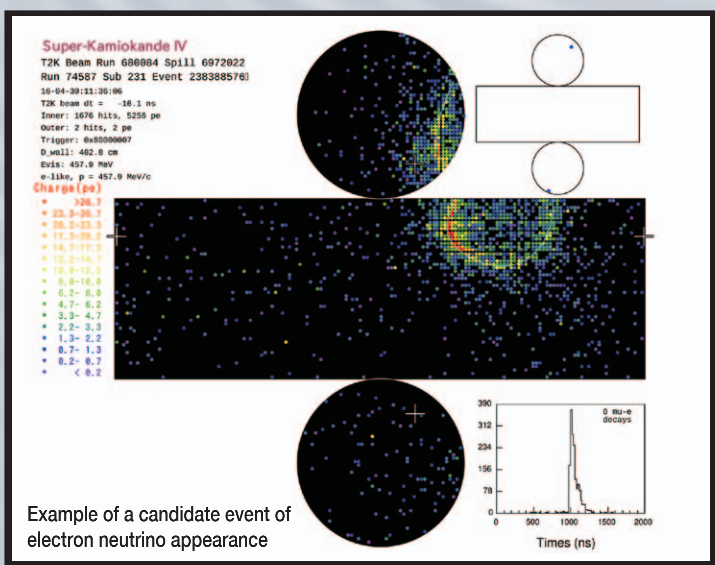
Tokai to Kamioka Long-baseline Neutrino Oscillation Experiment

T2K
Tokai to Kamioka



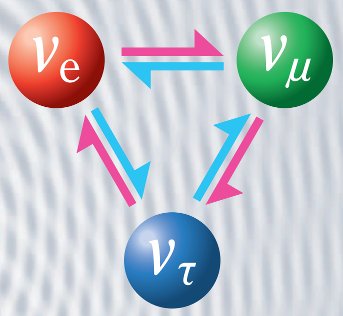
Example of a candidate event of electron neutrino appearance

T2K Collaboration
t2k-experiment.org

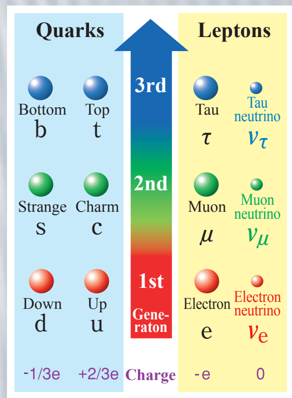
High Energy Accelerator Research Organization
www.kek.jp

March 2019

The T2K Experiment to Probe the Mysteries of the Picture of the Mass and Three Generation Mixing



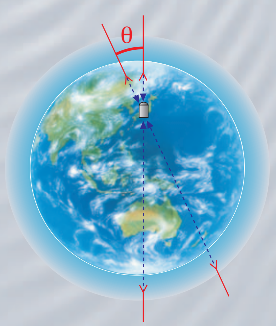
A diagram of neutrino oscillation. T2K aims to establish that neutrino oscillation occurs among the three neutrino generations (three generation mixing).

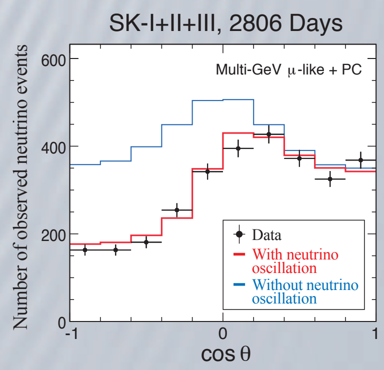


Quarks and Leptons are elementary particles which make up nature. There are three generations of quarks and leptons, respectively.

The History of Neutrino Research

●1930	Prediction of the existence of neutrinos (W. Pauli)
●1956	Discovery of the electron anti-neutrino (F. Reines, C. Cowan)
●1962	Discovery of the muon neutrino (L. Lederman et al.)
●1962	Proposal of the theory of neutrino oscillation (J. Maki, M. Nakagawa, S. Sakata)
●1987	Neutrinos generated by a supernova explosion are observed for the first time (M. Koshiba et al., Kamiokande experiment)
●1991	It is proven that light neutrinos exist in only three generations (LEP experiment)
●1998	Neutrino oscillation is discovered by the observation of atmospheric neutrinos (Y. Totsuka, T. Kajita et al., Super-Kamiokande experiment)
●1999	Successful observation of accelerator-produced neutrinos in K2K, the world's-first accelerator-based long-baseline neutrino oscillation experiment
●2000	Confirmation of the existence of the tau neutrino (K. Niwa et al., DONUT experiment)
●2001	The existence of neutrino oscillation of solar neutrinos is proven (Super-Kamiokande experiment and SNO experiment in Canada)
●2002	The oscillation of electron anti-neutrinos from nuclear reactors is observed (KamLAND experiment)
●2002	M. Koshiba, R. Davis Jr. et al. receive the Nobel Prize in Physics
●2004	Neutrino oscillation is established with an accelerator-produced neutrino beam (K2K experiment)
●2013	"Electron neutrino appearance" is discovered (T2K experiment)
●2015	T. Kajita and A. McDonald receive Nobel Prize in Physics
●2015	K. Nishikawa et al. and the K2K/T2K experiments receive the Breakthrough Prize
●2016	A hint of "CP violation" is seen in neutrinos (T2K experiment)





Distribution of zenith angles for atmospheric neutrinos produced by the reaction between cosmic rays and the atmosphere observed by Super-Kamiokande. The number of muon neutrinos coming from below (through the Earth) was smaller than the number coming from above (from the atmosphere).

The T2K Neutrino Oscillation Experiment

is an experiment to probe the mysteries of neutrinos. A high intensity neutrino beam is produced using a high intensity proton accelerator and the neutrino facility at J-PARC, which was newly constructed at Tokai village, Ibaraki prefecture in 2009. The neutrinos then travel over 295 km to the Super-Kamiokande 50 kton water Cherenkov detector, which is located 1000 m deep within Mt. Ikenoyama at the Kamioka mine in Gifu prefecture.

We aim for:

- ●Discovery of a new oscillation mode, $\nu_\mu \to \nu_e$ oscillation, which is complementary to the $\nu_\mu \to \nu_\tau$ neutrino oscillation mode discovered by the Super-Kamiokande experiment and verified by the K2K experiment
- ●Consequently, clarification of neutrino oscillation and neutrino mixing among three generations
- ●Furthermore, indication of the violation of CP symmetry (the symmetry between a particle and its anti-particle) in the lepton sector

Based on these studies, we are able to probe the following fundamental questions:

- ○What is the full picture of neutrino mass and three generation neutrino mixing?
- ○What is the origin of the matter dominant Universe?

What are neutrinos?

Neutrinos are elementary particles that have no electric charge. The mass of a neutrino is less than one millionth that of an electron.

It is known that there are three types (called "generations" or "flavors") of neutrinos: electron neutrino (ν_e), muon neutrino (ν_μ), and tau neutrino (ν_τ). For each neutrino there is also an associated anti-neutrino, which is the anti-particle of the neutrino.

There are many neutrinos around us. Every second, hundreds of trillions of neutrinos emitted by the Sun pass through our bodies. However, they do not harm us at all.

What is neutrino oscillation?

Neutrino oscillation is a phenomenon where if one type of neutrino is produced, a different type may be observed after the neutrino travels. For example, even if a 100% pure muon neutrino beam is produced by an accelerator, some of the muon neutrinos can be observed as tau or electron neutrinos after they travel over some distance. The probability of observing one neutrino type varies (oscillates) along with the travel distance. This phenomenon is called "neutrino oscillation".

Neutrino oscillation only occurs if neutrinos have a finite mass and if there is mixing of neutrinos among the three generations. Since neutrinos are massless particles in the Standard Model of particle physics, the phenomenon of neutrino oscillation indicates a new physics beyond the Standard Model. At present, neutrino oscillation is the only method to investigate both the extremely tiny mass and the three generation mixing of neutrinos.

Discovery of neutrino oscillation by Super-Kamiokande

In June 1998, the Super-Kamiokande collaboration reported the discovery of neutrino oscillation. They reported a difference in the distribution of zenith angles for atmospheric neutrinos, where the number of muon neutrinos coming from below (through the Earth) was smaller than the number coming from above (from the atmosphere). This was because muon neutrinos change into undetectable tau neutrinos due to neutrino oscillation. Therefore, these distributions provided the experimental proof that neutrinos have a finite mass and neutrino oscillation occurs.

Prof. Takaaki Kajita for the Super-Kamiokande experiment and Prof. Arthur McDonald for the SNO experiment were awarded the 2015 Nobel prize in physics for the experimental discovery of neutrino oscillations.

Matter Dominant Universe and Establish a Full of Neutrinos

Neutrino Beam Production using an Accelerator

When a high energy proton beam strikes a target, many π mesons (or pions) are produced from interactions between the protons and the nuclei in the target. Pions are an unstable particle, and decay into a muon and a muon neutrino after traveling tens of meters. These resulting muon neutrinos are used as a neutrino beam. The beam created by an accelerator in this way is a nearly pure beam of muon neutrinos.

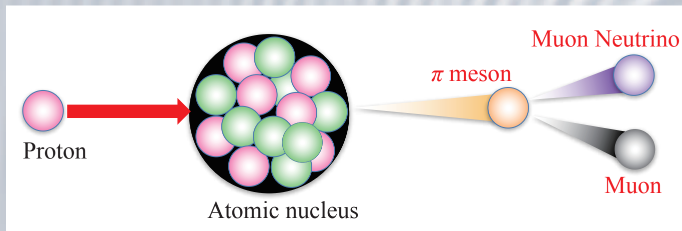


Diagram of the production of a neutrino beam using an accelerator

Study of Neutrino Oscillations using an Accelerator

Although an accelerator-generated neutrino beam consists of almost entirely muon neutrinos, the percentage of muon neutrinos observed decreases after the particles travel over a certain distance due to neutrino oscillation. It is possible to study neutrino oscillations by investigating the decrease in muon neutrinos or by directly detecting the neutrinos that have changed into a different type. When studying neutrino oscillation, is also important to measure the distribution of the observed neutrino energies, since the fraction of neutrinos oscillating to other types depends on the energy of the neutrinos.

In the T2K experiment, a nearly pure muon neutrino beam produced at J-PARC is sent to Super-Kamiokande. The T2K experiment aimed to discover $\nu_\mu \to \nu_e$ oscillation by observing electron neutrino events at the Super-Kamiokande detector.

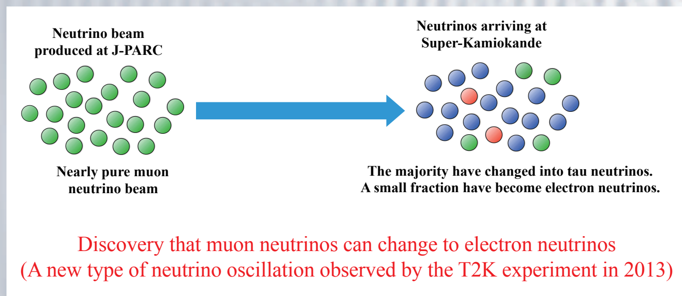
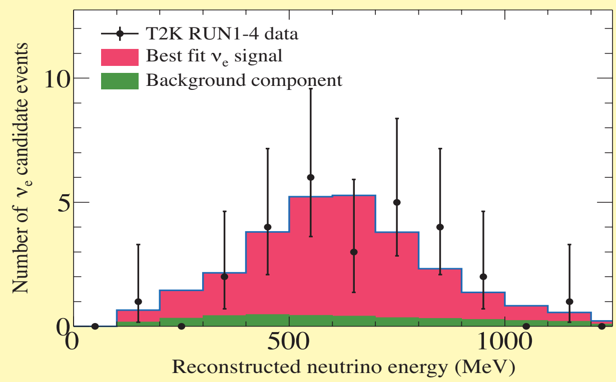


Diagram of "electron neutrino appearance", oscillation from muon neutrinos to electron neutrinos, directly observed by the T2K experiment

Discovery of $\nu_\mu \to \nu_e$ Oscillation by the T2K Experiment

The probability that a muon neutrino will change into an electron neutrino is small in comparison to the probability that it will change into a tau neutrino, and therefore $\nu_\mu \to \nu_e$ oscillation had not been experimentally observed prior to the T2K experiment. The J-PARC neutrino beamline was newly constructed to produce a high-intensity neutrino beam and the T2K experiment started taking data in 2010.

In July 2013, the T2K collaboration announced the discovery of $\nu_\mu \to \nu_e$ oscillation after observing electron neutrino appearance at the far detector, Super-Kamiokande. This is decisive evidence that a muon neutrino can change into an electron neutrino in-flight. This discovery indicates that neutrino oscillation occurs among all three neutrino generations. As a result of the T2K measurement, neutrino oscillation research has entered a new phase.



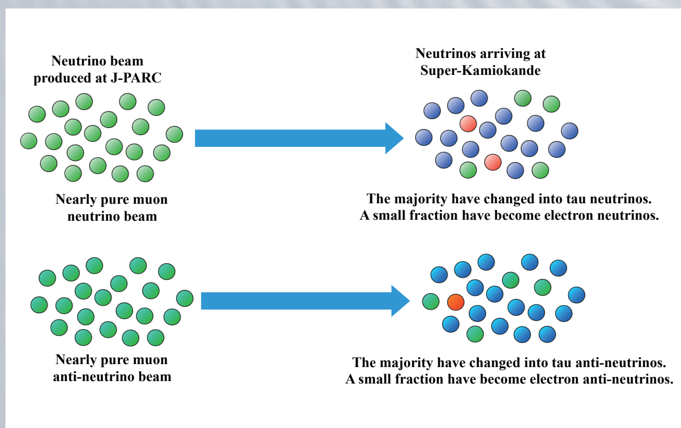
The neutrino energy distribution for the 28 observed electron neutrino events. It is clear that the data (black dots) closely match the sum of the number of expected background events (green) and the number of expected electron neutrino appearance events (red).

The probability to reproduce the observed number of events by a statistical fluctuation of the background is less than 1 in a trillion.

Violation of CP Symmetry in the Neutrino Sector

If CP symmetry is violated in neutrinos, its effects will appear as a difference between the probability of muon neutrino to electron neutrino oscillation compared to the probability of muon anti-neutrino to electron anti-neutrino oscillation. As a consequence, the discovery of $\nu_\mu \to \nu_e$ oscillation opens the door to search for a "violation of CP symmetry" in the neutrino sector. T2K is aiming to discover CP violation in neutrinos.

The T2K experimental group consists of an international collaboration of around 500 researchers from inside and outside of Japan working together at J-PARC and Super-Kamiokande.



The search for "CP symmetry violation" using electron neutrino appearance events. By comparing $\nu_\mu \to \nu_e$ oscillation of neutrinos and anti-neutrinos, "CP symmetry violation" will be explored.

The Experimental Facilities Distributed Across Oscillation Experiment

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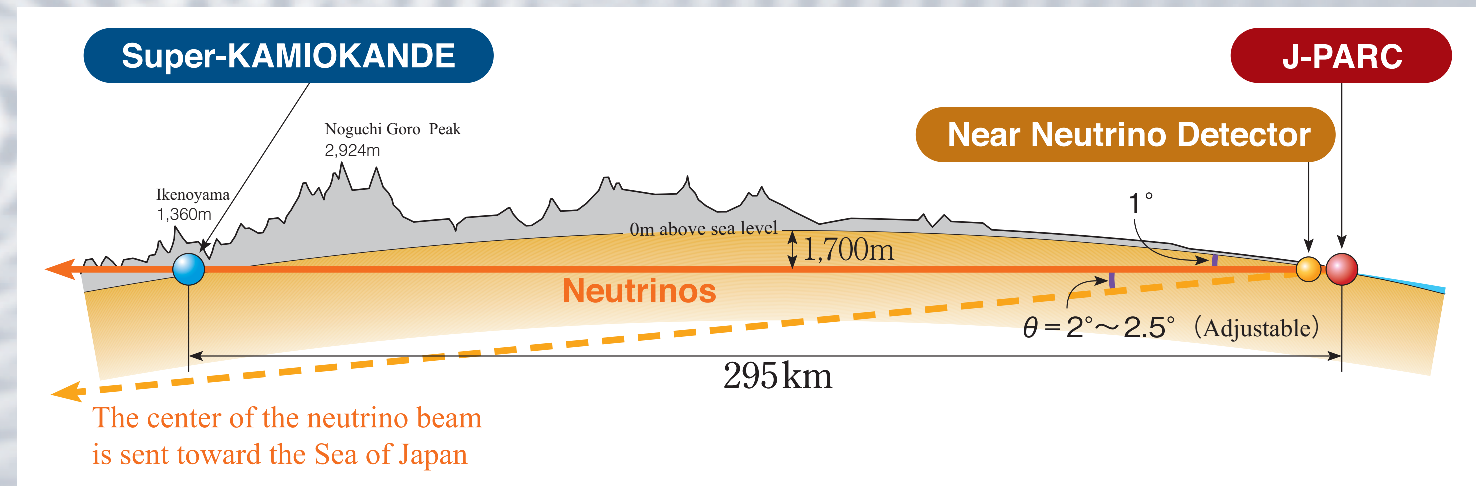
In the T2K experiment, the world's highest intensity neutrino beam is generated at the J-PARC Neutrino Experimental Facility and shot towards the Super-Kamiokande detector. The neutrinos can propagate through the earth as if there were no iron, concrete, or bedrock, and arrive at Kamioka, 295 km away from J-PARC, in approximately 1 millisecond. A small portion are then observed by the Super-Kamiokande detector.

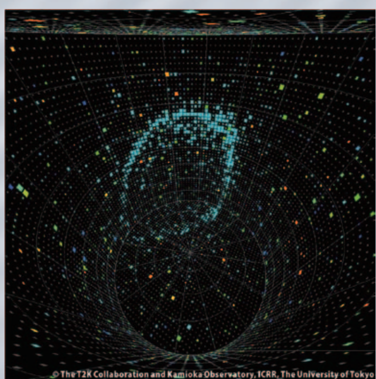
The neutrino beam is also monitored using a near detector at J-PARC. It is possible to study "neutrino oscillation", in which neutrinos change their type in flight, by comparing the observation at the near detector to the one at Super-Kamiokande.



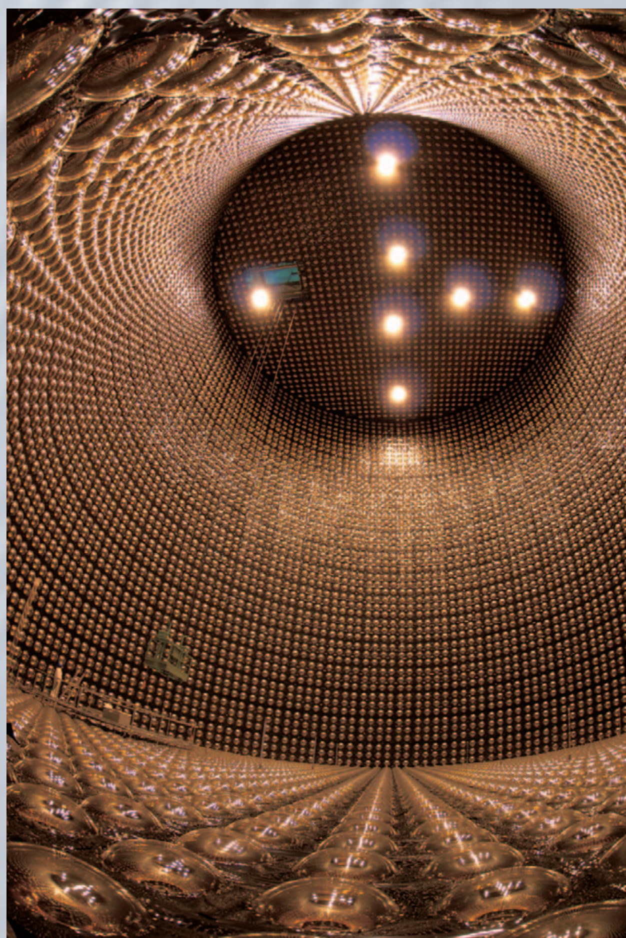
Super-KAMIOKANDE

Super-Kamiokande is a massive neutrino detection device operated by the University of Tokyo, Institute for Cosmic Ray Research. The detector is located 1,000m deep underground in the Kamioka mine in the city of Hida in Gifu prefecture. Super-Kamiokande operation began in April 1996, and even now the detector continues to observe neutrinos that come from outer space. The tank has a diameter of 39.3 meters, a height of 41.4 meters, and contains 50,000 tons of pure water. It is equipped with 11,129 highly-sensitive photodetectors (photomultiplier tubes), which detect the Cherenkov radiation light which is generated when the neutrinos interact with the water (a very rare process). This photodetector information can be used to determine the type, direction of arrival, and energy of the interacting neutrinos.

A photomultiplier tube used in Super-Kamiokande. The diameter is 50 cm — the world's largest.



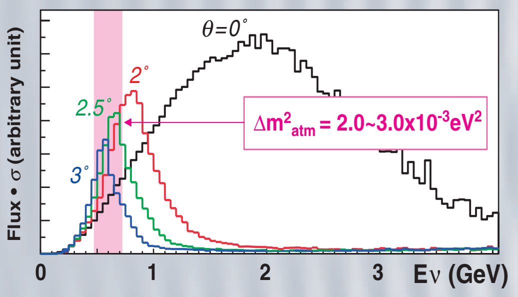
A candidate event for the world pioneering observation of electron neutrino appearance by the T2K experiment (May 2010)



Provided by: University of Tokyo, Institute for Cosmic Ray Research, Kamioka Observatory

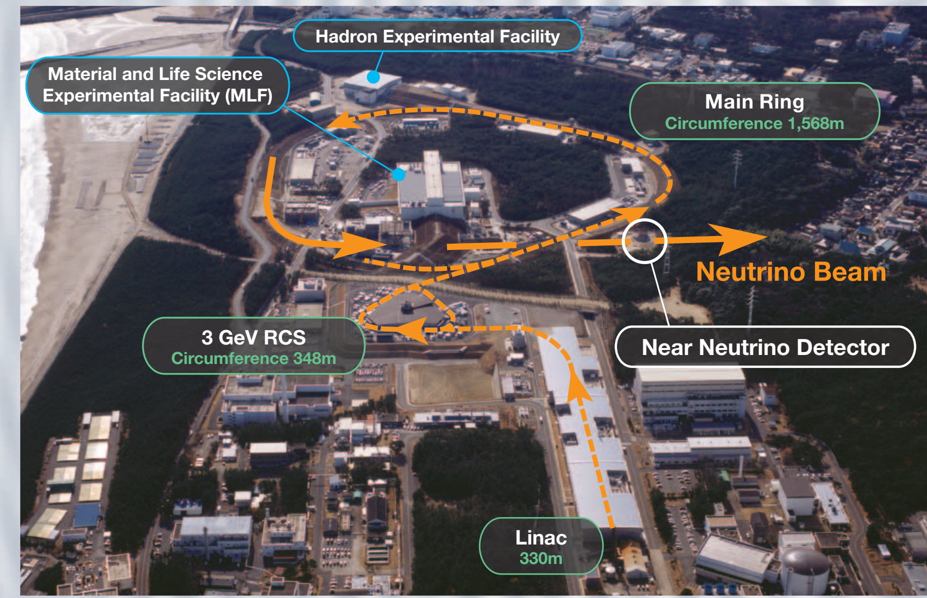
Japan for the T2K Long-Baseline Neutrino

Japan Proton Accelerator Research Complex J-PARC



Neutrino energy distributions for an on-axis beam (θ=0°) and off-axis beam (θ=2°~3°)

The neutrino beam produced at J-PARC is very broad. By pointing the central axis of the beam slightly lower than the Super-Kamiokande direction, the energy of the neutrinos arriving in Kamioka is reduced and the width of the energy distribution becomes narrower. The J-PARC Neutrino Experimental Facility was the first facility in the world to adopt this off-axis beam configuration.



J-PARC (Japan Proton Accelerator Research Complex) is a general term for the proton accelerator and surrounding facilities constructed in Tokai village, Ibaraki prefecture during 2001~2009 through the cooperation of the High Energy Accelerator Research Organization (KEK) and the Japan Atomic Energy Agency (JAEA).

At J-PARC, protons are accelerated in a linear accelerator, they are then accelerated to 3 GeV using a synchrotron (RCS), and are finally sent into the Main Ring (MR), where they are accelerated to 30 GeV. Protons are then extracted from the MR to the neutrino primary beamline, using electromagnets called “kickers”. In the primary beamline, the protons are bent towards the Kamioka direction. The protons then strike a target, which produces a neutrino beam headed towards Super-Kamiokande.

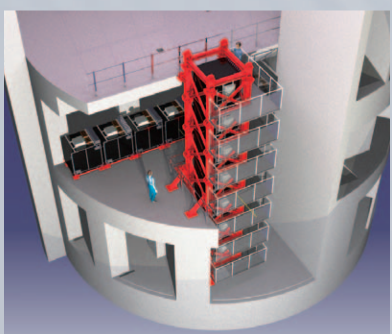
Near Neutrino Detector

A near neutrino detector is installed in a pit (at the neutrino monitoring building) located 280 meters downstream from the target. The pit is 33.5 meters deep and 17.5 meters in diameter.

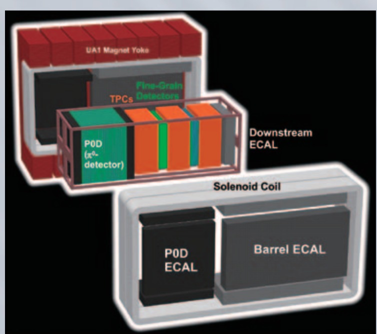
The near detector is composed of two independent detectors, the “on-axis INGRID detector”, sitting in the center of the beam, and the “ND280 off-axis detector”, sitting in the direction of Kamioka.

The INGRID detector monitors the stability of the neutrino beam direction and intensity, while the ND280 detector measures the energy distribution of the neutrino beam and the composition of muon and electron neutrinos in the beam.

The electromagnets surrounding the off-axis detector were manufactured in 1979 for the UA1 experiment at the CERN Proton-Antiproton Collider and contributed to the discovery of the W and Z bosons in 1983.



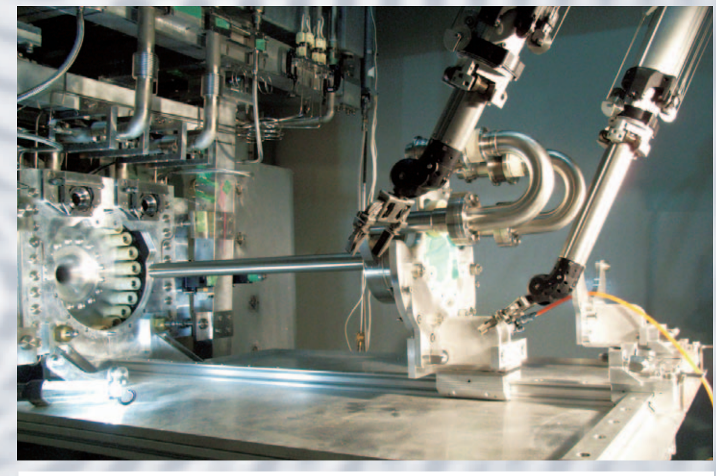
On-axis detector



Off-axis detector

The J-PARC Neutrino Experimental Facility Intensity Neutrino Beam in the World

30 GeV protons are extracted from the MR to the neutrino primary beamline using electromagnets called “kickers”. The protons pass through the primary beamline, which consists of a series of normal-conducting and super-conducting magnets, and has various beam monitors. The protons are bent to the west and strike a graphite target located in the target station. Many pions are produced when the protons interact with the target. These pions are focused in the forward direction by a special device called a magnetic horn, and fly into a 100-meter-long tunnel called the “decay volume”. They decay in flight into pairs of muon neutrinos and muons. All of the particles aside from the neutrinos and a fraction of the muons are then absorbed by the beam dump and do not leave the experimental facility.

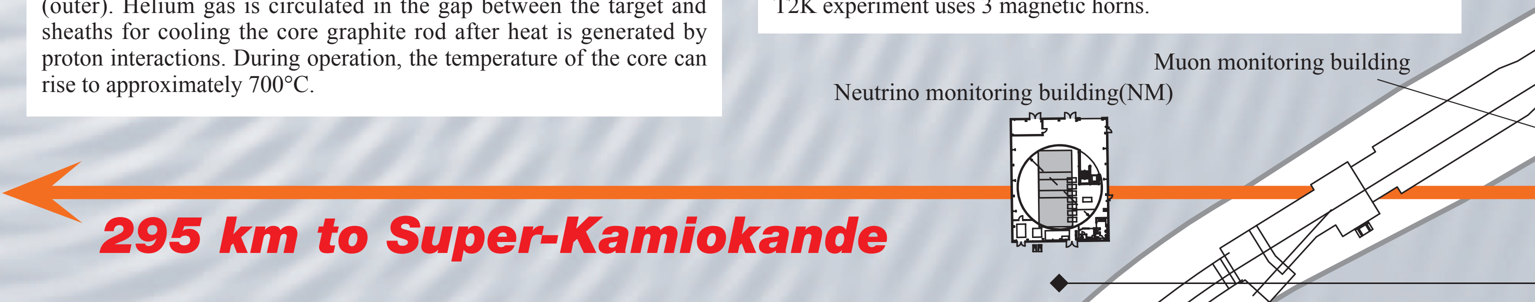


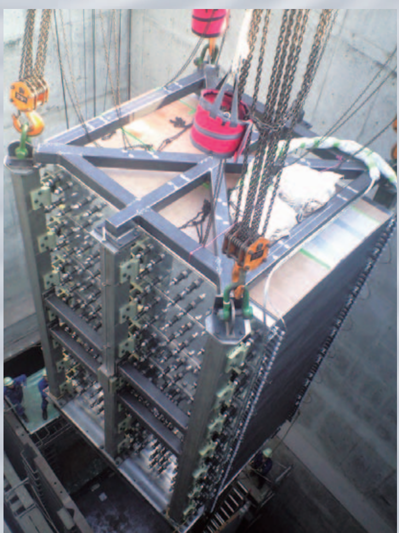
Target

The target is inserted into the center of the inner conductor of the first magnetic horn by a manipulator. Many pions are produced when protons interact with the target. The target is made of graphite and is covered with two sheaths made of graphite (inner) and titanium alloy (outer). Helium gas is circulated in the gap between the target and sheaths for cooling the core graphite rod after heat is generated by proton interactions. During operation, the temperature of the core can rise to approximately 700°C.

Magnetic horn

The magnetic horn is a device consisting of two layers of cylindrical aluminum conductors. A 2-tesla magnetic field between the inner and the outer conductors is generated using a pulsed current of up to 320,000 amperes, which focuses pions in the forward direction. The T2K experiment uses 3 magnetic horns.





⑥ Beam Dump installation

A stack of graphite blocks used as a beam dump is installed at the most downstream end of the beamline. It absorbs protons that did not interact in the target, as well as other outgoing particles. It also intercepts the heat and radiation generated by the beam.

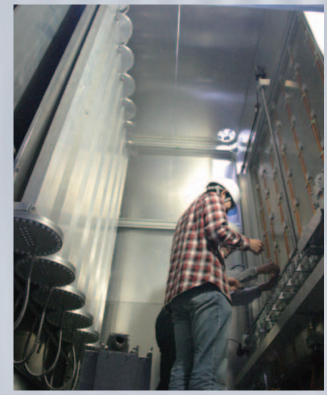
⑤ Decay Volume

The decay volume is a tunnel surrounded by approximately 6-meter-thick concrete. In order to cool the heat generated by secondary particles, water pipes are installed all over the interior of this tunnel.

② Super-conducting Combined Function Magnet (SCFM)

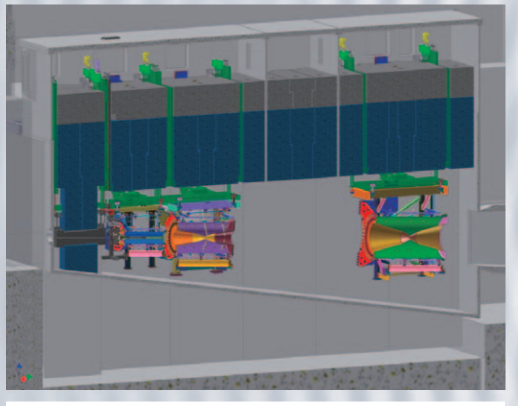
A superconducting magnet system is used in the arc section, where the proton beam extracted from the Main Ring is sharply bent towards the Kamioka direction. There are 28 combined function (dipole and quadrupole) magnets called “SCFMs”. Each SCFM is 3.3 meters long with a maximum dipole field of 2.5 tesla and a maximum quadrupole field gradient of 18.6 tesla per meter. In order

Produces the Highest



⑦ Muon Monitor

The muon monitor is a measurement device for indirectly observing the direction and stability of the neutrino beam. It functions by measuring the muons that are produced together with the neutrinos.

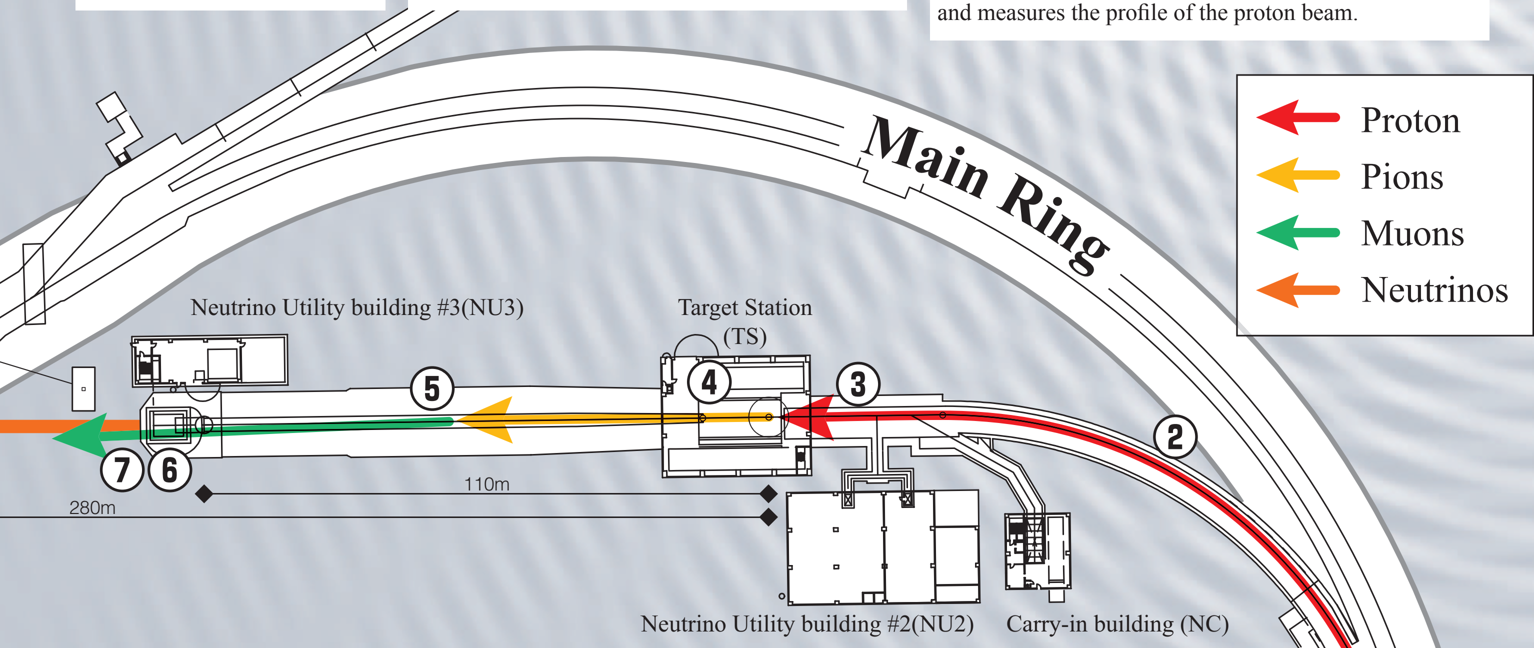


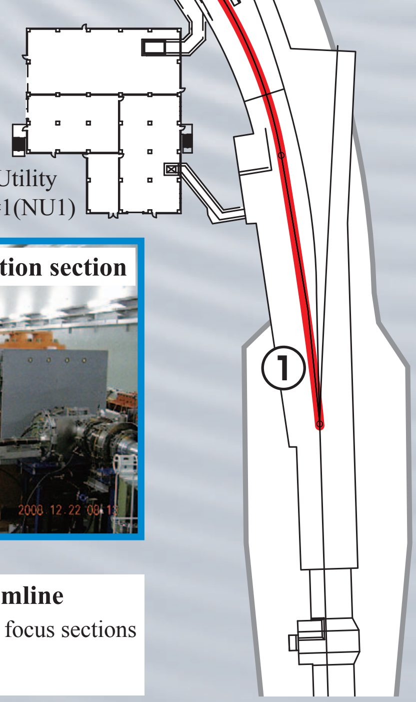
④ Target Station (TS)

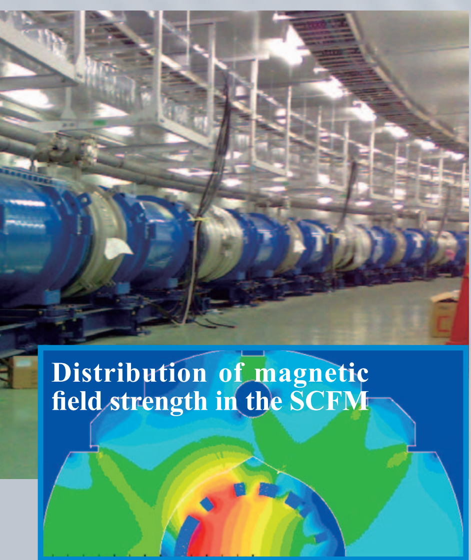
A massive helium container, which is integrated with the decay volume and has a volume of 1,500 m^3, sits in the basement of the target station. The three magnetic horns, the baffle protecting these horns, and other pieces of equipment sit in this helium container and are securely covered by steel and concrete, which provide shielding from radiation.

Beam Monitors

Various beam monitoring devices (CT, ESM, SSEM, BLM) monitor the intensity, position, profile and loss of the proton beam, and are installed in the primary beamline. These monitors ensure that the proton beam extracted from the Main Ring is safely sent to the target. An OTR monitor is also installed in front of the target and measures the profile of the proton beam.







③ Final focus section

① Preparation section

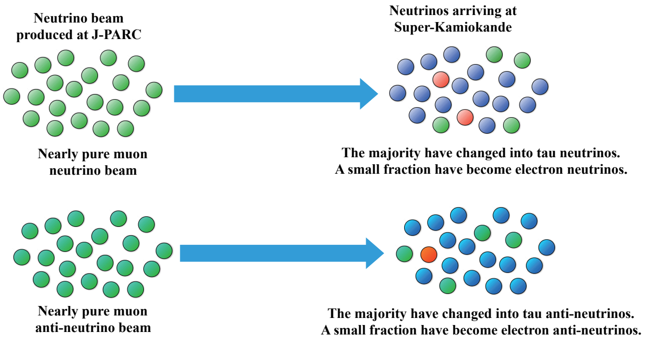
to keep the magnets in a superconducting state, the system is equipped with a helium freezer that has an absolute temperature of 4.5 degrees and a cooling capacity of 2 kilowatts.

Normal-conducting magnets in the primary beamline

Normal-conducting magnets are used at the preparation and final focus sections of the beamline.

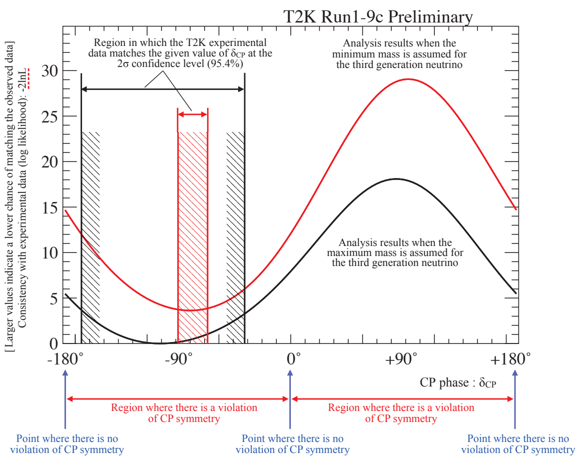
Challenges to discover "Violation of CP Symmetry" in the Neutrino Sector

In order to study the difference between neutrinos and anti-neutrinos, the T2K collaboration began measurements using an anti-neutrino beam in 2014. Data collected until 2016 indicates that there is a difference between neutrinos and anti-neutrinos with a 90% confidence level. This is the world's first indication that "CP symmetry violation" occurs in neutrinos. Since 2016, T2K has improved its measurement significance and has observed a difference in the probability of neutrino and anti-neutrino oscillations at the 2σ confidence level (95.4%) after increasing the amount of available data by using a higher intensity beam and new analysis methods.



Experimental data	Expected number (Assuming no CP symmetry violation)	Observed number
Neutrino	68	90
Anti-neutrino	13	9

(Note) The reason why the expected number of events differs between neutrinos and anti-neutrinos even with no "CP symmetry violation", is that the probability of interacting with water is different for neutrinos and anti-neutrinos, even if the same number of neutrinos and anti-neutrinos pass through the Super-Kamiokande detector.

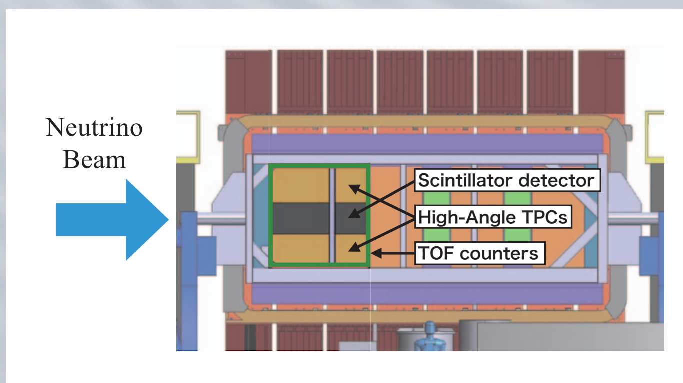


The figure on the left shows log likelihood values as a function of the CP phase (angle) δ_{CP}, which indicate the size of any observed "CP symmetry violation". Higher log likelihood values indicate that the experimental data have poorer agreement with the expectation at that value of δ_{CP}. The black and red curves show the log likelihood values for the two different neutrino mass scenarios. The black and red hatched regions show the allowed 2σ (95.4%) confidence level intervals.

The results of the T2K experiment show that the δ_{CP} values corresponding to no "violation of CP symmetry" (δ_{CP}=0°, ±180°) are outside of the 2σ confidence interval. This means that the T2K data exclude the conservation of CP symmetry in neutrinos at the 2σ (95.4%) level.

T2K Upgrade Plan Aimed at Discovering a "Violation of CP Symmetry"

The current results of the T2K experiment are interim results based on approximately 34% of the initially approved amount of data, but indicate a 2σ (95.4%) confidence level measurement of "CP symmetry violation in neutrinos". J-PARC and the T2K collaboration plan to increase the intensity of the proton beam to three times its current level and to accumulate 2.5 times more data than initially approved (approximately 8 times more data than has currently been collected). With these improvements, T2K aims to verify its measurement of "CP symmetry violation" in the neutrino sector at the 3σ confidence level (99.7%). As part of this plan, along with upgrading the neutrino beamline through improvements to the target, magnetic horns and other equipment, the performance of the near neutrino detector will also be improved by replacing a portion of the existing detectors with newly developed detectors.



Improvement plan for the near neutrino detector (off-axis detector). The upstream part of the detector will be replaced with newly developed detectors to allow for more precise measurements of neutrinos.