to 1 more p; p of whatever earlier that we had psi r.

So, that can also be written as p square the original wave function psi r, but what did we do? We first inverted the coordinates and when we apply the parity operation again we an inverted it again. So, applying parity operation twice will bring x y z, 2 minus x y minus x minus y minus z and applying it again will bring us back to x, y, z. So, it is as if we are not done anything we should have come back to the original stage when we apply parity operation twice. So, which then tells us that p square psi r should be equal to psi r, which then tells us that p square is equal to 1 or p is equal to plus or minus one.

So, if it is equal to plus 1, then we call it as even parity that a even parity of the corresponding physical system represented by psi r, we call it having even parity and if p is equal to minus 1 that is psi r goes to minus psi r under parity operation then we call this odd parity system say for example, deuteron under parity if the wave function remains the same, then it is an even parity wave function due parity wave function of the sorry parity of the deuteron is then called even and otherwise we say that deuteron has odd parity.

And then again experimentally we can find out what is the parity of deuteron right.

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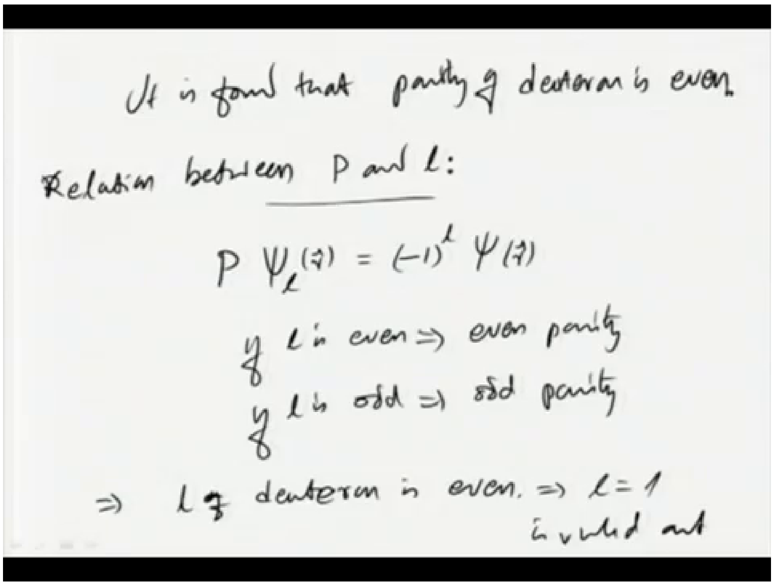

So, it is found that parity of deuteron is even. Now there is another point here that is related to the that is how parity is related to the orbital angular momentum. So, relation between parity and orbital angular momentum. So, if l is the orbital angular momentum of a particular system, I can denote the corresponding wave function as say psi L and it. So, happens that we can actually show this explicitly that in this in case the parity the value of the parity is actually minus 1 power l.

We know l can take into integer values including 0 and therefore, it is either plus 1 or minus 1. If l is an even number then it is even parity, the wave function corresponding to that will have even parity and if l is equal to l is odd. So, if l is even we have even parity and if l is odd and that will give you odd parity for the corresponding physical system. So, that will tell us that l of deuteron is even, because its parity experimentally is found to be even therefore, l is an even integer.

And then out of that tells us that l equal to 1 which we said earlier is a possible value for l for the deuteron is ruled out.

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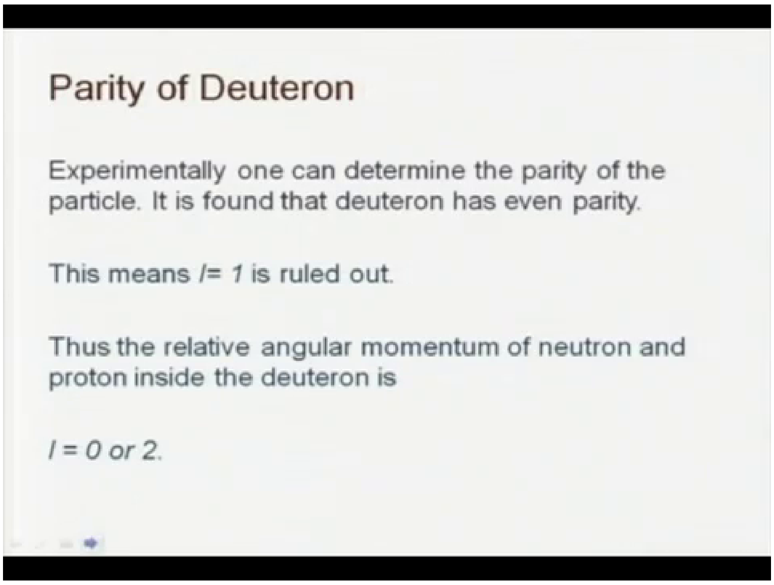

So that is what we are saying here experimentally one can determine the parity of the particle and it is found that the deuteron has even parity and therefore, l is equal to 1 is ruled out. So, the parity of the sorry the angular momentum orbital angular momentum of the np relative orbital angular momentum of the np neutron and proton inside the deuteron is either 0 or 2 or some combination of this ok.

So, our other properties of this deuteron that we would like to consider, but I think we will do that in the next lecture. So, before we actually conclude this lecture we will pass a question some simple question which we can think about.

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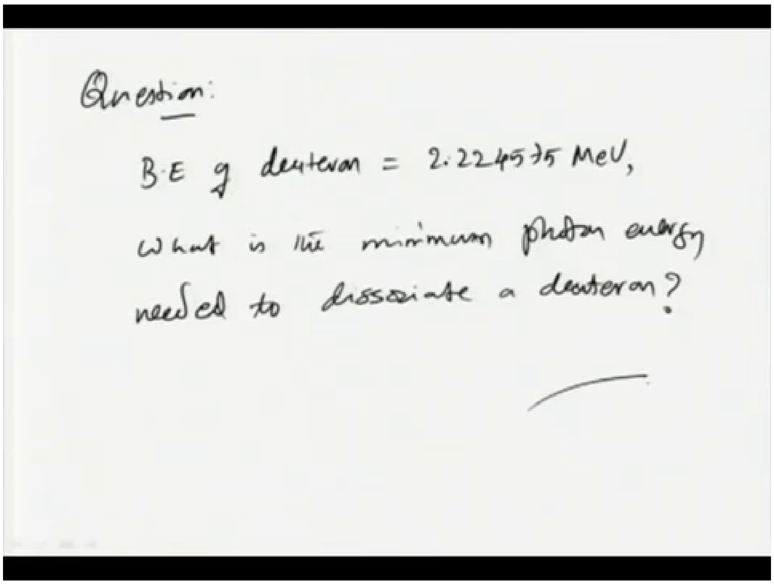

So, we said earlier that the binding energy of deuteron is equal to 2 point, let us take it to be 2.224575 MeV by the way I do not know if I mentioned, but MeV means mega electron volt.

So, here mega is 10 power 6. So, the whole thing is 2.224575 into 10 power 6 electron volt and electron volt is the energy that an electron acquires when it actually moves in 1 volt potential difference. So, if we know that this is the value of this 1 and then use this information to find the minimum photon energy needed to dissociate.

Now, what is the meaning of binding energy? If you give some amount of this energy this energy to the nucleons, then it will disintegrate or split apart into the separate free nucleons. So, question is what is the minimum photon energy needed to dissociate a deuteron. So, with that actually we will stop today's lecture.