Neutrino oscillation

The 2015 Nobel Prize in physics was awarded to two experimental physicists, Takaaki Kajita and Arthur McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass." In this article, I will try to explain the significance of this work, even though it is impossible to understand why neutrino oscillation occurs without some basic understanding of quantum mechanics. In my later article "Neutrino oscillation, clarified," I will explain neutrino oscillation using quantum mechanics.

To begin with, let me first introduce what a neutrino is and its historical background. According to a standard law of physics, the total energy before a process must be equal to the total energy after the process. This is known as "energy conservation." However, in the early 20th century, it was reported that experimental results seemed to suggest that energy was not conserved during a process called "beta decay." (During beta decay, an electron is emitted from an atomic nucleus. If energy is conserved, the energy of the emitted electron must have one discrete value as it should be simply given by the energy difference between the initial nucleus and the final nucleus. However, the measured energy of the emitted electrons varied widely.) This was a big puzzle for physicists. As an incorrect solution, Niels Bohr suggested that energy is not conserved in every process, but only on average.

Even though the initial reaction was skeptical, the correct solution came in 1930 when Wolfgang Pauli suggested that a hitherto unknown particle is emitted during beta decay, having an arbitrary proportion of energy. From energy conservation, the rest of the energy generated during beta decay (i.e. the energy difference just mentioned) should be allocated to the emitted electron. This explained why emitted electrons had wide range of energy. In 1932, Enrico Fermi named the unknown particle a "neutrino." In 1956, Clyde Cowan and Frederick Reines detected the neutrino and the latter received the 1995 Nobel Prize for this discovery. The reason it took such a long time to discover neutrino is that it interacts very weakly with other matter. Trillions of neutrinos pass through your body every second, but you don't notice them; actually most of the neutrinos pass through the earth as if it is transparent to them. Therefore, in observatories deep underground,[1] scientists have no problem of observing neutrinos from the sun, even though they cannot see the sunshine itself that far below the surface.

In 1962, Leon Lederman, Melvin Schwartz and Jack Steinberger discovered a new type ("flavor") of neutrino for which they earned the 1988 Nobel Prize. Before their work, a

[1]The neutrino detection is performed underground to prevent all the other particles from reaching the detector.

neutrino had been known to take part in the process that involves an electron.[2] However, the three researchers showed that a new flavor of neutrino takes part in the process that involves a particle called a "muon," which has very similar properties to electron except for its mass.[3] The hitherto known neutrino was re-named as "electron neutrino" and the new neutrino was named "muon neutrino." When a particle called "tau," which has very similar properties to the electron and muon except for its mass, was discovered in 1975, it was obvious that "tau neutrino" must exist. The discovery of the tau neutrino was reported in 2000.

In 1968, a new puzzle that baffled scientists arose. The standard solar model predicted that a certain amount of electron neutrinos are produced in the sun every second. However, when the amount of electron neutrinos reaching the earth was measured in an observatory 1478 meters underground in South Dakota, United States, the measured number was only about one-third of the expected. This problem was known as the "solar neutrino problem." Raymond Davis Jr, one of the scientists who led the observatory and first discovered this problem, was awarded the Nobel Prize in Physics in 2002. Some scientists have unsuccessfully tried to solve the problem by changing the solar model.

In 1962 three Japanese physicists, Maki, Nakagawa and Sakata first came up with the correct theory of neutrino oscillation, stating that neutrinos can change their flavors if they have masses. (We will come back to this later in the article.) This theory was further elaborated by Pontecorvo in 1967. In 1969, a year after the discovery of the solar neutrino problem, Gribov and Pontecorvo proposed that neutrino oscillation was the solution to the solar neutrino problem, as electron neutrinos produced in the sun could change to other flavors of neutrinos by the time they reach the earth.

However, through the 1970s, it was widely believed that neutrinos did not have masses, and therefore could not change their flavors. This was reasonable considering that in the 1970s the speed of neutrino was measured in an accelerator called "Fermilab" and found to be the same as the speed of light within the margin of error. Einstein's theory of relativity predicts that only massless particles such as photons (i.e. light particles) travel at the speed of light. Apparently, the actual masses of the neutrinos are so small that the difference between the speed of neutrino and the speed of light was not big enough to be detected, and remains undetectable as of the time of this writing (i.e. early 21st century).

In 1998 Kajita's team found the first firm evidence of neutrino oscillation in observatories deep underground. Many particles from the universe fall into the earth, (such particles are collectively called "cosmic rays") and through their interactions with the earth's atmosphere, many neutrinos, mainly electron-neutrinos and muon-neutrinos, are produced. Kajita's team carefully measured the number of electron neutrinos and the number of muon neutrinos detected in their observatories with their incoming direction. However, the number of muon neutrinos so obtained was discrepant from what it should be without neutrino oscillation,

[2] Precisely speaking, an electron or its anti-particle. I won't explain what anti-particle is, as it is not crucial to understand this article.

[3] Precisely speaking, muon or its anti-particle.

and the amount of the discrepancy depended on the incoming direction. By careful analysis of the data, Kajita's team showed that this was due to neutrino oscillation that transformed muon-neutrinos to tau-neutrinos. Downward going neutrinos came from the atmosphere right above the observatory, while upward going neutrinos came from the atmosphere on the opposite side of the earth, passing straight through the earth's interior. The distance neutrinos traveled in each case is clearly different, the former being very short and the latter being about the diameter of the earth. As the amount of the neutrino oscillation depends on the distance traveled, the amount of neutrino oscillations in these cases are different, and was shown to be exactly the pattern predicted by the neutrino oscillation theory.

In 2001, McDonald's team firmly solved the solar neutrino problem. All of the previous solar neutrino detectors could only detect electron-neutrinos. However, McDonald's team measured the number of electron-neutrinos as well as the total number of neutrinos of all three flavors; they directly showed that the deficit in the number of electron-neutrinos was due to the creation of neutrinos with other flavors.

In 2003, my math professor at Harvard mentioned in the class that he did some calculations based on the assumption that neutrinos were massless, but now those calculations were useless.

Now, as promised, let me try to explain why neutrinos can change their flavor if they have mass, although it's impossible to understand if you don't know the basics of quantum mechanics or at least linear algebra.

Most particles such as the electron, muon or tau have a single, uniquely-defined mass. For example, an electron has a mass of about 0.5 MeV or 9×10^{-31}kg. There is no other value. However, a neutrino of each flavor does not have a single, uniquely-defined mass, but is a mixture of three different states, each with a definite mass. (If you know some linear algebra: a neutrino of each flavor is not an eigenvector of a mass matrix, but a linear combination of eigenvectors of a mass matrix.) For example, current neutrino oscillation observations and experiments suggest that an electron neutrino is made out of 68% of a state with a certain mass which I call "m_1," 30% of a state with a certain mass which I call "m_2" and 2% of a state with a certain mass which I call "m_3." Notice here also that I am not saying that the mass of electron neutrino is given by the weighted average of m_1, m_2 and m_3 (i.e. $0.68 \times m_1 + 0.3 \times m_2 + 0.02 \times m_3$), nor am I saying that 68% of electron neutrinos have mass m_1, 30% have mass m_2, and 2% have m_3. Remember that I said one electron neutrino, not multiple electron neutrinos, is a mixture of states. Similarly, a muon neutrino and a tau neutrino are mixtures of mass states with "m_1," "m_2," and "m_3" with certain proportions.

Neutrino oscillation occurs when the neutrino of each flavor is not made out of a single, uniquely-defined mass, but made out of a mixture of different states with definite mass. One can show this using quantum mechanics. Given this, it is easy to see why there would be no neutrino oscillation if all three masses of neutrinos were same. In such a hypothetical case we have $m_1 = m_2 = m_3$, and a mixture of 68% of m_1, 30% of m_2 and 2% of m_3 would be the same thing as 100% of m_1 (or equivalently m_2 or m_3). Therefore, in such a case, an electron neutrino would have a definite, uniquely-defined mass. So would a muon neutrino and a tau neutrino; there would be no neutrino oscillation.

Now, it is easy to see why neutrino oscillation implies that neutrinos have mass. If neutrinos don't have mass, it means that the three masses of the neutrinos are all the same (zero), so there would be no neutrino oscillation. As neutrino oscillation is observed, not all the three masses of neutrinos are zero. From experiments and observations we now know at least two of the neutrino masses are not zero.

At the time of writing (i.e. early 21st century) we do not know the masses of the neutrino. (i.e. m_1, m_2 and m_3, mentioned earlier), nor do we have any means to measure them. But, from neutrino oscillation, we know the difference of masses squared. $m_2^2 - m_1^2$ is about 7.6×10^{-5} eV^2, [4] and $|m_2^2 - m_3^2| \approx |m_1^2 - m_3^2|$ is about 2.3×10^{-3} eV^2. We don't yet know whether m_1 and m_2 are bigger or smaller than m_3.

Final remark. I mentioned that most physicists believed that the neutrino was massless because it seemed to travel at the speed of light. In the history of science, we have a similar precedent in which the correct theory was criticized because its effect was too small to be detected. When Copernicus came up with heliocentrism in the 16th century, it was criticized because stellar parallax could not be observed. (The earth rotates around the sun. Therefore, the relative position of stars at night must seem different in different seasons just as the relative position of objects do when you see objects with a left eye or a right eye only. This is stellar parallax.) However, it was only in 19th century that the telescope was developed well enough to observe stellar parallax. By then, heliocentrism was already well established for a couple of centuries.

Summary

- There are three flavors of neutrinos, and each of them is a mixture of three different mass states of neutrinos.
- These three neutrinos change flavor. This phenomenon is called "neutrino oscillation," and would not happen if the three masses were same.
- Not knowing that neutrinos change flavor, scientists used to be baffled by the fact that less amount of electron-neutrinos from the Sun were observed than the standard solar model predicted.
- As neutrino oscillation was observed, it implies that the three masses are different, which in turn implies that at least two of the masses are not zero.

[4] I thought that we didn't know whether m_1 is bigger or smaller than m_2, as neutrino oscillation experiments can only determine the absolute value of the difference of neutrino masses squared. Also, that's what Wikipedia said and what I heard over and over. However, from McDonald's Nobel lecture, I found out that we now know that m_2 is bigger than m_1 from what is called MSW effect.