Research Report

Progress in Neutrino Oscillation

New Results of the T2K Experiment and Status of the Hyper-Kamiokande Project

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1. Introduction

There were two major achievements in the field of neutrino oscillation in the summer of 2017. The T2K experiment released a new result showing that the symmetry between matter and antimatter (CP symmetry) may be violated in neutrino oscillation with a 95% (2σ) confidence level. The Hyper-Kamiokande project, which is the successor to the Super-Kamiokande experiment, was chosen for inclusion in the Ministry of Education, Culture, Sports, Science and Technology (MEXT) Large Project Roadmap. This is a major milestone for the realization of the project. These achievements are reported in this article.

2. New results from the T2K experiment

2.1 Accelerator-based neutrino oscillation experiment and CP-violation

Neutrino oscillation was discovered through the observation of atmospheric neutrinos and solar neutrinos and is a phenomenon in which neutrinos change (oscillate) their types. There are three types of neutrino: electron neutrino, muon neutrino, and tau neutrino. Neutrino oscillation consists of beats of quantum waves. It occurs when each type of neutrino is made of three different waves (wave functions) corresponding to three different masses and those waves interfere. Interestingly, the beats can be different for particle and antiparticle when the three quantum waves interfere and CP symmetry is broken. This kind of CP-symmetry breaking has not yet been observed in neutrino oscillation, and the parameter of the CP-phase, which represents the magnitude of CP-violation, has not yet been measured. To study the CP-violation effect, it is necessary to measure appearance, that is, to which type the neutrino has changed as a result of oscillation. In practice, this is possible only by conducting experiments using an accelerator-produced neutrino beam. The well-controlled neutrino type, energy, and flight length of the beam from accelerators enable the measurement of rare appearance events.

2.2 T2K (Tokai-to-Kamioka) experiment

The T2K experiment observes accelerator-produced neutrinos at a detector 295 km away. Either a muon-neutrino beam or a muon-antineutrino beam is produced with the J-PARC proton accelerator complex at Tokai village in Ibaraki prefecture. The neutrino detector, Super-Kamiokande, is located at Kamioka in Hida city, Gifu prefecture. By comparing the rate of change of muon neutrinos to electron neutrinos and that of muon antineutrinos to electron antineutrinos, the experiment probes CP-violation. If CP-symmetry is violated, these rates are different. The value of CP-phase can also be determined by comparing them with the predictions made by

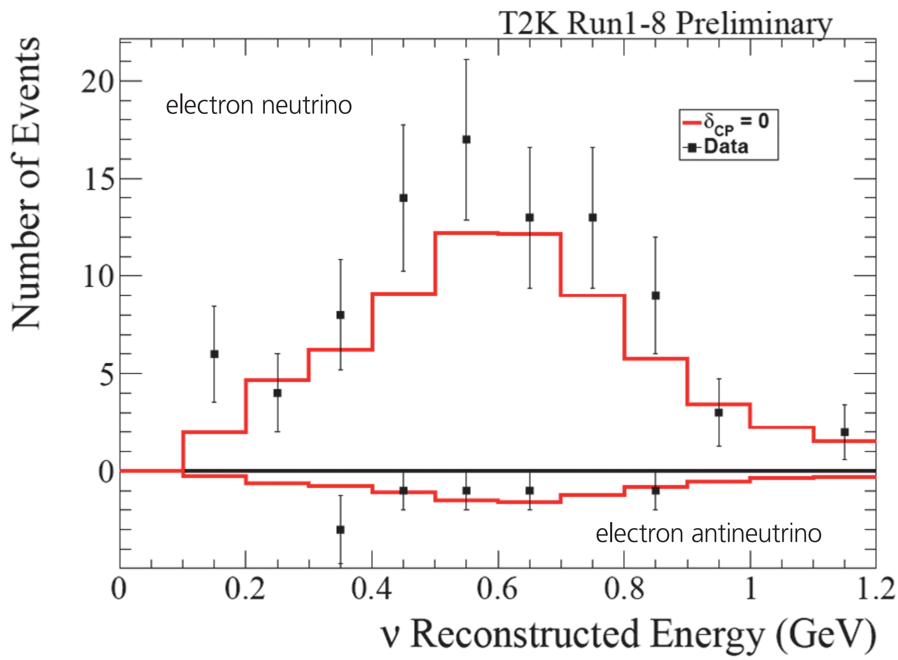

Figure 1: Observed energy spectra for electron neutrino (top) and electron antineutrino (bottom). The red line is the expectation in case CP-phase is equal to zero

assuming CP-phase is 0 (which corresponds to the case in which CP-symmetry is conserved). Since the interaction rate of antineutrinos with matter is about one third of that of neutrinos, observation of oscillation is quicker with the neutrino beam.

T2K started data taking with the neutrino beam in 2010 and observed electron neutrino appearance with a 7σ confidence level in 2013. After that, data taking with antineutrino beams continued until the middle of 2016. The result then showed weak indication of CP-violation. From October 2016 to April 2017, data was accumulated with the neutrino beam. Thanks to the accelerator intensity increase from 250 kW up to 480 kW, the data for the neutrino beam doubled in the past year.

2.3 Hint of CP violation?

T2K also succeeded in improving the method of analysis; electron neutrino events are selected 30% more efficiently compared to the previous analysis, mainly by increasing the volume usable for analysis inside the detector. By applying the new analysis to all the data collected to date, T2K observed 89 electron neutrino events. The expectation when CP symmetry is conserved is 67, so the observation is larger than this prediction. On the other hand, the expected number of electron antineutrinos in the case of CP-conservation is 9 while the observed number is 7, smaller than expected. Figure 1 shows the energy spectra for electron neutrinos and electron antineutrinos. An analysis was performed using this observation, together with the observations of muon neutrinos and antineutrinos in the T2K experiment, and results of the measurements of reactor neutrinos and solar neutrinos to obtain the value of CP-phase. The value which reproduces the observations best was found to be -105 degrees. The statistically allowed region with 95% probability is from -171 degrees to -70 degrees. This means that the CP conserving case is excluded at a 95% (2σ) confidence level. The T2K experiment will further increase the data, aiming to confirm CP-violation at a 3σ confidence level in the case that CP is significantly violated. From this autumn, the experiment will collect data with the antineutrino beam.

3. Status of Hyper-Kamiokande project

The Hyper-Kamiokande project is to build a large water Cherenkov detector of 260,000 tons of water (190,000 tons of fiducial volume) in Kamioka to advance neutrino research and to explore proton decay as evidence for the Grand Unification Theory (GUT) with the world's best sensitivity. The effective volume of Hyper-Kamiokande is roughly 10 times larger than that of Super-Kamiokande. The project was selected in the "Japanese Master Plan of Large Research Projects (Master Plan 2017)" by the Science Council of Japan (SCJ). Recently, it was also chosen for inclusion in the MEXT Large Project Roadmap 2017. This is a major and necessary milestone toward the approval of the project.

3.1 Goals of the Hyper-Kamiokande experiment

This summer, T2K showed a hint of CP violation in neutrinos with 2σ significance. In order to establish CP violation, measurement with more than 5σ significance is expected in the Hyper-Kamiokande experiment. In addition, observation of atmospheric neutrino oscillations inside the Earth could determine the mass ordering of neutrinos. Furthermore, precise measurements of neutrino oscillations in Hyper-Kamiokande will explore the possibility that neutrinos beyond the known three flavors may exist. Observation of solar neutrinos will provide important information of neutrino oscillation inside the sun. If we observe supernova neutrinos from an explosion occurring in our galaxy, we can expect to obtain important information on the explosion mechanism of supernovae. Due to the size of Hyper-Kamiokande, it is possible to search for a burst of supernova neutrinos coming from as far away as the Andromeda galaxy. If we can measure the diffuse flux of neutrinos existing in our universe from past supernova explosions, we can explore the evolutionary history of the universe.

In addition to these neutrino investigations, an important goal of Hyper-Kamiokande is to search for proton decay, which is one of the most fundamental questions in particle physics and predicted by GUT. Although proton decay has not yet been found in Super-Kamiokande, most elementary particle physicists believe in GUT. Hyper-Kamiokande will search for proton decay with a sensitivity more than 10 times better than the current best thanks to the large volume.

With the Hyper-Kamiokande project, we can provide answers to unsolved problems in neutrinos; advance neutrino astronomy; and have a good chance to discover the evidence for GUT, which is a dream of particle physicists. It really is a unique and powerful project.

3.2 Hyper-Kamiokande detector

A sketch of the Hyper-Kamiokande detector is shown in Figure 2. Approximately 40,000 photo-sensors are mounted in a tank that contains 260,000 tons of ultrapure water. The detector can measure Cherenkov light to observe the signals of neutrinos and proton decay. The photosensors have a diameter of 50 cm, and the performance is twice as good as that of Super-Kamiokande for sensitivity to a photon, time response, and energy resolution. The photo-sensors cover 40% of the inner surface to detect faint signals of neutrino interactions and proton decays.

3.3 Status and prospect of the Hyper-Kamiokande project

The Hyper-Kamiokande experiment is regarded as a high-priority project in the communities of Cosmic Ray Research and High Energy Physics in Japan. The experimental collaboration consists of 300 scientists from 15 countries all over the world. The Letter of Intent was published in 2011, and the Design Report in 2015. At present, the University of Tokyo is requesting funding from the government. For funding to be approved, recognition of Hyper-Kamiokande as an important project by MEXT is required. It is good news and a major step forward that Hyper-Kamiokande has been selected for the MEXT Roadmap 2017. If the requested budget is approved in FY 2018, the experiment will start operation in 2026 after 8 years of construction.

4. Summary

Neutrino research is a field in which Japan has led the world. In 2017, an important result on CP violation was announced to the world from the T2K experiment. Recently, the financial situation of Japan for basic science has been facing severe difficulties, but basic science is an investment in the future. Great progress in basic science is desired for the future of Japan. Hyper Kamiokande is a long-term project with 8 years of construction and over 10 years of operation; it is truly an investment in the future. The project will give dreams to young researchers in the near future. In cooperation with the many people involved in the project, we expect that the Hyper-Kamiokande project will be realized, and basic science in Japan will be moving forward even 10 or 20 years from now.

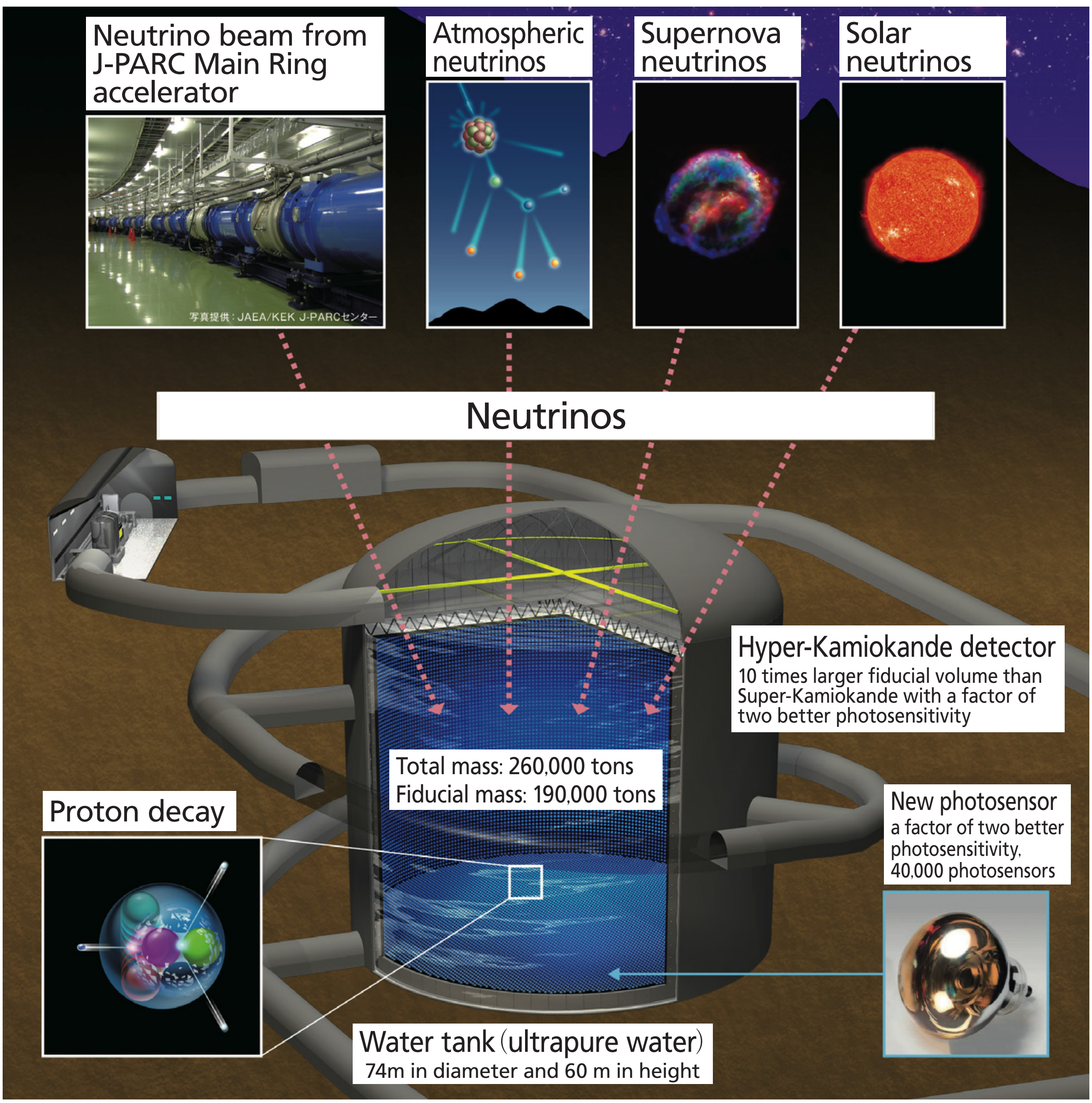

Figure 2: Sketch of the Hyper-Kamiokande detector. The objects of research are also shown.