MITOCW | L8.4 Neutrino Physics: Experimental Study

MARKUS KLUTE: Welcome back to 8.701. So in this video, we want to look at experimental studies of neutrino oscillations. The first question is, where do we get the neutrinos? How do we produce the neutrinos?

The answer is, there's numerous sources for neutrinos. You might be lucky and find them in supernova explosions. Or if we're really trying hard, we can observe them as relics of the Big Bang. There is a lot of neutrinos as a relic of the Big Bang around us. Problem is that they have very low energies and are difficult to observe.

Easier-- so is the use of neutrinos in the-- generated in cosmic ray showers. There's a lot of neutrinos coming from the sun. Beams, beamlines-- accelerators can be used to smash particles into a material, and then in the decay product, produce also neutrinos.

And also, reactors. Nuclear reactors can be used as neutrino sources. By the way, neutrinos can also be used in order to monitor the nuclear activity around the globe.

OK. Studies of neutrino oscillations. So we can make this table here and ask ourselves, what kind of-- the experimental parameters are the length, the energy, and the sensitivity to a specific mass range. So for the solar neutrinos, you know the distance between the Earth and the sun is pretty much fixed to first order. The energy of the neutrinos coming out is in the order of 1 meV.

We are going to look at the table. And so the mass range you can probe is 10 to the minus 10 in delta m squared. For atmospheric neutrinos, they're produced in the upper atmosphere, 10 to the 4, 10 to 7 meters. Energies can range-- have a large range, let's say 10 to the 2 to 10 to the 5 meV.

And then reactors, typically meV range. It's kind of the nuclear range for the neutrino energies. And the range is given by how much space do you have around or away from a nuclear reactor.

Similarly for accelerators. You build an accelerator or use an existing accelerator, and then you build your detectors, maybe close to it, and maybe another one far away. And that's limited by the size of our planet or wherever you want to build your detectors. Energy ranges there depends on the energy range of the accelerator. And that is in the order of 10 to the 3, 10 to the 4 meV.

So you see that it's actually rather a straightforward study. Also, it's interesting to see-- and we'll see this next-- what kind of flavor of neutrinos, and whether or not we can study neutrinos or antineutrinos with other experiment is important. Let's go through this. So it's been a little bit of a history in how this all occurred.

So the first question is, what happens to the solar neutrinos? So solar neutrinos are basically produced in the core of the sun, together with light. It turns out that the light of the sun takes about 10,000 years to come out of the sun, while the neutrinos come out immediately. So when first experiments tried to observe solar neutrinos, they had to theoretically estimate how many neutrinos to expect, and they saw less.

And so one explanation would have been, or could have been, or was, maybe something happened at the core of the sun and we just haven't seen it yet, because the light which come out of the sun has a delay of up to 10,000 years. That didn't turn out to be the case.

So here is the spectrum of the neutrino energies and the specific sources of neutrinos from the sun. In our nuclear physics discussion, we'll get to the point that we understand how the neutrino-- how the sun produces energy, and then some of this becomes more clear. The story to take away at this point is that there are certain-- there's several processes in the sun producing neutrinos. And they all come with their characteristic energy distribution. But the bottom line is you find meV scale neutrinos from the sun.

There's a soup of electron neutrinos. They start interacting with the sun. And there's a little bit of a flavor evolution within-- when they go through the material of the sun. But, you know, what you want to really do is look for disappearance in detectors which are sensitive to electron neutrinos.

And that has been done in a number of experiments. Most famous may be the Davis experiments which had a big tank of chlorine. And in the interaction, you were looking for finding argon in your detector, and you just every now and then went in there and saw how much argon was actually produced. And it turned out that those experiments, all of them, found a reduced number of neutrinos, reduced with respect to the theoretical expectation.

So far so good. The assumption was that-- or there was no knowledge of neutrino oscillations or mixing at this time. So that needed to be explained. And one way to explain-- it's not just using the charge interaction, which allows you to probe the flavor of the neutrino, but also lose a neutral-- the neutral scattering, which then allows you to measure the total number of neutrinos.

And if you do this-- this was done by the SNO experiment-- you find that the total number of neutrinos is in good agreement with the theoretical expectation. Hence, those neutrinos are not really lost, they're just more from one flavor into the next. So this was the first evidence for solar neutrinos to be oscillating.

By now there's-- this first experiment was Homestake. By now, there is a larger number of solar neutrino experiments, and you see the long time of neutrino studies. Different materials are being used, different energy thresholds being tested, different scale of the experiments, and experiments become more sensitive the larger they are. And so this you can-- something you can see from this table.

The next sort of neutrinos is the ones which are produced in the atmosphere. So they are produced in decays of pions and kaons and by the cosmic rays interact with the atmosphere, or the Earth's atmosphere. And so you find, for example, a pi plus decaying into a muon and a muon neutrino. And then the muon itself can decay into an electron, an electron neutrino, and a muon antineutrino.

So if you, for example, build a ratio of muon/antimuon over electron/anti-electron neutrinos, you find it should be around 2. You have two neutrinos-- muon neutrinos here, and an electron neutrino.

And also, this wasn't really observed. And you can see here, as a function of the column of the zenith, of looking up upwards towards the atmosphere or downwards, you find that there is an effect of this kind of oscillation. So the actual measurement depends on the energy range. And you can see that the muon neutrinos, the muon-like neutrinos, they disappear. You see here in this very clear plot the prediction without oscillation compared to the experimental results, so you see the muon neutrinos actually disappear.

Moving on, accelerators can be used. And the big accelerator on the Earth at CERN or at Fermilab. The beamline at Fermilab is called NuMI, Fermilab National Accelerator Laboratory, FNAL. Or CERN, or in Japan. Those are the big sources of accelerator-driven neutrinos.

And with those, there's big detectors, typically a detector very close to the accelerator and one further away. The close one probes the total flux of the neutrino at the experiment, and then the one which is away in order to probe the effect of the neutrino oscillation in order to study appearance or disappearance.

And again here, you see this is a long program. But it basically took off quite a bit in the 2000s and after. So a lot of neutrino physics happened in those years. A lot of information about the neutrino was gathered in those years. And again here-- this is from the T2K experiment-- you see the comparison between unoscillated predictions and oscillated using some additional constraints about expectation of the total flux of the neutrinos, and that compared to the data. And you see very clearly that the-- that the neutrinos oscillate, that there is evidence of oscillation.

All right. The last source are reactor neutrinos. We'll talk about nuclear physics starting from next week. Here neutrinos are produced in nuclear fission of heavy isotopes, mainly uranium and polonium. The flux can be calculated in various ways, for example by knowing the nuclear processes and the thermal power produced in the reactor, or by just looking at how much fuel is being-- nuclear fuel is being used by the reactor itself.

What's being studied here is the anti-electron neutrino disappearance. And what you do here is you use this inverse beta decay, where you have a collision or scattering of a anti-electron neutrino with a proton, creating an electron-- a positron and a neutron. And again, there's a number of experiments. Basically, whenever you have a large neutrino experiment, it can probe surrounding nuclear reactors. There's many of them in France and Japan, also in China. And they're being used in those experiments.

Again, you see that this topic became really hot in the 2000s. And again, a lot of-- a lot has been learned. So this part here shows you as a function of the energy-- the length over the energy-- so kilometer over meV-- the oscillation, the survival probability, meaning that you can actually see directly the oscillation of the neutrinos.