Nuclear and Particle Physics
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Module -10
Guage Symmetry
Lecture - 01
Weak Interactions

Start our discussion on the Weak Interactions and some of the discrete symmetries associated with it. So, we had been discussing the electromagnetic interactions and then we saw that there are convenient ways to actually represent this by using diagrams, to describe the scattering of charged particles.

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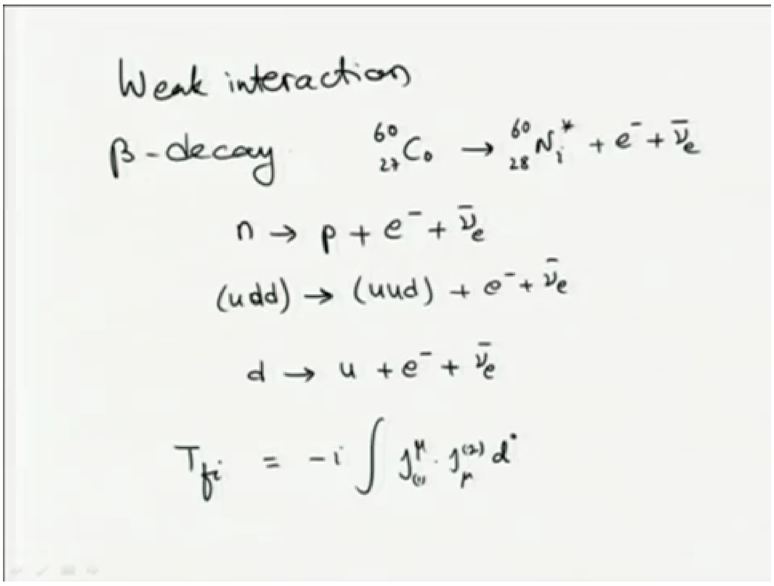

Now, we know there is this weak interaction, as already introduced somewhere in the beginning of the discussion that we had. We said it was observed that certain nuclei undergo beta decay. An example of weak interaction is beta decay. Say for example, Cobalt 60 with mass number 60 undergoes beta decay by converting itself into Nickel and emitting electron and neutral particle.

When you consider the nucleon level of interaction, this is essentially conversion of one of the neutrons to proton by emitting an electron and the neutral particles. Electric charge is conserved on both sides. So, is what is called the Lepton number and Varian number.

At the quark level we know we can think about this as a u quark and a d quark and the d quark converting into u quark u quark and d quark plus e minus plus e or you can say that one of the d quarks converts itself into a u quark and an electron plus nu e bar. And we had been describing the transition amplitudes in terms of current interactions current interaction.

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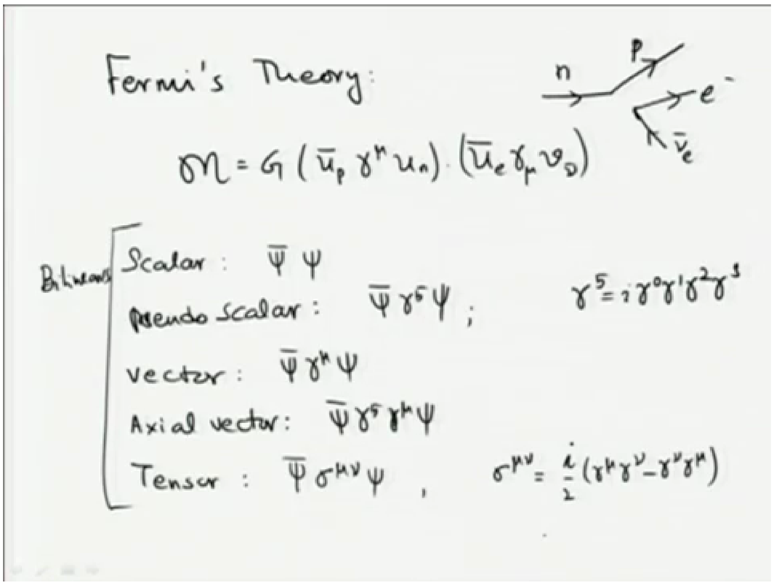

So, Fermi thought that it is possible to understand weak interactions also in a similar form. He said the invariant amplitude can be written in terms of two currents, one is an n p current and the other is basically electron and neutrino. So, these currents can be written in corresponding in terms of the corresponding spinners, u p bar gamma mu u n, u e bar gamma mu. It should be the anti neutrino that is coming with it because it is the lepton and anti lepton together that will be emitted not the lepton and the lepton. So, we will have a v nu bar associated with.

So, this is basically the kind of picture that Fermi thought is possible, with of course some kind of constant or coupling which connects these two currents. He did not introduce any exchange particle between any propagation any propagator or any particle propagating between these so that was one thing. Other thing was the structure of the current was very similar to that of the that used in the case of electromagnetic interactions, this is what Fermi proposed.

But then it turned out that it is not able to describe all aspects of beta decay and then investigation of other possibilities leads though to the following. With the same kind of the spinners and the conjugate spinner the bar u bar and u and v and v bar, what are the other objects that we can construct similar to these currents j mu j mu? So, possible radius r we can make scalar quantity psi bar psi, which is a scalar under the Lorentz transformation. We can actually have a pseudo scalar by pseudo scalar we mean something which changes sign under parity.

So, it is gamma 5 psi where we define gamma 5 as i, gamma 0, gamma 1, gamma 2, gamma 3 product of all the 4 gamma matrices multiplied by an i. We will not go into the detailed properties of this gamma 5 etcetera; we will not also go into how we say that and what is the transformation property of this object under Lorentz transformation. We will just take it for granted that gamma 5, when put between psi bar and psi the whole object transform like a pseudo scalar. Then we have the familiar vector which is psi bar gamma mu psi and axial vector which is psi bar gamma 5 gamma mu psi.

So, vector and axial vector how do they differ? A vector when you take the special components that is gamma 1, gamma 2, gamma 3 part of cyber gamma mu psi, they transform under parity like any ordinary vector position vector x or momentum vector p or any other ordinary vector which means they change sign under parity. So, but axial vector is something which will not change sign under parity, the special components of the axial vector will not change sign under parity similar to orbital angular momentum or spin orbital spin angular momentum, we will come to that in a little while.

But then there is another object a tensor of second rank that can be constructed out of the gammas and psi bar and psi, which is for short written in this fashion, gamma psi bar sigma mu nu psi where sigma mu nu is a second rank tensor of rate, gamma mu, gamma nu tensor gamma mu gamma nu minus gamma nu gamma mu the anti-symmetric tensor obtained i over 2.

These are the different type of what are called the by lineage set of by lineage with proper Lorentz transformation structure, that can be constructed from using gamma mu and psi and psi bar. Again we will not go into the details of why this particular set and how we confine say that this is the this Lexus the we cannot add anything more to it again let us take it for granted that that is the way it is.

So, this is with this now we cannot also think about other possibilities for the invariant amplitude m. In particular we can think about the pseudo scalars for example, sorry pseudo the axial vectors for example, how do we decide all these things? It was sort of own by because of various experimental reasons one of which is what is called the Parity Violation Observed in beta decay.

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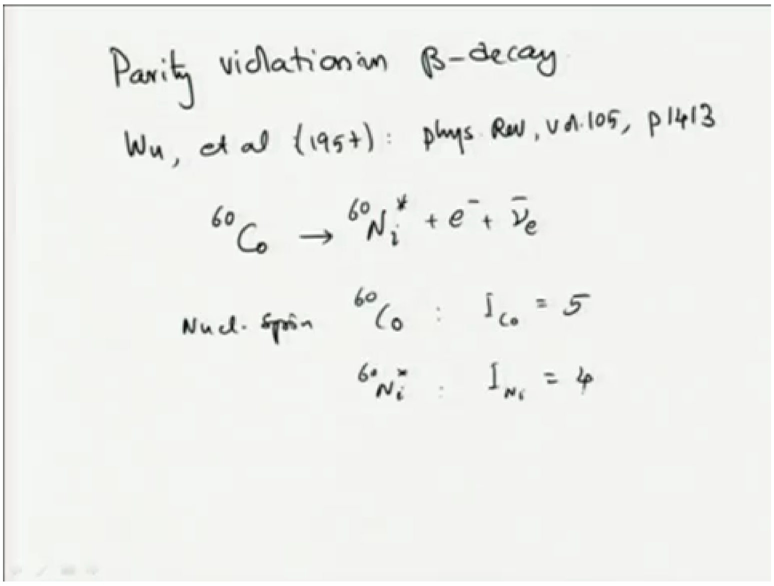

This was suggested actually by lee and t d lee and seon young and they later on got Nobel Prize for theoretical support that they gave for that arguments that, they put forward for that which was experimentally proven.

So, the experiment that actually proved or showed first that the parity is violated in beta decay was conducted by W u and others W u and others conducted an experiment in 1957, result of which is published in physical review volume 105 page 1413. The experiment was basically conducted, but radioactive sample of cobalt, which as we said in the earlier the discussion earlier sign could decay into nickel and electron and anti neutrino. Parity says that and say how things behave under special inversion for that, when we say special inversion we need to have some reference direction about which you invert this thing.

So, that such a direction was needed here, then like for us the cobalt 60 nucleus has a large nuclear spin. So, the nuclear spin of cobalt 60 is let me denote it by I Co 5. And the nickel it is for very large nuclear spin associated with both the nuclei and this could be a reference direction. First thing was has to actually align all this in a particular direction for that they use large magnetic field and cool the sample to a low temperature, then observed their decay properties.

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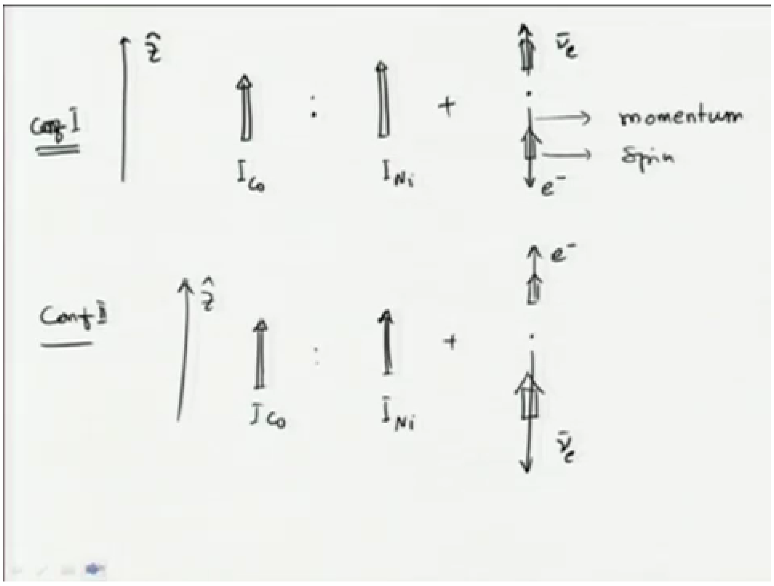

So, if you look at the spin or a configuration of cobalt, let us say this is spin of the cobalt that we are considering, that is what we have the initial state and in the final state we have the spin of the nickel and then, you also have electrons and neutrinos coming out. We can consider cobalt and nickel to be at rest and electron and neutrino to come out. So, to get the specific spin configuration to agree with the spin angular momentum conservation, we need the spins of the outgoing particle to be aligned along with the spin of the cobalt, which is also the direction of the spin of the nickel which is coming out.

So, now one possibility is that electron comes out opposite to the spin direction of the cobalt and neutrino or anti neutrino goes with the momentum goes along the direction of the cobalt 60 spin. So, let me actually call this reference direction as Z direction and this is basically can be you need some heavy magnetic high magnetic field in that direction for the spins to be aligned in this fashion. And to here this thin line represents momentum direction linear momentum and thick line is denotes the spin direction for either of the particle. So, let me call this configuration 1. Possible also to have a second configuration in which case, I cobalt is in the same direction as the Z cap again and I nickel is also in the same direction.

Now, particles which are coming out will again have the same spin directions that along the Z direction, but it could be the electron going in the positive direction now z direction now and anti neutrino coming out in the negative Z direction, this is another possibility. If you apply parity to this what is parity?

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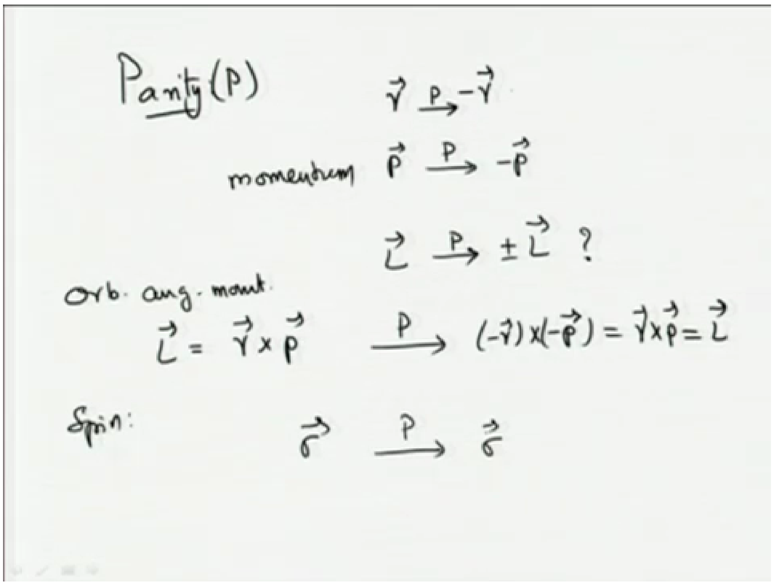

We already mentioned that, but parity let me denote the operator by operation by P. It changes r to minus r position vector and also it is not (Refer Time: 17:13) r goes to minus r under parity and p linear momentum goes to minus p, whereas, if you look at the angular momentum, that goes to what? Remember L s orbital angular momentum is r cross p; both r and p changes sign. So, it goes to minus r cross minus p which is equal to plus r cross p. So, it is equal to L.

So, this is the orbital angular momentum. Spin is similar to the orbital angular momentum. So, if I denote it by sigma I will say that this also goes unchanged under parity, because it is similar in all ways to orbital angular momentum. So, both sigma and L are axial vectors, where as the position vector and linear momentum are ordinary polar vectors as they are called consider particle with spin aligned along the linear momentum.

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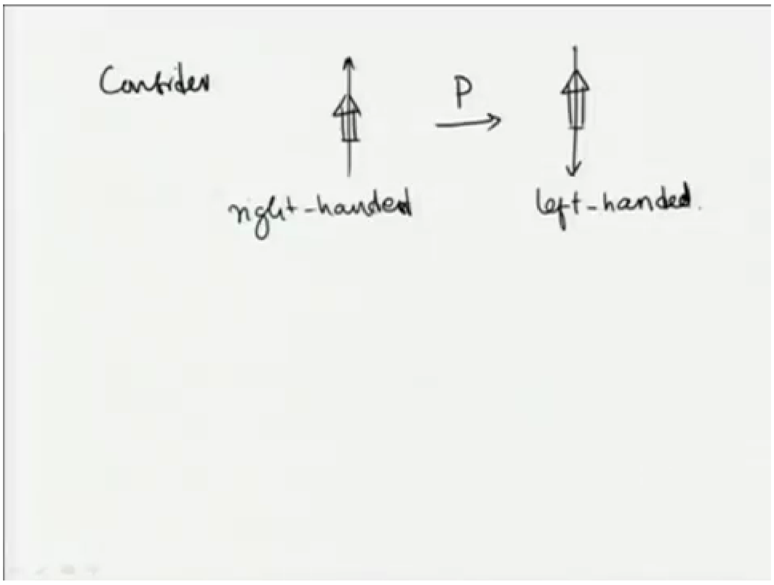

Under parity what you expect is, that the spin is spin direction is unchanged while the momentum direction is opposite. So, as we mentioned in a in a earlier location, this particle with momentum aligned or the spin aligned along the momentum are called a right handed particle and the other ones aligned opposite to the linear momentum are called left handed particles. So, the parity operating on a right handed partic system particle takes it to a right left handed particle.

In an experiment what it means is that, if parity is a good corner number is a good symmetry of the interaction of the system as a whole including the interactions, then if configuration 1 happens, the other possibility configuration 2 which is obtained by applying parity on configuration 1. When you apply configuration parity and configuration 1 you get the spin of the cobalt unchanged, spin of nickel unchanged, spin of electron unchanged, a spin of neutrino anti neutrino unchanged, the directions of it. Whereas, the direction of electron momentum linear momentum is changed goes to a opposite direction. In configuration 1 it was along the negative z direction and in configuration 2 it is along the z axis, similarly for the anti-neutrino.

So, you can say you can get configuration 2 from configuration 1 by applying a parity operation. Experimentally the statement is that, if configuration 1 is observed that is if you see electrons coming out opposite to the direction of the spin of cobalt, then you should see electrons coming out along the spin of the cobalt also. You remember that what we are working with is a quantum mechanical system and therefore, all the statements are statistical in nature.

In the sense that you observe a large number of such interactions such decays, then say that out of many such this things say 1000 decays, you expect approximately 50 percent of the time electron comes out along the spin direction of the cobalt along the z axis and 50 percent of the time opposite to this thing. Or if you take the positive z hemisphere and negative z hemisphere, you will see that with all the uncertainties and experimental details taken into account. You will you should see approximately the same number of electrons coming out in the negative z hemisphere and the positive z hemisphere.

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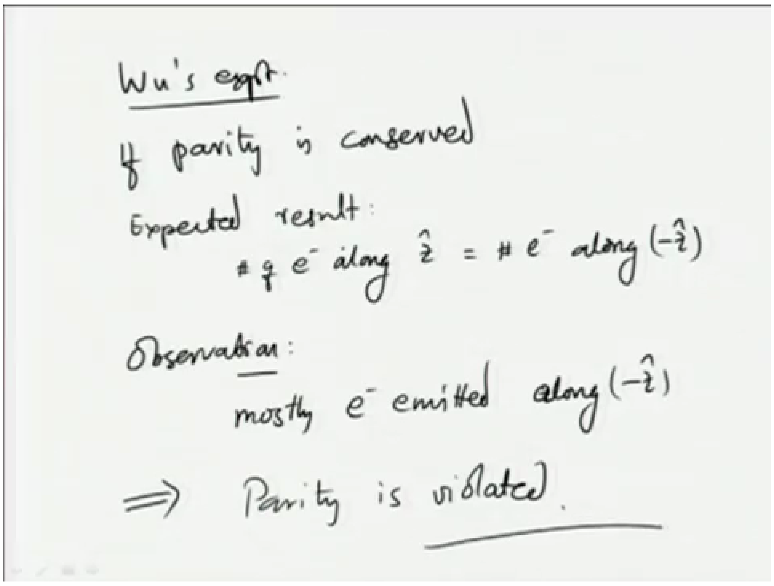

Wu's experiment: If parity is conserved. Expected result; number of electrons in the or along z direction, which is the direction of the cobalt 60 spin approximately statistically; number of electrons opposite to or along the negative z axis opposite to positive z axis. Observation: Mostly electrons emitted along negative z axis z direction opposite to the cobalt 60 spin. Conclusion parity is violated.

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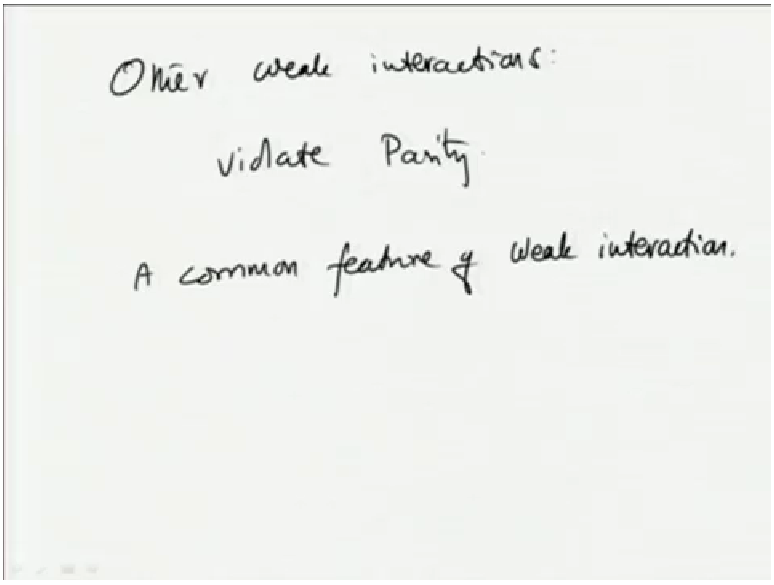

And you can see that later on other weak interactions, confirm that they are violate the parity. So, parity violation is a common feature of weak interaction ok. In fact, this was a very important experimental confirmation of theoretical expectation and it was very important to understand the interaction weak interactions ok.

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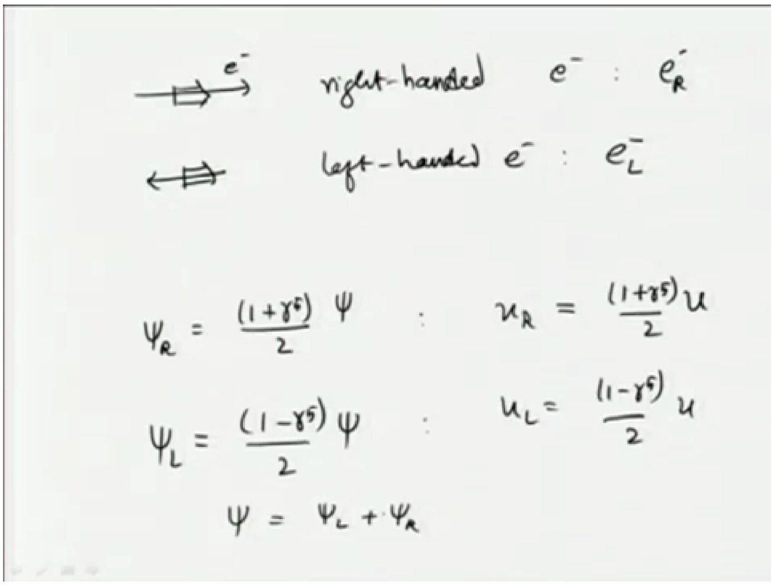

Let us look at how to accommodate how one accommodates that in a theoretical framework. So, we will not go into the details, but let us give some flavor of this as this kind of right handed particles say electrons are denoted by e R and can be represented by psi R, which can be written as psi l operated by an operator 1 minus gamma 5 which we had defined earlier by 2 or in terms of the spinners it is u a spinner u it is u R equal to 1 plus of course 1 plus gamma 5 by 2 u.

Similarly you can represent the left handed electron by e L minus and that can be represented by wave function psi L 1 minus gamma 5 by 2 psi, for u L is 1 minus gamma 5 by 2 u. This half factor is for un-polarized without any specific left handed or right handed or a mixture of these two can be written as psi L plus psi R equal amount of these two. You can you see that when you add this to the gamma 5 factor drops out. This is how you can represent them and then this is the kind of thing that will come in the current for example, when you consider only the left handed electrons in interactions.

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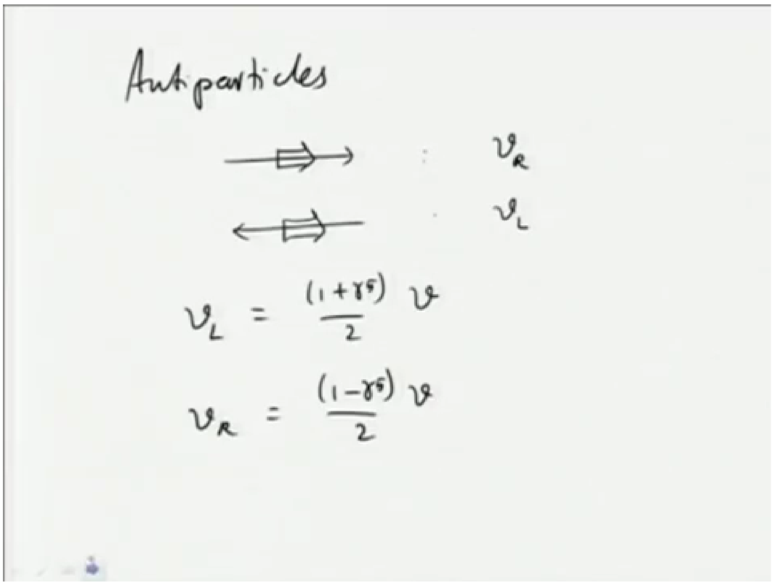

Similarly, for antiparticles, it is again the same notation v R for the right handed ones and v L for the left handed ones and v L is 1 1 plus gamma 5 by 2, we know it is the other way around v R is equal to 1 minus gamma 5 by 2 v. How do we conclude this etcetera ah take us slightly far from our main focus in this course? So, we will not go into that, you have you can take any standard introduction to introductory book on high energy physics or particle physics and that will all be describing these aspects. So, we will not do that in this discussions now similar to parity there is another important symmetry called Charge Conjugation which is again important in weak interactions.

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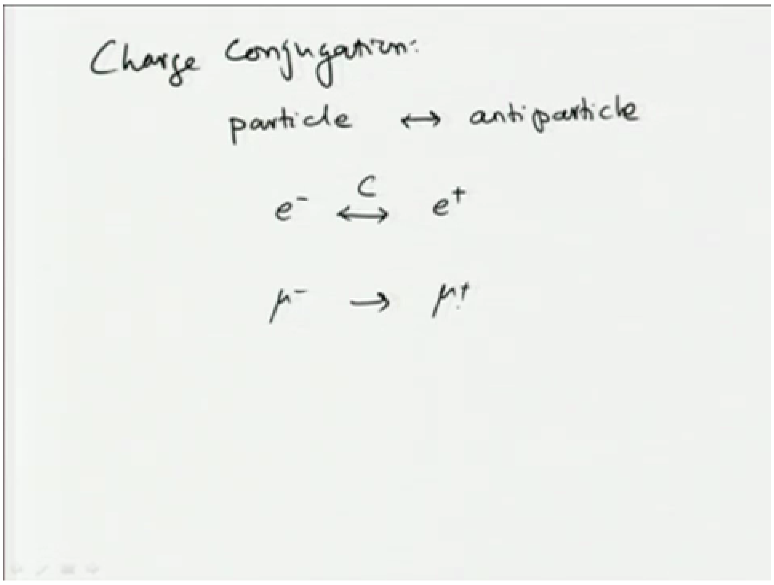

Essentially it is a symmetry that takes a particle to an anti-particle. For example, electron goes to positron under C or positron goes to electron under c or mu on goes to mu plus under c ok.

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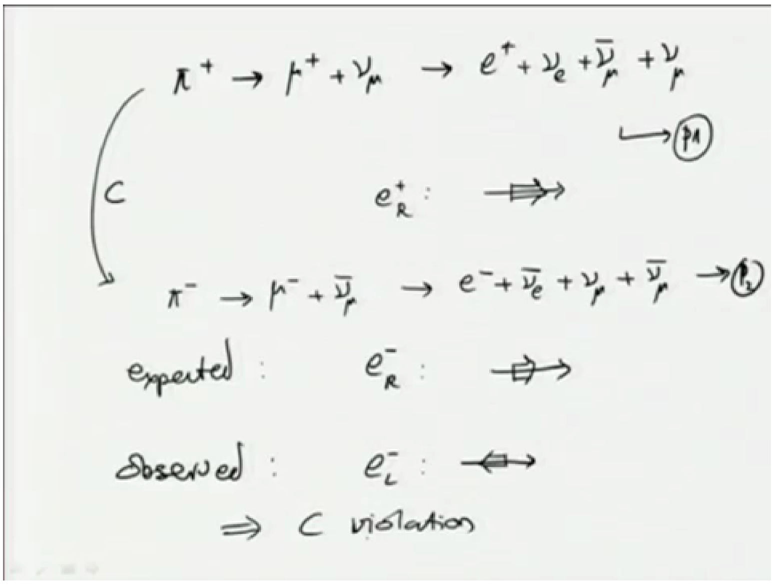

Now, let us look at one particular process weak process pi on with charge plus 1 decays to mu on plus the neutrino corresponding to the mu 1, mu 1 further decays to electron and electron type neutrino and mu 1 type neutrino mu 1 type anti neutrino and then the other neutrino already exist let me call this process 1. Experimentally it is observed that we can measure the let us say like the earlier beta decay experiment say we can find out what is the spin orientation of the electron or the positron coming out of this and it is found that the positron coming out is right handed one always.

Now, consider another process which is obtained by applying charge conjugation to process 1. So, pi plus goes to its antiparticle pi minus we already discussed this earlier, that pi minus is an antiparticle of pi plus mu minus nu mu bar goes to e minus nu e bar plus nu mu plus nu mu bar; let me call this process 2 p 2. Expected that electron coming out of this is also a right handed particle. It is e R which is coming on. Why? Because charge conjugation operation will not do anything on the spin or the momentum. It only changes the type of the particle from particle to antiparticle and antiparticle to particle.

So, if it is the positron with right handed or the spin aligned along the momentum that is coming out in process 1. If charge conjugation is a good symmetry that nothing changes under charge conjugation, then we expect this electron coming out in process 2 to be also right handed. What is observed experimentally is that, electron is always, but left handed. This is that charge conjugation is violated c violation.

So, there are other examples also, enough example lot of examples in weak interactions, where one can see that the charge conjugation is not a good symmetry which means that the different processes which are related by charge conjugation do not happen at the same rate at least or some of them do not happen at all like in this case.

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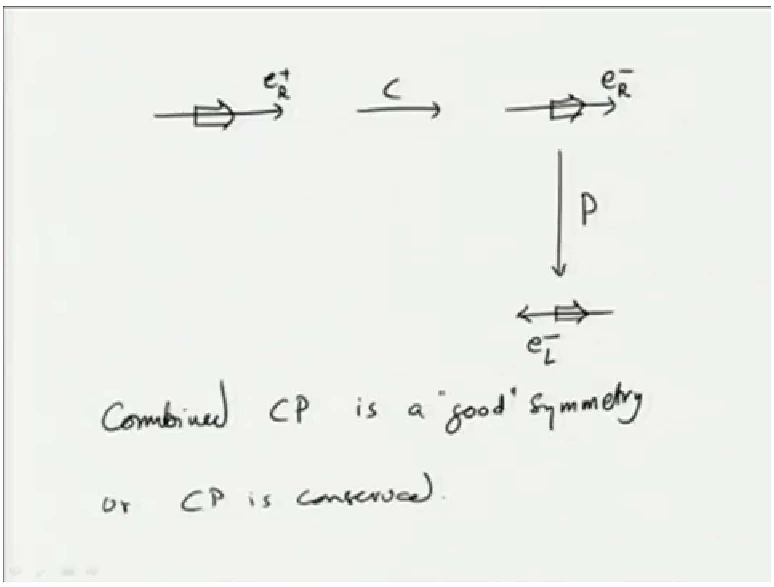

But now, let us look at this same set of positron and electron coming out. So, e plus under charge conjugation is expected to go to, e minus with the same momentum and spin, but now let me apply parity to it and that should give me opposite momentum, but the spin orientation the same particle remains the same what is that? It is an electron with spin oriented opposite to the momentum.

So, start with its a right handed positron, under charge conjugation goes to a right handed electron, under parity goes to a left handed electron and that is fine that is observed. So, if in the combined charge conjugation and parity transformation, it seems to be alright. So, combined C P is a good. When I say good symmetry, it means that processes interaction which conserves the C P. This is why we mean by C P is conserved or C P is a good symmetry C P is conserved. So, most of the C P, weak interactions, conserve charge conjugation and parity together.

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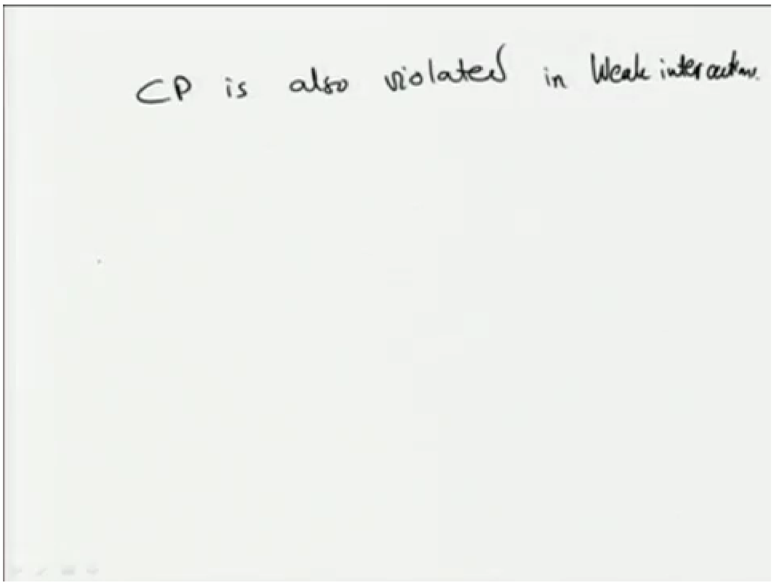

But then later on it is found that C P is also violated. When I say C P, it is a combined charge conjugation and parity symmetry is also violated in weak interactions. To understand this we will need to discuss some more aspects of parity and charge conjugation and we will do that in the next discussion.