Welcome back to 8.701. In this lecture, we'll talk about CP symmetry or CP violation. In previous lectures, we discussed that the weak interaction is not invariant under parity and charge conjugation transformation. But now we can ask the question, how about CP-- so transformation which does change conjugation and parity transformation.

The classical example to show parity violation is the decay of a pion. So we have here this charge pion with spin 0. And it decays into a muon and a neutrino, an anti-muon and a neutrino. And so since the neutrino is left-handed, the-- [INAUDIBLE] decay coming onto muon needs to be left-handed as well.

So if you do parity transformation of this decay, you see that the outcoming muon would be right-handed. On the other hand, there is no right-handed neutrino. And therefore, this decay is not possible. So this is not-- so this mirror symmetry is not realized in nature, as a consequence of the weak interaction.

So similarly, we could do a charge transformation, a charge conjugation, of this decay. So you turn particles into the antiparticles. And you find here this antineutrino, which is left-handed. And also, those don't exist in nature. So parity or charge conjugation doesn't really work on those decays, those [INAUDIBLE] decays.

But what does work, if you apply the parity and a charge conjugation, we turn the positively-charged pion into a negatively-charge pion, the antimuon into a muon, and the neutrino into an antineutrino. And you see here that the antineutrino is right-handed. So is the muon. And so that decay is actually observed in nature.

Good. So we saved the day. It seems like that CP, that the weak interaction is invariant in the CP transformation. However, that's not quite true. Gell-Mann and Pais noted that in systems of neutral kaons, there's an artifact. And the fact is that a particle, a K0, can turn into an antiparticle by changing the strangeness. And that's possible in this kind of box diagrams, which include a box with a couple of W's.

And it's easy to see that if you could prepare a kaon, it will oscillate, because those diagrams are possible, into an antiparticle. So now what is happening now to CP here, if I apply CP on a kaon, I find a minus sign and an antikaon.

So if you want to analyze this further, you might want to find the eigenstates to this. And so the eigenstates can be found, as well as K1 and K2, which are admixtures of the K0 and the anti-K0. And you find this symmetric, the symmetric and the anti-symmetric states. Good. So if you apply CP on the eigenstates, you find eigenvalues of 1 and minus 1.

It turns out that the lifetime of decay 1 decay 2, those eigenstates, is very different. One is 10 to the minus 10, and one is 5 times 10 to the minus 8. So decay 1 decays much, much quicker than decay 2.

So this, then, sets the stage to a test of CP violation. So what you're going to do is prepare a beam of K0's and let them decay. And only after some time, you study the beam again, which then should be made up solely of K2's.

So if you in that beam observe decays of the K2 into two pions, you noted that there is an admixture again, which violates CP. So you have an admixture of K1's in a beam which should just be of K2's. So that mixture, then, will violate CP invariance.

And exactly that was done. So Croning and Fitch picked up this idea. They set up an experiment in which they produced kaons. They had them decay. And then they studied later in the beam whether or not they could find two pion decays.

And they did, indeed, observe 42-- 45 pion decays, two-pion decays, in a total of 22,700 decays. So that means that this K long beam, the long-lived kaon beam, is actually an admixture of K2's with a small additional component of K1's. So here they observed CP violation through the mixture of those states. And this epsilon gives you, you know, size of the strength of the CP violation.

So here is a note of the paper. We'll have another discussion of this in class by a student presentation, Croning and Fitch. Here this is Croning, and this is Fitch.

It turns out that Croning is actually a student, or was a student, of Enrico Fermi and also worked in Chicago. So that's quite an interesting family tree here, to which also Jerry Friedman belongs. Jerry Friedman is a retired faculty at MIT and discovered that protons are made out of quarks. So this is a very interesting family tree. If you have some time, you might want to look into this.

But here's the experiment. So you take protons, you dump them into a beam. You try to, with this magnet, filter out a neutral component, get rid of all photons, and then let this beam decay, and look in the spectrometer for decays of two photons.

Here's a bigger picture of the same spectrum. So this is actually a blow-up view of this. So you have your kaons, neutral kaons coming in, the K2's. And then you look for pion decays.

The instrumentation and how we actually would do this is part of later discussions where we actually talk about detectors in more detail. All right. So we just saw that Croning and Fitch observed CP violation in mixture of states.

But we can also observe CP violation in direct decays. And the classical example here is the case of the K long and semileptonic decays. So semileptonic here means we have a decay of the K long, a neutral particle and a charged pion, an electron and antineutrino-- or it might very well also decay into a pi minus, a positron, and a neutrino.

And it turns out, when you really count those events and perform a precise experiment, that the K longs prefer decays to positrons over decays to electrons. And so the fractional amount of this imbalance is 3 times 10 to the minus 3. So this is a rather small effect, again, of CP violation here in direct decays.

Since then, CP violation has also been shown in the decay of B mesons. And the program of studying B mesons is a big part of the LHC experiment at the LHC. There's also experiments in Japan going on right now which study B mesons in order to learn further about B systems.

Tests are also underway, for those who listened to the colloquium on Monday, in the neutrino sector. So here we have a completely different part, so not quarks are involved in weak interaction but neutrinos. And so the question is whether or not in that sector of physics, that sector of the standard model, there is CP violation. Those are aspects we'll discuss later on when we talk about neutrinos specifically.

Before I close, a few more remarks on the matter-antimatter symmetry. So one of the biggest mysteries in physics, I would claim, is the fact that we're even here to ask this question. So there is apparently more matter in the universe than antimatter. You start from a big bang, there was this symmetry, and now we live in a universe which is dominated by matter.

So how is this possible? So in 1967, Zakharov proposed that this is possible in a system where baryon number is violated. So this is almost a trivial statement. If you start from an equal number of baryons and antibaryons, the sum is then 0. The baryon number is 0 of this system. And you end up in a system which is dominated by baryons, then baryon number needs to be violated.

But there's also the need of CP violation in this. So we just saw that this is realized in nature. But the amount of CP violation we observe in the system I just discussed is not sufficient to explain the matter-antimatter symmetry we observe in nature. So there is more to be found. There's new physics to be looked for in CP violation on this overall question. And there's also a need for the actions to be out of equilibrium, meaning that you don't revert the processes as you go forward.

Yet another point of discussion, which I will not go into much detail in this lecture, is that our quantum field theory, which describes quasi-standard model and describes the interaction of particles, is invariant, and the CPT transformations. That means that if CP is violated, time reversal cannot be a symmetry. So meaning, going backwards and forwards in time is not symmetric.

And you can test this. You can design experiments which test [INAUDIBLE] the fact. You can also design experiments which test CPT directly. But this is-- those are all interesting questions, but we will not go into any of those in this lecture. We will, however, come back to understanding the origin of CP violation in the standard model when we talk in more detail about the weak interaction.