FEATURE

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Research Area : Experimental Physics

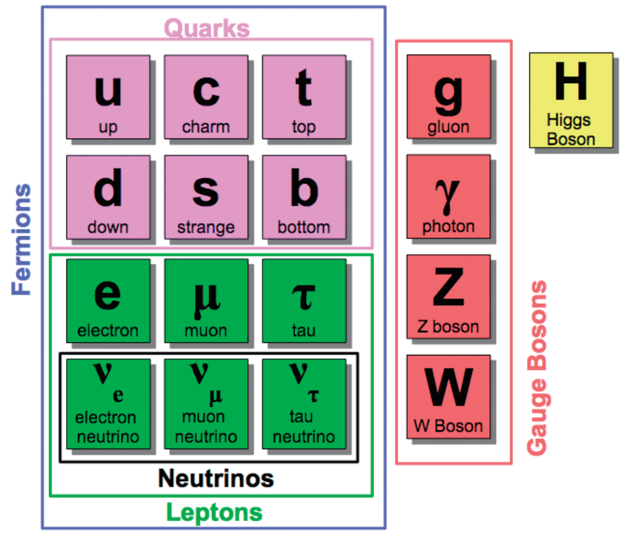
Probing the Fundamental Laws of Nature with Neutrinos

The Standard Model of particle physics describes the fundamental building blocks of matter in the universe and the interactions in which matter participates. Included in the Standard Model are the particles associated with matter itself, the fermions, the particles associated with interactions, the gauge bosons, and the particle responsible for generating the masses, the Higgs boson. The Standard Model also includes anti-particles that have opposite electrical charge and are mirror images of the particles. The ordinary matter we see in the universe is made of the Standard Model particles, but we know that the anti-matter particles exist since they are produced by some physical processes in nature, and they can be produced in laboratories. The Standard Model particles are summarized in Figure 1. The neutrinos are fermions that have a unique position in the Standard Model. Neutrinos are electrically neutral particles that only participate in the weakest type of interactions and have masses much smaller than any of the other fermions. In fact, the neutrino masses are so small that we don't yet know the precise value. However, we can say that the neutrino masses are less than about 1 millionth of the mass of the electron, the next lightest fermion. The mystery of why the neutrino masses are so small compared to the other fermions can only be solved by expanding our understanding of nature beyond the current Standard Model.

How do we know neutrinos have non-zero masses?

If the neutrino masses aren't precisely known, how do we know neutrinos are not massless like the photon? The discovery of neutrino masses is one of the great stories of science in the last half century. It begins in the late 1960s with the famous Homestake experiment led by Nobel Prize winner Raymond Davis. In this experiment, neutrinos produced in the sun, solar neutrinos, were detected in a deep underground mine in South Dakota, USA. The detected rate of neutrinos was significantly less than what was expected, and scientists considered the possibility that our model of the physics inside the sun was wrong. The mystery deepened in the 1980s when detectors such as the Kamiokande-II detector in Japan also detected indications of a deficit of neutrinos produced when cosmic rays interact in the earth's atmosphere, so-called atmospheric neutrinos. These deficits could be explained by the behavior of neutrinos, rather

Figure 1. The particles in the Standard Model of particle physics are shown. The neutrinos are the lightest fermions, and they only interact by the weak force through the Z and W bosons.



than the processes that produced them. There are three types of neutrinos: electron neutrinos, muon neutrinos and tau neutrinos. Electron neutrinos are produced inside the sun, while the atmospheric neutrinos are predominantly muon and electron neutrinos. In the Homestake or Kamiokande-II experiments, only the electron neutrinos or muon and electron neutrinos were detected, respectively. Hence, if an electron neutrino could transform into a muon or tau neutrino, it would be undetectable by the Homestake experiment. By the same reasoning electron and muon neutrinos transforming into a tau neutrinos would not be detected at Kamiokande-II. This phenomenon called neutrino oscillations could explain the deficits, but it requires that the neutrinos have masses.

Why do neutrino oscillations imply massive neutrinos?

Why do neutrino oscillations require that neutrinos have mass? The electron neutrino, muon neutrino and tau neutrino names are derived from how each type of neutrino interacts. The interactions of electron neutrinos are associated with the production of an electron, while muon neutrino interactions produce muons and tau neutrino interactions produce taus. Physicists have named this property of neutrinos their flavor and we say that neutrinos can be described by states of definite flavor. Another property of neutrinos is their mass. The mass determines how a neutrino of a particular energy propagates between two points. In the same way that there are states of definite flavor, there can also be states of definite mass. In the strange world of quantum physics, it is possible that each neutrino state of a definite flavor consists of a combination of different neutrinos states of definite mass. When the neutrino of definite flavor is produced, its components of definite mass can propagate differently because the masses are different. This causes the relative fraction of each mass component to vary as the neutrino propagates. After propagating some distance, the neutrino no longer has its initial flavor, but it becomes a combination of the all three flavors and may interact as a different flavor than the original flavor, as illustrated in Figure 2. This process of neutrino oscillations requires that neutrino masses exist and differ, because the differences in propagation due to the neutrino masses cause the oscillation effect.

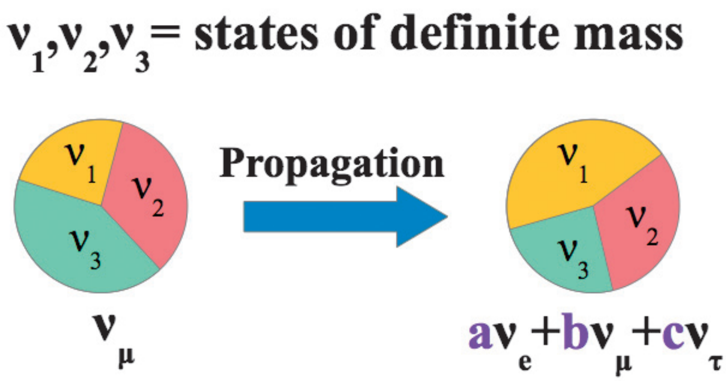


Figure 2. The muon neutrino, ν_μ, of definite flavor is a combination of neutrinos of definite mass, ν_1, ν_2 and ν_3. As it propagates, the relative fraction of the mass states changes and the neutrino becomes a combination of the flavor states. The probability to interact as ν_e, ν_μ or ν_τ depends on the size of a, b and c.

The discovery of neutrino oscillations

The hypothesis of neutrino oscillations was triumphantly confirmed by two experiments in the late 1990s and early 2000s. First, the Super-Kamiokande experiment, a larger version of Kamiokande-II, showed that the deficit in atmospheric neutrinos was a real effect and it depended on the distance the neutrinos traveled to reach the detector in a way that was consistent with neutrino oscillations. Soon after, the SNO experiment measured both the electron neutrino rate and the sum of the electron, muon and tau neutrino rates from the sun. They found that total rate from all flavors is consistent with the prediction from solar models, while confirming the deficit of electron neutrinos. This showed that the electron neutrino deficit was due to electron neutrinos oscillating to muon and tau neutrinos. It was for these discoveries that Takaaki Kajita from Super-Kamiokande and Arthur McDonald from SNO received the 2015 Nobel Prize in physics.

Precision measurements of neutrino oscillations at T2K

Since neutrino oscillations have been established, experimental particle physicists are now engaged in precisely measuring the properties of these oscillations. For precise measurements, we turn to man-made sources of neutrinos. These include neutrinos produced in nuclear reactors and neutrinos made with particle accelerators. The author and colleagues at the Kavli IPMU are collaborators on the T2K experiment, which uses accelerator neutrinos. The accelerator neutrinos are produced by the same process that produces atmospheric neutrinos, but instead of using naturally occurring cosmic rays, we use protons that are accelerated to a large fraction of the speed of light in a particle accelerator. This allows us to produce a high intensity beam of neutrinos where the direction, energy and flavor content of the beam are controlled. T2K stands for Tokai-to-Kamioka, since the neutrinos are produced on the east coast of Japan at the J-PARC accelerator in Tokai-mura and they travel 295 km through the earth to Kamioka, where a very small fraction of them interact in the previously mentioned Super-Kamiokande detector, as illustrated in Figure 3. When a neutrino interacts in Super-Kamiokande, we call this a neutrino event. Since the interaction probability of neutrinos is very low, we only detect

Figure 3. The T2K experiment uses a neutrino beam produced in the J-PARC facility in Tokai-mura on the east coast of Japan. A small fraction of the neutrinos are detected at the Super-Kamiokande detector located 295 km away.

hundreds of neutrino events in Super-Kamiokande, even though more than a billion billion accelerator neutrinos will pass through Super-Kamiokande over the lifetime of the T2K experiment.

The T2K neutrino beam consists of almost 100% muon neutrinos. The main process we are interested in measuring is the oscillation of muon neutrinos to electron neutrinos. At Super-Kamiokande, we can detect the difference between a muon neutrino and an electron neutrino interaction. Recall that electron neutrino interactions produce an electron, while muon neutrino interactions produce a muon. Super-Kamiokande detects the electrons and muons from neutrino interactions through a process called Cherenkov radiation that produces a ring of light on the detector wall. Electrons produce a ring with fuzzy edges, while muons produce sharp ring edges, and this difference can be used to differentiate electrons and muons. Examples of the patterns observed for muons and electrons in Super-Kamiokande are shown in Figure 4.

The muon neutrino to electron neutrino oscillation process is interesting for a couple of reasons. First, its detection marks the first direct evidence of one neutrino flavor oscillating into another specific flavor. Second, this oscillation process can be different for neutrinos and their anti-matter partners, the antineutrinos. The search for matter/anti-matter asymmetries in the laws of nature connects to our understanding of how the universe came into being. If matter and anti-matter followed the same rules, we would expect the universe to be made out of equal parts matter and anti-matter. Since the universe consists of matter, we search for physical processes that can produce an imbalance. The oscillation of neutrinos is one such process where an imbalance can occur.

In June of 2011, after the operation of T2K was temporarily stopped by the Tohoku earthquake, T2K published the first indication of muon neutrino to electron neutrino oscillations. T2K observed 6 events when only 1.5 events were expected from sources other than oscillations. The probability for the 6 events to be explained by the non-oscillation sources was 0.7%. With great effort, the J-PARC accelerator and T2K experiment were able to recover from the Tohoku earthquake after 1 year, and the experiment resumed. In February of 2014, T2K published an update of the search for electron neutrinos. The new result found 28 events when only 4.9 events were expected from non-oscillation sources. With this number of observed events, the probability that they could be explained by non-oscillation sources dropped to much less

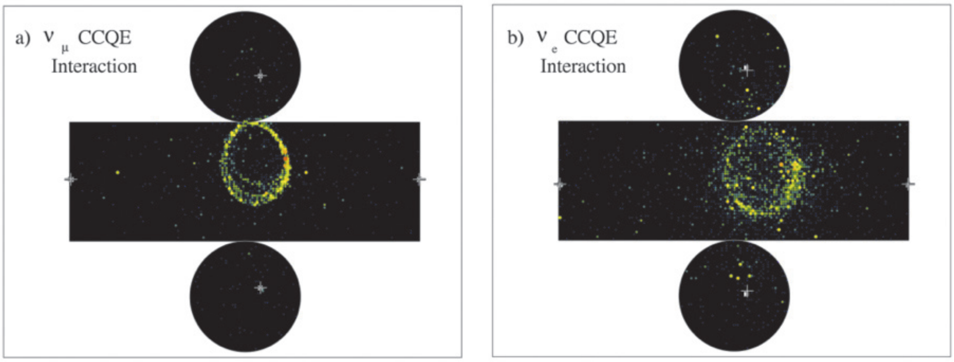


Figure 4. Examples of the simulated pattern observed by Super-Kamiokande when a neutrino interacts to produce a muon (left) and an electron (right). The muons are identified by a ring with sharp edges, while the ring produced by electrons is fuzzy.

than 1 part in a billion, strong enough evidence to claim a discovery of the muon neutrino to electron neutrino oscillation process. The energy distribution of the 28 observed events is shown in Figure 5.

T2K's future and beyond

Now that T2K has discovered the muon neutrino to electron neutrino oscillations, T2K has switched to a beam of muon antineutrinos to search for muon antineutrino to electron antineutrino oscillations. By measuring the rate of this oscillation for both neutrinos and antineutrinos, T2K can search for the previously mentioned matter/antimatter asymmetry. In the summer of 2015, T2K showed its first search for electron antineutrino appearance. 3 events were observed with an expected background of 1.8 events. The amount of data is still too low to claim a discovery of muon antineutrino to electron antineutrino oscillations, but T2K continues to collect more data.

Over the lifetime of the experiment, T2K expects to collect hundreds electron neutrino and antineutrino events. If we are lucky, we may observe the matter/anti-matter asymmetry with 99% confidence. The rate of collecting neutrino and antineutrino interactions is so low because they only interact weakly. To make an exhaustive search for the matter/anti-matter asymmetry and to make precise measurements of its properties, we need thousands of events rather than hundreds. We can increase the rate of events in two ways. First, we can make the neutrino detector more massive. The current Super-Kamiokande detector contains 50,000 tons of water in which the neutrinos can interact. Scientists in Japan (including the Kavli IPMU) and from around the world have proposed a new neutrino detector called Hyper-Kamiokande, which would be constructed near the current Super-Kamiokande detector. Hyper-Kamiokande would contain 1 million tons of water, making it 20 times more massive than Super-Kamiokande. This would increase the rate of neutrino interactions in the detector by a factor of 20. The second way to increase the neutrino interaction rate is by producing a more intense beam of neutrinos. It is expected that the J-PARC neutrino beam intensity can be increased by at least a factor of 3 by the time that Hyper-Kamiokande is built. The combination of the high intensity neutrino beam and ultra-massive detector will make Hyper-Kamiokande the world's most sensitive experiment

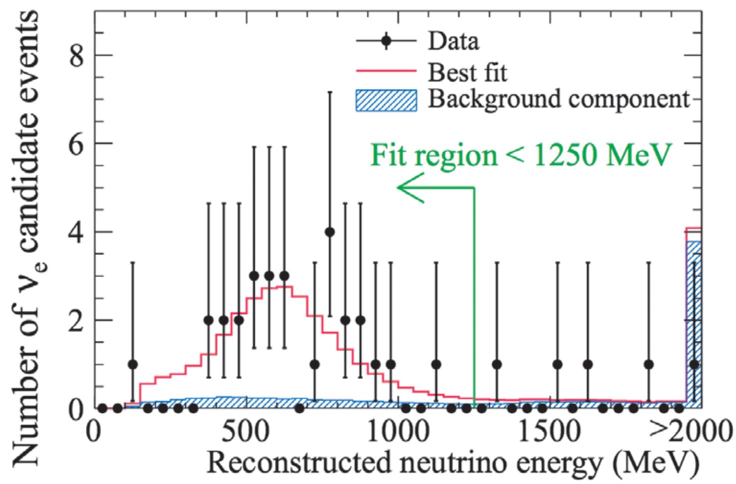


Figure 5. The energy dependence of the observed electron neutrino candidate events by T2K is shown in black. The blue hatched region shows the contribution from non-oscillation sources. The red line shows the contribution from oscillations. The data are consistent with oscillations.

to search for the matter/anti-matter asymmetry in neutrino oscillations.

Summary

Neutrinos play a unique role in the Standard Model of particle physics due to their very small masses, which point to as-yet unexplained physics. In particular, the oscillations of neutrinos provide information about the neutrino masses and may even include a new source of matter/anti-matter asymmetry, which can help explain why the universe consists of matter and not equal parts matter and anti-matter. Scientist at the Kavli IPMU are now involved in the T2K experiment, which uses high intensity of muon neutrino and muon antineutrino beams to search for muon neutrino to electron neutrino oscillations and muon antineutrino to electron antineutrino oscillations. If we are lucky, T2K may discover the first indications of the matter/anti-matter asymmetry in neutrino oscillations with these measurements. Making an exhaustive search for the matter/antimatter asymmetry and precision measurements of the neutrino oscillations will require at least an order of magnitude more neutrino events than T2K will detect. To achieve this additional sensitivity, scientists from around the world have proposed the Hyper-Kamiokande experiment, which consists of neutrino detector 20 times larger than the current Super-Kamiokande detector. If the Hyper-Kamiokande detector is built, we expect that it will continue the tradition of Nobel prize worthy experimental neutrino physics in Japan that has been established with the Kamiokande and Super-Kamiokande experiments.