
The T2K Long-Baseline Neutrino Experiment

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1 Introduction – The Current Situation in Neutrino Oscillation Physics

The neutrino oscillation phenomenon and the existence of the finite neutrino mass had been discovered through the observation of the neutrinos from the Sun and atmosphere. Initial indication came from the observation of the deficit of the solar neutrino flux by the pioneering experiments of Ray Davis and his collaborators [1] and by the Kamiokande experiment [2, 3].

The neutrino oscillation phenomenon occurs when neutrino being observed is a superposition of more than two different mass eigenstates and when the mass difference is so small that the waves interfere. Usually neutrino is produced as a flavor eigenstate. After traveling long distance, that flavor changes as a consequence of the interference. In a simple case of two types of neutrino, flavor eigenstates, $|\nu_\alpha\rangle$ and $|\nu_\beta\rangle$, can be written as follows:

$$|\nu_\alpha\rangle = e^{-i(E_1 t - p_1 L)} \cos \theta + e^{-i(E_2 t - p_2 L)} \sin \theta, \quad (1)$$

$$|\nu_\beta\rangle = e^{-i(E_1 t - p_1 L)} \sin \theta - e^{-i(E_2 t - p_2 L)} \cos \theta, \quad (2)$$

where t and L are time and position, respectively, at observation; E_i and p_i are the energy and momentum of mass eigenstates with mass m_i , respectively; and θ is the mixing angle. Since the neutrino mass is so small t can be approximated as L and $E_i \approx p + m_i^2/2E$ with the average energy E . Then, the phase factor is approximated to $e^{-i(m_i^2/2E)L}$.

With this approximation and with the initial condition that a neutrino is produced as an eigenstate $|\nu_\alpha\rangle$ with energy E (GeV), the probability that it has another flavor β after traveling distance L (km) can be calculated as follows:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E), \quad (3)$$

where $\Delta m^2 = m_1^2 - m_2^2$ in eV^2 . In the actual observation, flavor of neutrino is identified by the charged current interaction. The charged current interaction

is not allowed when the energy of the neutrino is lower than the threshold energy to produce the corresponding charged lepton. Therefore, if the energy of the oscillating neutrino is lower than the threshold for the appearing flavor, then the neutrino oscillation is observed as “disappearance.”

In reality, it has been confirmed that, at least, three flavors exist in neutrino, that is, ν_e, ν_μ , and ν_τ . Then the mixing among them with mass eigenstates can be naturally extended by a unitary 3×3 matrix (Maki–Nakagawa–Sakata [4] (MNS) matrix) defined by a product of three rotation matrices with three angles (θ_{12} , θ_{23} , and θ_{13}) and a complex phase (δ) as in the Cabibbo–Kobayashi–Maskawa matrix [5]:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{\alpha i} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}, \quad (4)$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad (5)$$

where $\alpha = e, \mu, \tau$ are the flavor indices, $i = 1, 2, 3$ are the indices of the mass eigenstates, and S_{ij} (C_{ij}) represents $\sin \theta_{ij}$ ($\cos \theta_{ij}$). Neutrinos are produced as a flavor eigenstate and each component of mass eigenstate gets a different phase after traveling a certain distance. The detection of neutrinos by the charged current interactions projects these new states back onto flavor eigenstates. When only two of the mass states dominate the oscillations, the oscillation probability is same as Eq. (3). Note that these oscillations depend only on $|\Delta m^2|$, that is, they do not depend on either the absolute mass scale or ordering of the mass states. While this formula is valid in vacuum, interactions with electrons in matter can modify the oscillations [6, 7]. It is called the matter effect which depends on the sign of Δm^2 and provides a way to determine the ordering of the mass states. In other words, the vacuum oscillation cannot distinguish a mixing angle θ and $(\pi/2 - \theta)$ (see Eq. (3)). However, with significant matter effect, this degeneracy can be resolved.

After the experiments of Davis et al. and Kamiokande, their results were supported by measurements of the low-energy solar neutrino fluxes by the SAGE [8, 9] and GALLEX [10–12] experiments. While the solar neutrino anomaly was under investigation, the Super-Kamiokande (SK) experiment showed a zenith-angle-dependent suppression of the ν_μ flux (atmospheric neutrino flux, arising from cosmic ray interactions with the atmosphere), which indicated that neutrinos have mass [13, 14]. Recently the SNO [15–17] experiment has demonstrated that the solar neutrino anomaly is caused by neutrinos changing flavor, which was shown to be consistent with neutrino oscillations by the recent results from the KamLAND experiment [18, 19]. The K2K long-baseline experiment [20] has observed the disappearance of ν_μ with a controlled neutrino beam produced with an accelerator. The observed disappearance feature is very consistent with the atmospheric neutrino anomaly

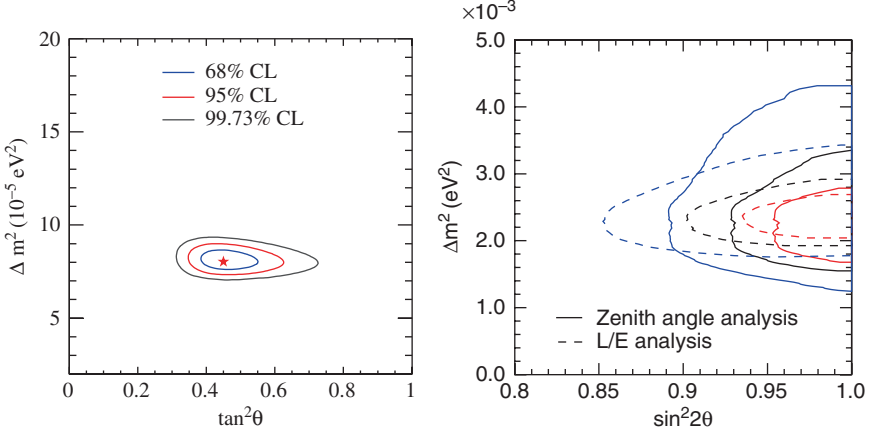


Fig. 1. Allowed regions for 2-neutrino mixing parameters for solar+KamLAND (*left figure*) and from the latest Super-Kamiokande analysis (*right figure*). Thanks to the matter effect, the degeneracy on a mixing angle θ and $\pi/2 - \theta$ is resolved and the plot on the $\tan^2 \theta$ has been obtained in the case of the *left figure*.

observed by Super-Kamiokande. It has been established that the neutrino does oscillate and two Δm^2 s exist.

The current results for oscillations from solar neutrino plus KamLAND data can be fit using two-neutrino oscillations with the matter effect, and the resulting parameters are shown in the left part of Fig. 1. Similarly, for the atmospheric oscillations the current best-fit parameters from Super-Kamiokande are shown in the right part of Fig. 1. These results constrain θ_{12} , θ_{23} , Δm_{21}^2 , and $|\Delta m_{23}^2|$.

Two accelerator-based experiments are now running. The MINOS experiment is using the NuMI neutrino beam from Fermilab. Its far detector locates in the Soudan mine, 735 km away from Fermilab. It is making a sensitive measurement of the muon neutrino disappearance [21] and thereby is making a measurement of Δm_{23}^2 accurate to about 10%. The CNGS neutrino beam from CERN is aimed at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy, where the OPERA [22] experiment starts data-taking and the ICARUS [23] experiment is under construction. The baseline length is 730 km. These two experiments are aimed at making a conclusive demonstration of the mechanism for the atmospheric neutrino disappearance by actually observing the appearance of ν_τ from the $\nu_\mu \rightarrow \nu_\tau$ oscillation.

There are still three undetermined parameters in the MNS matrix – the angle θ_{13} , the sign of Δm_{23}^2 , and the value of the CP-violating phase δ . These are fundamental parameters which should be predicted by a deeper theory of the particle physics, and hence intrinsically interesting in themselves.

Our current knowledge of θ_{13} comes from three sources. Atmospheric and solar neutrino oscillation results give some information, but the most useful

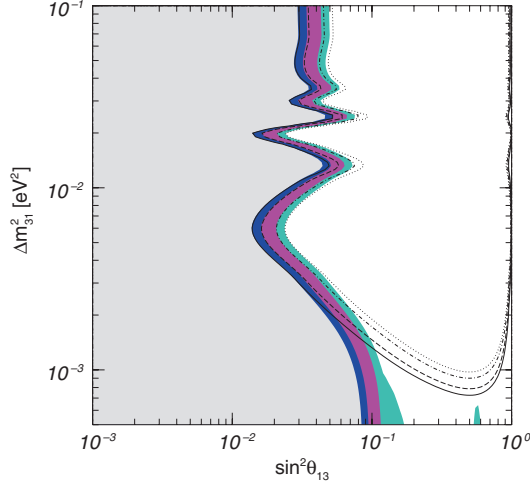


Fig. 2. Allowed region for θ_{13} from CHOOZ alone (*lines*) and also including data from solar neutrino experiments and KamLAND (*colored regions*) at 90, 95, 99%, and 3σ . From Maltoni et al. hep-ph/0309130.

data for constraining the value of θ_{13} comes from the CHOOZ reactor $\bar{\nu}_e$ oscillation experiment [24, 25]. This experiment measured the flux of $\bar{\nu}_e$ at a distance of 1 km from the CHOOZ reactor in France. The constraint from these measurements is summarized in Fig. 2.

The next goal would then be to improve our sensitivity to θ_{13} in the hope of a positive observation. Our current knowledge of neutrino oscillations tells us that Δm_{13}^2 is approximately equal to Δm_{23}^2 because $\Delta m_{12}^2 \ll |\Delta m_{23}^2|$ and that oscillation originated by θ_{13} may be observable as the appearance of ν_e from ν_μ beam at the same distance and energy as the experiment optimized to observe the ν_μ disappearance by θ_{23} . In the three-generation frame, the oscillation probability for $\nu_\mu \rightarrow \nu_e$ can be written as [26]

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) = & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \Phi_{31} \times \left(1 + \frac{2a}{\Delta m_{31}^2} (1 - 2S_{13}^2) \right) \\
 & + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos \delta - S_{12} S_{13} S_{23}) \cos \Phi_{32} \cdot \sin \Phi_{31} \cdot \sin \Phi_{21} \\
 & - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin \delta \cdot \sin \Phi_{32} \cdot \sin \Phi_{31} \cdot \sin \Phi_{21} \\
 & + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos \delta) \sin^2 \Phi_{21} \\
 & - 8C_{13}^2 S_{13}^2 S_{23}^2 (1 - 2S_{13}^2) \frac{aL}{4E_\nu} \cos \Phi_{32} \cdot \sin \Phi_{31}, \tag{6}
 \end{aligned}$$

where $\Phi_{ij} \equiv \Delta m_{ij}^2 L / 4E$. The terms multiplied by the parameter a represent “matter effect.” When neutrinos pass through inside the Earth, the Sun, or any dense object, they feel the potential by the weak interaction with matter.

Since the matter is made of quarks and electron, not of muon nor tau, the potential is different for ν_e and ν_μ/ν_τ . That potential difference causes another shift of the phase of propagation. In the above equation, the matter effect is simplified by approximating that the matter density ρ is constant across the path of the neutrino. Then,

$$a = 2\sqrt{2}G_F n_e E = 7.6 \times 10^{-5} \rho(g/cm^3) E(GeV) [(eV)^2]. \quad (7)$$

Given the already known limits on the parameters and under the condition that the matter effect is quite small, Eq. (6) can be approximated as

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) \approx & \sin^2 2\theta_{13} \sin^2 \Phi_{31} \\ & + 1.9 S_{13} \cos \delta \cos \Phi_{32} \cdot \sin \Phi_{31} \cdot \sin \Phi_{21} \\ & - 1.9 S_{13} \sin \delta \sin \Phi_{32} \cdot \sin \Phi_{31} \cdot \sin \Phi_{21} \\ & + 0.44 \sin^2 \Phi_{21}, \end{aligned} \quad (8)$$

where the values of $\theta_{12} = 33.9^\circ$, $\theta_{23} = 45^\circ$ are used.

If the value of $\sin^2 2\theta_{13}$ is within an order of magnitude lower than its current upper limit, the first term dominates and Eq. (8) becomes a relatively simple formula for the oscillatory appearance of ν_e in ν_μ beam.

The goal of the first phase of the T2K experiment, which is the main topic of this literature, is to discover finite θ_{13} with at least an order of magnitude better sensitivity than the current upper limit by searching for the ν_e appearance signal from the ν_μ beam. At the same time measuring θ_{23} and $|\Delta m_{23}^2|$ with greater precision by observing the disappearance of ν_μ is interesting in its own right. In particular, deviation of θ_{23} from $\pi/4$ is a matter of great interest.

Once the appearance of ν_e is observed, the goal of the experiment would be expanded dramatically. The new developments in the solar and reactor neutrino experiments confirmed that ν_μ oscillates to ν_e with a rather large mixing angle and Δm_{21}^2 among the regions allowed before these measurements. Then it makes non-negligible contribution to Eq. (8) as the fourth term. This oscillation can compete with the first term of Eq. (8). The former oscillation is suppressed by a small Δm_{21}^2 compared to $|\Delta m_{23}^2|$ and the latter is suppressed by a small mixing angle θ_{13} . Hence, the two processes can compete. This is one of the necessary conditions for a CP violation effect to be observable. The second and third terms of Eq. (8) are generated by the interference between these two oscillations. These features are illustrated in Fig. 3. Indeed, the third term has $\sin \delta$ and changes its sign depending on whether the observing neutrino is neutrino or anti-neutrino. Therefore, the CP violation phase δ may be observable through the comparison of the appearance signal from ν_μ beam and $\bar{\nu}_\mu$ beam. One possible source of the matter-antimatter asymmetry of the present-day universe is the CP violation in the neutrino sector via the mechanism known as leptogenesis [27]. Measuring the CP-violating phase δ in the MNS matrix should give valuable insights into the CP properties of

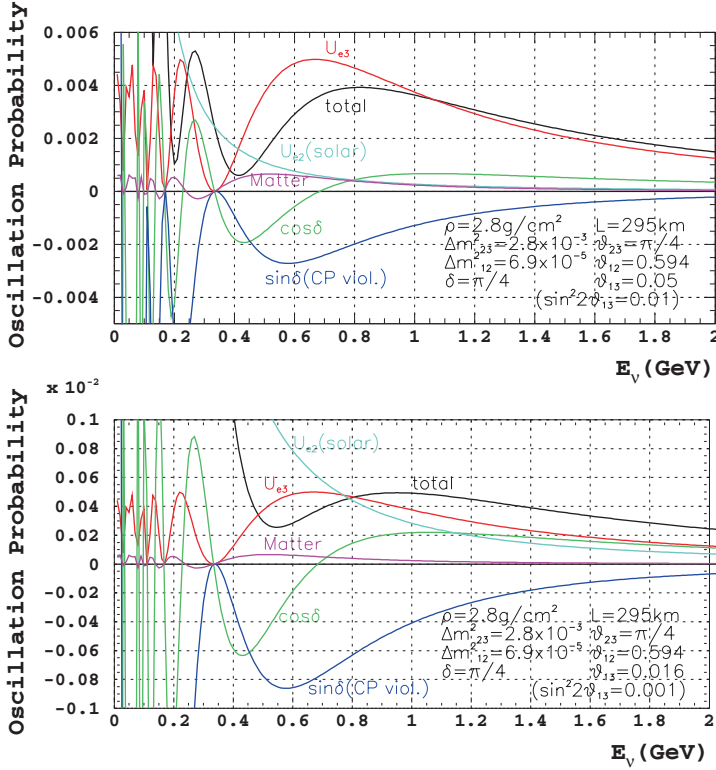


Fig. 3. Contribution of different components to $\nu_\mu \rightarrow \nu_e$ appearance at $\sin^2 2\theta_{13} = 0.01$ and 0.001 .

neutrinos. Measurement of δ is only possible if θ_{13} is sufficiently large, and hence a measurement of θ_{13} is a critical step for future neutrino physics.

2 The T2K Long-Baseline Experiment

The T2K experiment is a long-baseline neutrino oscillation experiment. An almost pure muon neutrino beam is produced using a high-intensity proton accelerator complex, J-PARC at Tokai village, Japan. Then, after traveling 295 km, it is measured at a gigantic water Cerenkov detector, Super-Kamiokande, at Kamioka, Japan. Figure 4 shows the baseline of the experiment.

The main physics motivation of the T2K experiment comprises three goals.

1. Discovery of $\nu_\mu \rightarrow \nu_e$. More than an order of magnitude improvement in sensitivity over the present upper limit is possible in 5 years running with full operation of the J-PARC accelerator. The goal is to extend the search down to $\sin^2 2\theta_{13} \simeq 2 \sin^2 2\theta_{\mu e} > 0.008$.

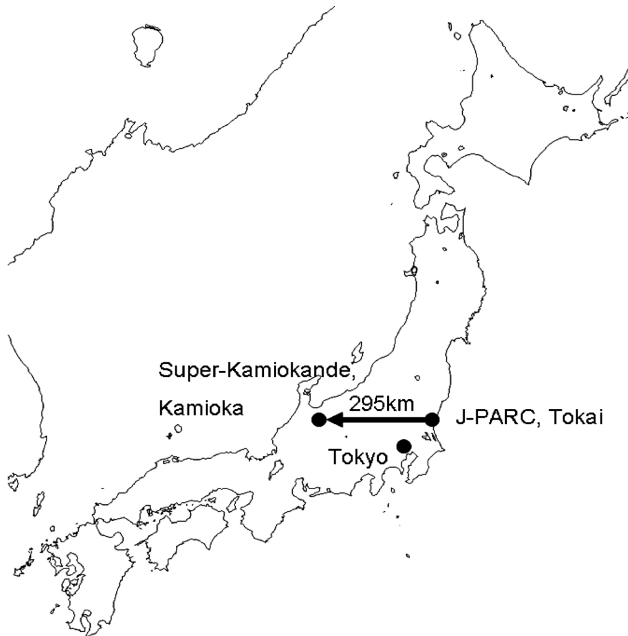


Fig. 4. Baseline of the T2K experiment.

2. Precision measurements of oscillation parameters in ν_μ disappearance. The goal is an observation of the oscillation minimum, a 1% measurement (about the same precision as Cabibbo angle in the quark sector) of the mixing angle and a 10% measurement of $|\Delta m^2|$ ($\delta(\Delta m_{23}^2) = 10^{-4} \text{ eV}^2$ and $\delta(\sin^2 2\theta_{23}) = 0.01$). Deviation from or consistency with the maximal mixing at 1% accuracy may impose a constraint on the quark-lepton unification in future.
3. Search for sterile components in ν_μ disappearance by detecting the neutral-current events. If a non-zero sterile component is found, the physics of fermions will need modification to accommodate extra member(s) of leptons.

The J-PARC accelerator complex and neutrino facility is currently being constructed and the first beam is expected in April 2009.

With the successful achievement of these measurements, the construction of 1 Mt Hyper-Kamiokande detector at Kamioka, and a possible upgrade of the accelerator from 0.75 MW to a few MW in beam power, further experiments can be envisaged. These include another order of magnitude improvement in the $\nu_\mu \rightarrow \nu_e$ oscillation sensitivity, a sensitive search for the CP violation in the lepton sector (CP phase δ down to $10\text{--}20^\circ$), and an order of magnitude improvement in the proton decay sensitivity.

2.1 Neutrino Beam at J-PARC

A layout of the J-PARC facility is shown in Fig. 5.

A neutrino beam at J-PARC is produced with the “conventional method” where pions produced by hitting protons on a target decay into ν_μ and muons. The pions are focused by toroidal magnets called the electromagnetic horns and injected into a volume where they decay in flight (decay volume). The beam is almost pure ν_μ . ν_μ or $\bar{\nu}_\mu$ can be selected by flipping the polarity of the horns.

A key element of the design of the T2K facility is that the neutrino beam is directed so that the beam axis actually misses Super-Kamiokande as shown in Fig. 7. This method is called off-axis neutrino beam [28]. This, rather surprisingly, actually results in a considerable improvement in the quality of the beam for the ν_e appearance experiment. This arises from the kinematics of the π decay. As shown in Fig. 6, the neutrino energy is proportional to the energy of the parent π meson when the off-axis (OA) angle is 0 (general wide-band beam), while it is almost independent of the π meson energy with non-zero OA angle. Since pions in a wide momentum range contribute to narrow energy range of neutrino, a narrow intense neutrino beam is obtained.

The peak neutrino energy can be adjusted by choosing the off-axis angle. Recent results from the SK [13, 14], K2K [20], and MINOS [29] experiments point at $\Delta m_{23}^2 = 2 \sim 3 \times 10^{-3} \text{ eV}^2$. With this parameter, the oscillation maximum is at around the neutrino energy of 500–700 MeV at the SK, i.e., 295 km away from the source. The off-axis beam has three major advantages

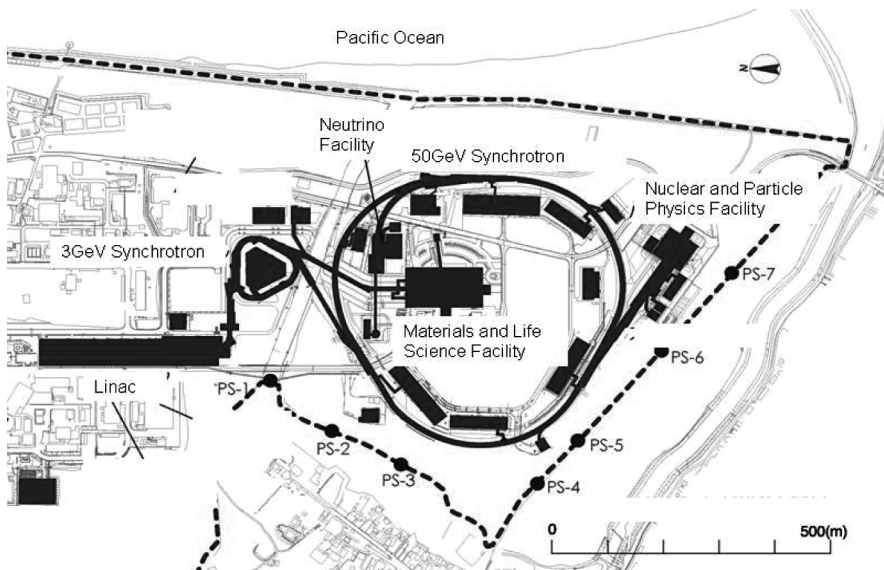


Fig. 5. Layout of the J-PARC facility.

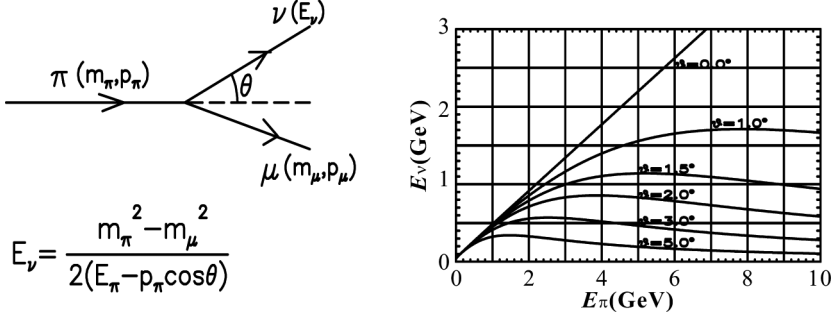


Fig. 6. Kinematics of the off-axis beam.

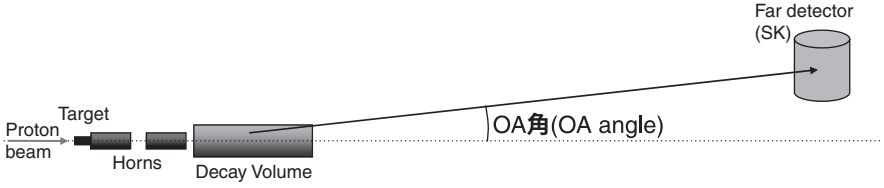


Fig. 7. Schematic of the off-axis beam.

over the conventional on-axis beam. First, the off-axis neutrino flux at the desired energy (near the oscillation maximum) is actually higher than that with on-axis. Second, there are fewer high-energy neutrinos, which do not contribute to the appearance signal but do contribute to its backgrounds in particular through the neutral current production of π^0 s. The daughter γ s from the π^0 decay are sometimes misidentified for the single electron signal. Third, the background due to the intrinsic contamination of the beam ν_e is actually less at the off-axis position due to the different kinematics of the decays that lead to ν_e .

The very kinematics that gives a useful selection in energy, however, means that the characteristics of the beam changes rapidly with the off-axis angle. Detailed measurement of the beam properties are therefore required to minimize the systematic uncertainties in any neutrino oscillation measurements. These detailed measurements will be made with a set of near detectors at 280m downstream of the target.

Monte Carlo (MC) simulations using GEANT3 [30] have been used to optimize the beamline and to estimate the expected neutrino spectra and the number of events. Figure 8 shows the expected neutrino flux spectra. The J-PARC neutrino facility is capable to produce a beam whose off-axis angle is from 2.0–2.5°. The on-axis beam spectrum is shown as a reference in Fig. 8(a). The energy spectra of the contaminated ν_e s are plotted in Fig. 8(b). The ν_e contamination in the beam is expected to be 1% at the off-axis angle of 2° (OA2°). The sources of ν_e are $\pi \rightarrow \mu \rightarrow e$ decay chain and K decay (K_{e3}). Their fractions are 37% for the μ decay and 63% for the K decay at OA2°.

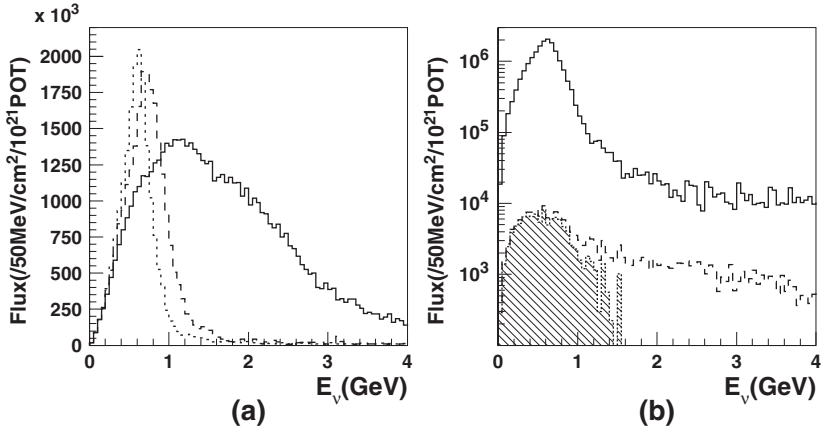


Fig. 8. (a) Energy spectra of the on-axis and off-axis ν_μ beams: *solid line* (on-axis), *dashed line* (2.0°), and *dotted line* (2.5°). As the off-axis angle increases, the energy peak narrows and moves lower in energy. (b) Energy spectra of the off-axis 2.5° beams: *solid line* (ν_μ) and *dashed line* (ν_e). The *hatched area* shows contribution to ν_e from the muon decay. Another main contributor is the K decay. Both histograms are normalized to 10^{21} 30-GeV protons on target, which roughly corresponds to 0.6-year operation at the designed intensity.

At the peak energy of the ν_μ spectrum, the ν_e/ν_μ ratio is as small as 0.2%. This indicates that the beam ν_e background is greatly suppressed (factor ~ 4) by applying an energy cut on the reconstructed neutrino energy.

Figure 9 shows the expected energy spectra for ν_μ s interacted in the Super-Kamiokande fiducial volume. The expected number of the total and CC interactions in 22.5 kton fiducial volume of SK is 2,300 events/yr and 1,700 events/yr, respectively, at 2.5° off-axis in the case of no oscillation with the 30-GeV, 0.75-MW, 3000-h/yr operation.

Neutrino Facility in J-PARC

A layout of the neutrino facility in J-PARC is illustrated in Fig. 10.

The neutrino facility consists of the following:

- primary proton beamline,
- target station,
- decay volume,
- beam dump,
- muon monitor,
- near neutrino detector,

and several utility buildings.

Special features of the T2K beamline are (1) the first use of superconducting combined function magnets [31] in the primary proton beamline, (2) the first application of the off-axis (OA) beam [28], and (3) capability for

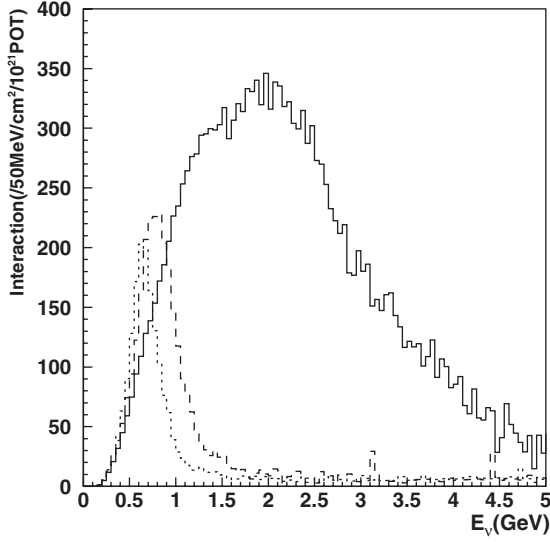


Fig. 9. Energy spectra for ν_μ s interacted in the Super-Kamiokande fiducial volume: *solid* (on-axis), *dash* (2.0°), and *dot* (2.5°). The histogram is normalized to 10^{21} 30-GeV protons on target, which roughly corresponds to 0.6-year operation at the designed intensity.

radiation heating and shielding. In order to have tunability of the neutrino energy spectrum, the neutrino beamline is designed to cover OA angle from 2° to 2.5° .

Proton beam is extracted from the 50-GeV PS in a single turn (fast extraction). The design intensity of the beam is 3.3×10^{14} protons/pulse and repetition period is 3.5 s, resulting in the beam power of 0.75 MW at 50-GeV operation. The “50-GeV” PS will be operated at 30 or 40 GeV in early stages. One pulse (spill) consists of eight bunches each with 58-ns full width and separated by 598 ns, and the total spill width is $\sim 4.2 \mu\text{s}$.

The primary proton beamline transfers the proton beam from the 50-GeV PS to the neutrino production target. It consists of the preparation, arc, and final focusing sections.

Target station (TS) accommodates a production target and electromagnetic horns. The target is a graphite rod of 26 mm diameter and 90 cm length. About 85% of the incoming protons interact with the target material. When pulsed beam hits the target, big heat is generated in a very short period. This causes dynamical shock to the material. Hence graphite, which is rather light and strong against the heat shock, is adopted. Heat load from the beam is about 60 kJ/spill (~ 20 kW). This heat is removed by forced-flow Helium gas. The target is followed by three electromagnetic horns which focus generated pions in the forward direction. They are driven by pulsed current of 320 kA

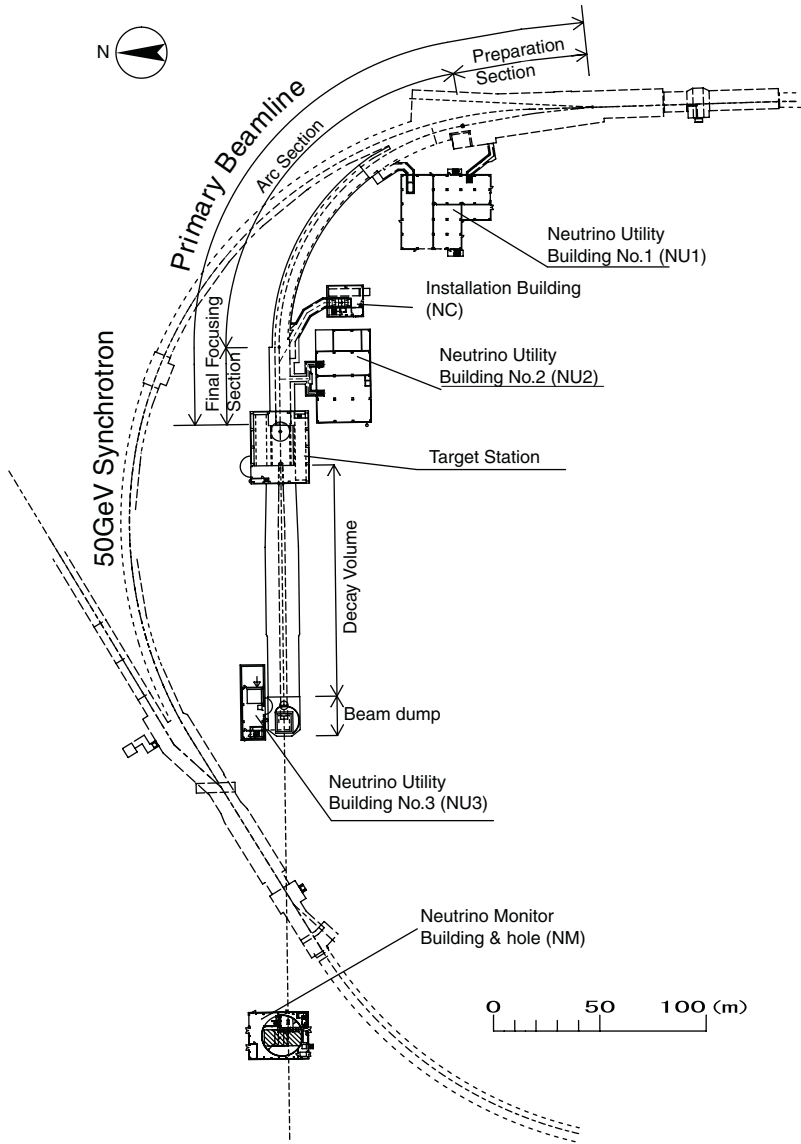


Fig. 10. Layout of the neutrino facility complex.

at peak synchronized with the proton beam timing. Strong force is applied on the horns by both the heat load and the Lorenz force, which is produced by the interaction of electrical current and magnetic field. The target station is filled with the helium gas in order to reduce tritium and NO_x production. The separation of the target station helium gas and the primary beamline

vacuum is done by a beam window at the upstream entrance of the target station. It is made of Ti alloy and is cooled by helium gas. Everything inside the target station will be highly radio-activated and will never be accessible by hands once beam operation starts. All the beamline components in TS will be maintained remotely.

The decay volume (DV) is a free space downstream of the horn where pions decay in flight into ν_μ s and muons. The length between the target and the end of the decay volume is about 110 m. DV is filled with helium gas to reduce pion absorption and is surrounded by concrete shields of about 6 m thick. The wall of helium vessel is water cooled to remove the heat load by the beam.

The beam dump is placed at the end of DV and stops hadrons such as remaining protons and secondary mesons. The dump consists of graphite blocks of 3.2 m thickness, 2.5 m thick iron, and 1 m thick concrete. The graphite blocks are cooled by aluminum blocks in which cooling water pipes are embedded.

The muon monitor is placed just behind the beam dump to measure the muon flux. While almost all hadrons are absorbed by the beam dump, muons of energy > 5 GeV can penetrate the beam dump. Expected muon flux is $\sim 10^8/\text{cm}^2/\text{spill}$. The muon monitor is designed to provide pulse-by-pulse information on the intensity and profile (direction) of the beam. By monitoring the muon flux, the proton beam direction can be monitored with an accuracy of better than 1 mrad for each spill by segmented ionization chambers and/or semi-conductor detectors. The muon monitor also tracks the stability of the neutrino yield.

2.2 Near Detectors

The neutrino beam properties just after its production and interaction cross section will be measured precisely at the near detector experimental hall at 280 m from the target point. The location of the ND280 hall is shown as NM in Fig. 10.

The ND280 hall has a pit with a diameter of 17.5 m and a depth of 37 m, which incorporates both the on-axis and off-axis detectors. The B1 floor, which is about 24 m deep, is for the off-axis detector. The off-axis detector is nearly located on the line between the target point and the SK position. The B2 floor, which is about 33 m deep, is for the horizontal part of the on-axis detector. The B3 floor, which is 37 m deep, is for the deepest part of the vertical on-axis detector.

The On-Axis Neutrino Monitor (INGRID)

The muon monitor observes only the small fraction of muons because it observes muons whose energy is greater than 5 GeV. Therefore, it is also

important to directly measure the direction of the neutrino beam. The on-axis neutrino monitor (INGRID) will be installed in the near detector hall to measure the neutrino beam direction and profile using neutrinos directly. It is required to measure the neutrino beam direction with precision much better than 1 mrad as the muon monitor.

The neutrino event rate around the beam center is estimated to be ~ 0.3 events/ton/spill. In order to monitor the stability of the neutrino event rate (direction) at the 1% (1 mrad) precision within a single day ($\simeq 2.5 \times 10^4$ spills), $\mathcal{O}(1)$ ton fiducial mass is necessary for the detector. The variation of the efficiency of the detector across the beam profile should be calibrated at a precision of 1% during the experiment.

The INGRID detector is designed to consist of $7 + 7 + 2$ identical units, arranged to form a grid which samples the beam on $8 \times 8 \text{ m}^2$ ($\pm 4 \text{ m} \times \pm 4 \text{ m}$) area, as shown in Fig. 11. The design of one unit is shown in Fig. 12. The target of neutrino interaction is iron. Scintillators are used to detect a muon from the interaction.

Off-Axis Detector, ND280

Measurements of the flux of ν_μ/ν_e and their spectra are important for oscillation analysis. In addition, cross sections, which are quite unknown for neutrinos, need to be measured both for the reconstruction of spectra and background estimation at the far detector.

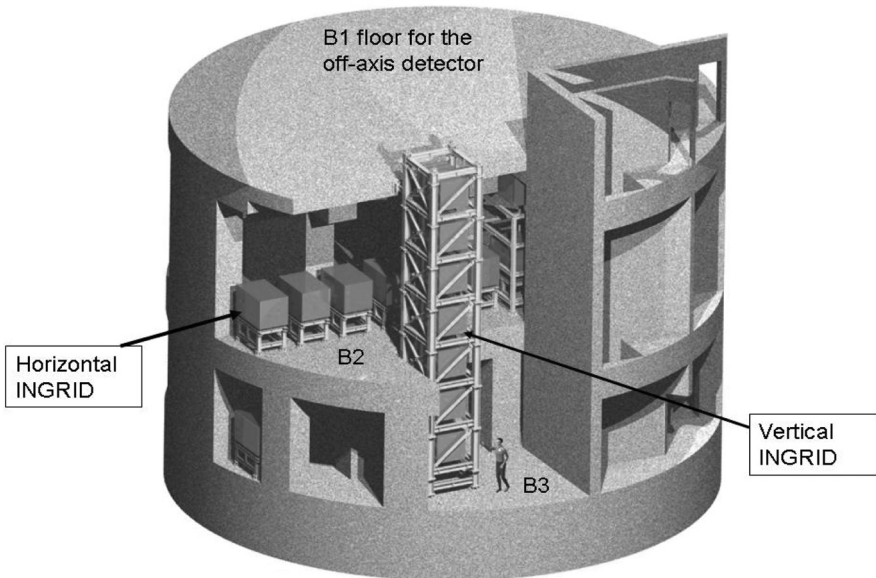


Fig. 11. The arrangement of the INGRID detectors at the near detector hall.



Fig. 12. One unit of the INGRID detector. Veto scintillators will surround this unit.

To make these measurements to the required precision, a highly segmented large volume detector, capable of charged and neutral particle energy measurements and particle identification will be constructed.

The reconstruction of the neutrino energy at the near detector is based on the charged current quasi-elastic (CC-QE) interaction, where the neutrino energy E_ν is reconstructed measuring the muon or electron energy E_l and its angle θ_l against the neutrino beam direction according to a formula

$$E_\nu = \frac{m_N E_l - m_l^2/2}{m_N - E_l + p_l \cos \theta_l}, \quad (9)$$

where m_N and m_l are the masses of the neutron and lepton ($= e$ or μ), respectively. The inelastic reactions of high-energy neutrinos constitute the background to E_ν measurement with CC-QE. In addition, the inelastic reactions produce π^0 s which contribute to the main background for ν_e appearance search. Then the detection of γ s and reconstruction of π^0 s are also required for the background estimation.

The near detector complex (ND280) at 280 m from the target contains a fine-resolution magnetized detector designed to measure the neutrino beam's energy spectrum, flux, flavor content, and interaction cross sections before the neutrino beam has a chance to oscillate. This detector sits off-axis in the neutrino beam along a line between the average pion decay point in the decay volume and the Super-Kamiokande detector, at a distance of 280 m from the hadron production target.

The ND280 detector consists of the following elements, illustrated in Fig. 13:

- **Magnet:** ND280 uses the UA1 magnet from CERN. It will be operated with a magnetic field of 0.2 T to measure the momenta of penetrating charged particles produced by neutrino interactions in the near detector. The inner dimensions of the magnet are $3.5 \text{ m} \times 3.6 \text{ m} \times 7.0 \text{ m}$.

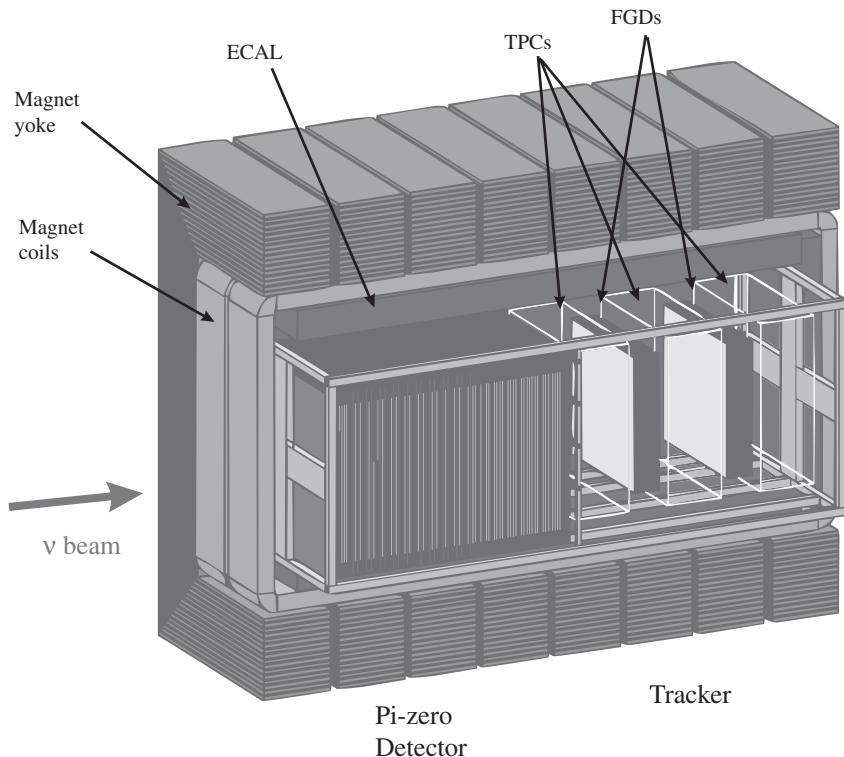


Fig. 13. Cutaway view of the T2K 280 m near detector. The neutrino beam enters from the *left*.

- Pi-zero detector (P0D): The P0D sits at the upstream end of ND280 and is optimized for measuring the rate of the neutral current π^0 production. The P0D consists of tracking planes composed of scintillating bars alternating with lead foil. Inactive layers of passive water in sections of the P0D provide a water target for measuring interactions on oxygen. The P0D is approximately cubical and is covered by the electromagnetic calorimeter.
- Tracker: Downstream of the P0D is a tracking detector optimized for measuring the momenta of charged particles, particularly muons and pions produced by the CC interactions, and for measuring the ν_e background in the beam.
 1. Time projection chambers (TPCs): Three time projection chambers will measure the momentum vector of muons produced by charged current interactions in the detector and will provide the most accurate measurement of the neutrino energy spectrum. The 3D tracking and dE/dx measurements in the TPC will also determine the sign of charged particles and identify muons, pions, and electrons.

2. Fine-grained detectors (FGDs): Two FGD modules, placed after the first and second TPCs, consist of layers of finely segmented scintillating tracker bars. The FGDs provide the target mass for neutrino interactions that will be measured by the TPCs and also measure the direction and ranges of recoil protons produced by the CC interactions in the FGDs, giving clean identification of the CC-QE and non-CC-QE interactions. One FGD module will consist entirely of plastic scintillator, while the second will consist of plastic scintillator and water to allow the separate determination of exclusive neutrino cross sections on carbon and on water.
- Electromagnetic calorimeter (ECAL): Surrounding the P0D and the tracker is an electromagnetic calorimeter. ECAL is a segmented Pb-scintillator detector whose main purpose is to measure γ -rays produced in ND280. It is critical for the reconstruction of π^0 decays.
- Side muon range detector (SMRD): Air gaps in the sides of the UA1 magnet are instrumented with plastic scintillator bars to measure the ranges of muons that exit the sides of the ND280. SMRD can also provide a veto for events entering the detector from the outside and a trigger useful for calibration.

2.3 Far Detector: Super-Kamiokande

The far detector, Super-Kamiokande, is located in the Kamioka Observatory, Institute for Cosmic Ray Research (ICRR), University of Tokyo, which has been successfully taking data since 1996. The detector was also used as a far detector for the K2K experiment, which was the first accelerator-based long-baseline experiment. In 2001, more than half of the photomultiplier tubes were destroyed by an accident. However, with the slogan “We will rebuild the detector. There is no question,” the collaborators and volunteers have fully rebuilt it.

It is a 50,000 ton water Čerenkov detector located at a depth of 2,700 m water equivalent in the Kamioka mine in Japan. Its performance and results in atmospheric neutrinos and solar neutrinos have been well documented in [32–35].

A schematic view of the detector is shown in Fig. 14. The detector cavity is 42 m in height and 39 m in diameter, filled with 50,000 tons of pure water. There is an inner detector (ID), 33.8 m diameter and 36.2 m high, surrounded by an outer detector (OD) approximately 2 m thick. The inner detector has 11,146, 50 cm ϕ PMTs, instrumented on a 70.7 cm grid spacing on all surfaces of the inner detector. The outer detector is instrumented with 1,885, 20 cm ϕ PMTs and is used as an anti-counter to identify entering/exiting particles to/from ID. The fiducial volume is defined as 2 m away from the ID wall and the total fiducial mass is 22,500 ton.

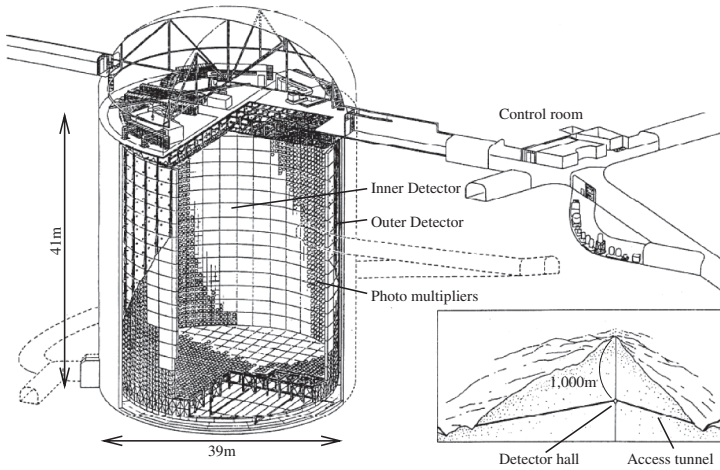


Fig. 14. A schematic view of the Super-Kamiokande detector.

The ID PMTs detect Čerenkov rings produced by relativistic charged particles. The trigger threshold was achieved to be as low as 4.3 MeV. The pulse height and timing information of the PMTs are fitted to reconstruct the vertex, direction, energy, and particle identification of the Čerenkov rings. A typical vertex, angle, and energy resolution for a 1-GeV μ is 30 cm, 3° , and 3%, respectively. The Čerenkov ring shape, clear ring for muons and fuzzy ring for electrons, provides good e/μ identification. A typical rejection factor to separate μ s from e s (or vice versa) is about 100 for single Čerenkov ring events at 1 GeV. The e s and μ s are further separated by detecting decay electrons from the μ decays. A typical detection efficiency of decay electrons from cosmic stopping muons is roughly 80%. A 4π coverage around the interaction vertex provides an efficient π^0 detection and e/π^0 separation.

Interactions of the neutrinos from an accelerator are identified by synchronizing the timing between the beam extraction time at the accelerator and the trigger time at Super-Kamiokande using the global positioning system (GPS). The synchronization accuracy of the two sites is demonstrated to be less than 200 ns in the K2K experiment. Because of this stringent time constraint, and the quiet environment of the deep Kamioka mine, chance coincidence of any entering background is negligibly low. A typical chance coincidence rate of the atmospheric neutrino events is $10^{-10}/\text{spill}$, which is much smaller than the signal rate of about $10^{-3}/\text{spill}$.

3 T2K Physics Goals

The main physics goals of the T2K experiment are as follows:

- A precision measurement of the neutrino oscillation parameters, ($\sin^2 2\theta_{23}, \Delta m_{23}^2$), by measuring the ν_μ disappearance

- The determination of $\sin^2 2\theta_{13}$ via the measurement of the $\nu_\mu \rightarrow \nu_e$ appearance signal
- Search for sterile components in the ν_μ disappearance or confirmation of $\nu_\mu \rightarrow \nu_\tau$ oscillation by detecting the neutral current events

3.1 ν_μ Disappearance

The neutrino oscillation parameters ($\sin^2 2\theta_{23}, \Delta m_{23}^2$) will be determined by measuring the survival probability of ν_μ after traveling 295 km. Neutrino events in SK are selected as fully contained events with visible energy ($E_{vis.}$) greater than 30 MeV in the fiducial volume of 22.5 kton. The events are further selected by requiring the presence of a single muon-like ring. The expected number of events without oscillation for an off-axis angle of 2.5° and 5×10^{21} protons on target (POT) are summarized in Table 1. The numbers of events after oscillation as a function of Δm_{23}^2 are shown in Table 2 for the values of oscillation parameters $\sin^2 2\theta_{23} = 1.0$ and $\sin^2 2\theta_{13} = 0.0$.

The neutrino energy is reconstructed for the fully contained single muon-like ring events with the formula

$$E_\nu = \frac{m_N E_l - m_l^2/2}{m_N - E_l + p_l \cos \theta_l}, \quad (10)$$

Table 1. The expected number of neutrino events for 5×10^{21} POT for ν_μ disappearance analysis without oscillation. CC-QE refers to charged current quasi-elastic events and CC-non-QE to other charged current events, and NC refers to neutral current events.

	CC-QE	CC-non-QE	NC	All ν_μ
Generated in FV	4,114	3,737	3,149	11,000
(1) FCFV	3,885	3,011	1,369	8,265
(2) $E_{vis.} \geq 30$ MeV	3,788	2,820	945	7,553
(3) Single ring μ -like	3,620	1,089	96	4,805

Table 2. The expected number of neutrino events with neutrino oscillation at different values of Δm_{23}^2 . The 5×10^{21} POT, $\sin^2 2\theta_{23} = 1.0$, and $\sin^2 2\theta_{13} = 0.0$ are assumed.

Δm^2 (eV ²)	CC-QE	CC-non-QE	NC	All ν_μ
No oscillation	3,620	1,089	96	4,805
2.0×10^{-3}	933	607	96	1,636
2.3×10^{-3}	723	525	96	1,344
2.7×10^{-3}	681	446	96	1,223
3.0×10^{-3}	800	414	96	1,310

where E_l , p_l , and $\cos\theta_l$ are energy, momentum, and scattered angle, respectively, and m_N and m_l are the masses of the neutron and muon with the assumption that the event is caused by the charged current quasi-elastic (CC-QE) interaction. In order to measure the oscillation parameters, the reconstructed energy distribution is fit assuming neutrino oscillation with an extended-maximum likelihood method. Figure 15 was generated by an MC simulation and shows the reconstructed neutrino energy distribution and the ratio of the distribution with oscillation to one without oscillation. The expected statistical uncertainty on the measurements is shown as a function of the true Δm_{23}^2 in Fig. 16. It is 0.009 for $\sin^2 2\theta_{23}$ and $5 \times 10^{-5} \text{ eV}^2$ for Δm_{23}^2 at $(\sin^2 2\theta_{23}, \Delta m_{23}^2) = (1, 2.7 \times 10^3 \text{ eV}^2)$.

Systematic uncertainties have to be kept way down to achieve these sensitivities. Following systematic uncertainties have been studied:

1. prediction for the number of the fully contained single ring μ -like events (flux)
2. non-QE/QE ratio (non-QE/QE)
3. energy scale (energy scale)
4. spectrum shape (shape)
5. spectrum width (width)

Figure 17 shows the effect of systematic errors on $\sin^2 2\theta$ and Δm^2 measurement with the uncertainty of 10% for flux, 20% for non-QE/QE, 4% for energy scale, and 10% for width. To see the effect of the shape, the neutrino spectrum is multiplied with a weighting factor of $1 + 0.2(1 - E_\nu) + \text{const.}$. This change roughly represents the difference in spectra predicted by MARS

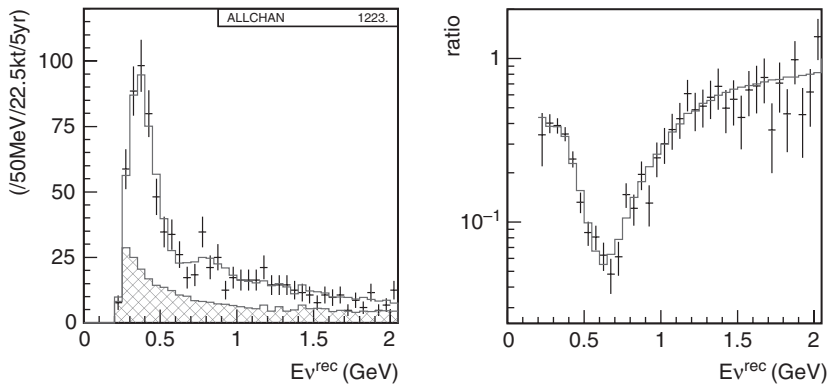


Fig. 15. Results of an MC simulation for the ν_μ disappearance. The $(\sin^2 2\theta_{23}, \Delta m_{23}^2) = (1.0, 2.7 \times 10^{-3} \text{ eV}^2)$ is assumed. (*Left*) The reconstructed neutrino energy distribution. The *line* is a prediction with the best-fit oscillation parameters. The *hatched area* shows the non-QE component. (*Right*) The ratio of the reconstructed neutrino energy distribution against the prediction without oscillation. The *line* is that of a prediction with the best-fit oscillation parameters.

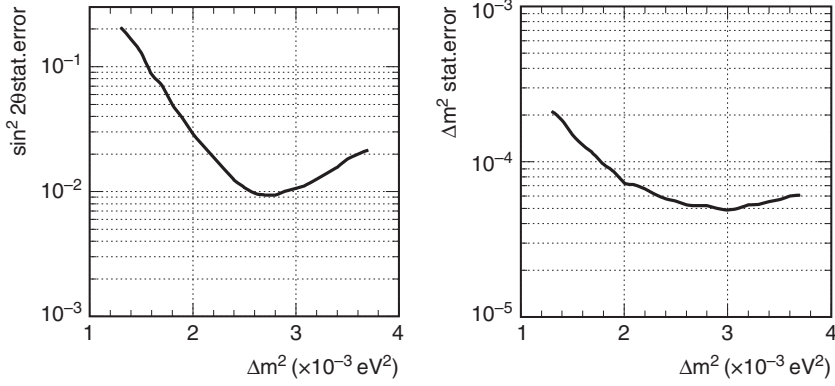


Fig. 16. The statistical uncertainty of the oscillation parameters as a function of true Δm_{23}^2 . The value of $\sin^2 2\theta_{23}$ is assumed to be 1.

[36–38] and FLUKA [39] hadron production models. In order to keep the systematic uncertainties below the statistical error, the uncertainties should be less than about 5% for the prediction of the number of events, 2% for the energy scale, 5–10% for the non-QE/QE ratio, and 10% for the spectrum width. The spectrum shape uncertainty should be less than the difference of the hadron production models MARS and FLUKA. This should be achieved through the measurement at the near detector, calibration of the far detector, and measurement of the hadron production.

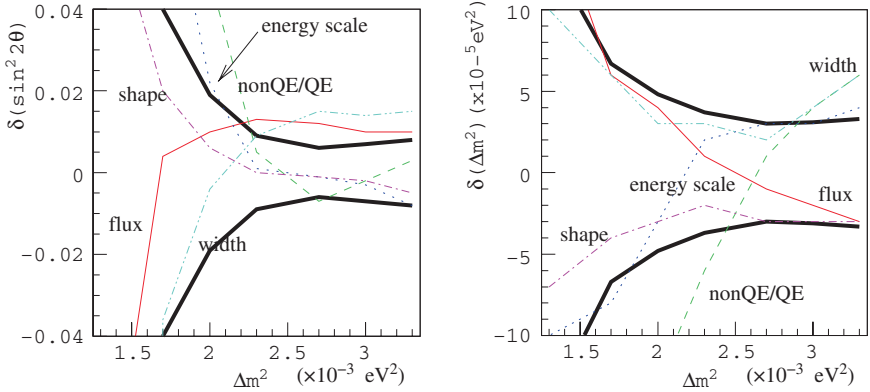


Fig. 17. Effects of systematic uncertainties on determination of oscillation parameters (OA2.5°). *Red curve*: the effect when flux is changed by 10%; *green*: non-QE/QE ratio changed by 20%; *blue*: energy scale changed by 4%; *pink*: spectrum shape (see text); *light blue*: width of spectrum changed by 10%. The *bold curves* indicate 1σ statistical error.

3.2 ν_e Appearance

The ν_e selection cuts are based on the SK-1 atmospheric neutrino analysis. Events are required to be fully contained within the 22.5 kton fiducial volume, and to have visible energy ($E_{vis.}$) greater than 100 MeV, a single electron like (e-like) ring, and no decay electrons. The electron identification eliminates most of the muon background events and the decay electron cut further reduces events from the inelastic charged current (CC) processes associated with the π^0 production. The dominant source of background events (see Table 3) at this stage is single π^0 production in the neutral current (NC) interactions. The backgrounds can be further reduced by requiring the reconstructed neutrino energy to be around the oscillation maximum: $0.35 \text{ GeV} \leq E_{\nu}^{rec.} \leq 0.85 \text{ GeV}$.

The remaining background from π^0 is further reduced with specific “e/ π^0 separation” cuts. The π^0 background has a steep forward peak toward the neutrino direction due to the coherent π^0 production. Thus events in the extreme forward direction ($\cos \theta_{\nu_e} \geq 0.9$) are rejected. Then events with only one high-energy gamma detected in the asymmetric decay of the π^0 are the dominant backgrounds. In order to find the hidden lower energy gamma ring, the photomultiplier hit pattern, including scattered light, is fit under the hypothesis of two gamma rings. The energy and direction of each gamma ring are reconstructed, and the invariant mass of the two rings is calculated. The π^0 background is further suppressed by rejecting events with the mass at around the π^0 mass ($m_{2\gamma}^{rec.} \geq 100 \text{ MeV}/c^2$). These further “e/ π^0 separation” cuts significantly reduce the π^0 background. The background level due to NC- π^0 is expected to be comparable to the predicted background from intrinsic ν_e in the beam.

Table 3 summarizes the expected number of events after the event selections for the 5×10^{21} POT exposure at $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$ and $\sin^2 2\theta_{13} = 0.1$. Figure 18 is the expected reconstructed energy distribution for the selected event.

Figure 19 shows the 90% CL ν_e sensitivity for 5×10^{21} POT exposure and for $\sin^2 2\theta_{23} = 1$ and $\delta = 0, \pi/2, -\pi/2, \pi$, assuming a 10% systematic uncertainty in the background subtraction. Here, the sensitivity is defined as the value where the expected observation is consistent with background rate

Table 3. The number of events selected by the ν_e appearance analysis, as predicted by NEUT Monte Carlo for 5×10^{21} POT exposure. For the calculation of oscillated ν_e , $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$ and $\sin^2 2\theta_{13} = 0.1$ are assumed.

	ν_{μ} CC BG	ν_{μ} NC BG	Beam ν_e BG	ν_e CC signal
Fully contained, $E_{vis} \geq 100 \text{ MeV}$	2215	847	184	243
1 ring e-like, no decay-e	12	156	71	187
$0.35 \leq E_{\nu}^{rec.} \leq 0.85 \text{ GeV}$	1.8	47	21	146
e/ π^0 separations	0.7	9	13	103

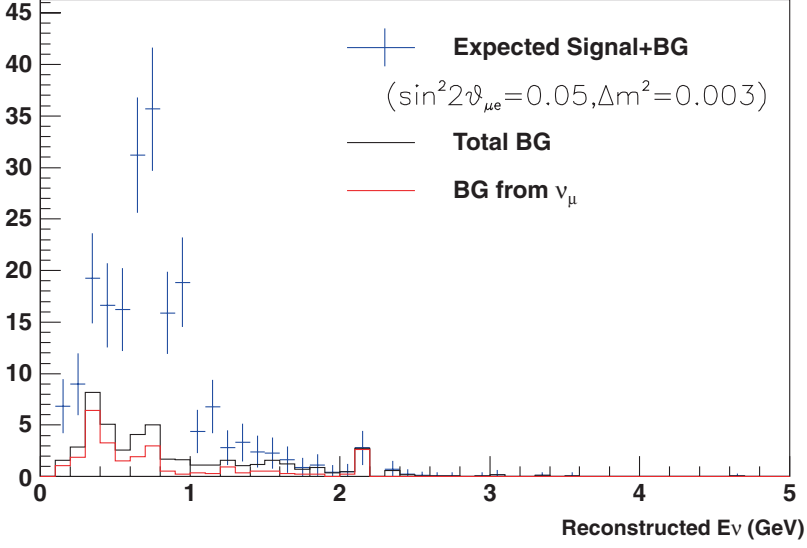


Fig. 18. Expected reconstructed energy distribution for the selected event as ν_e appearance signal.

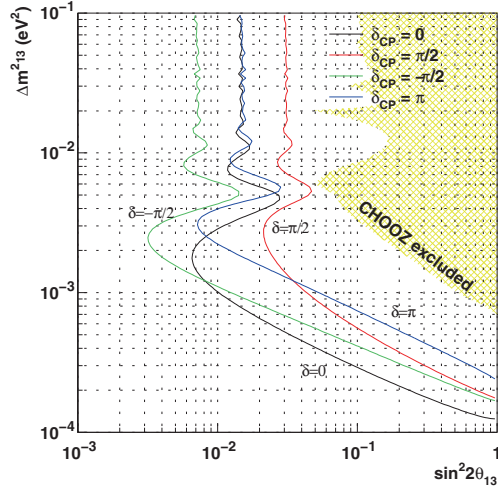


Fig. 19. The 90% CL sensitivity to $\sin^2 2\theta_{13}$ for an exposure of 5×10^{21} POT with the assumption of maximum mixing, $\sin^2 2\theta_{23} = 1.0$, and the CP violation phase $\delta = 0, \pi/2, -\pi/2, \pi$. The 90% excluded region of CHOOZ is overlaid for comparison to $\sin^2 2\theta_{23} = 1.0$.

within that confidence level. At $\Delta m^2 \sim 2.5 \times 10^{-3} \text{eV}^2$, the sensitivity is $\sin^2 2\theta_{13} = 0.008$ at 90% CL.

3.3 ν_τ Versus ν_{sterile} Analysis

The analysis of the ν_τ appearance has been performed by the Super-Kamiokande collaboration [40]. This measurement disfavors a pure $\nu_\mu \rightarrow \nu_{\text{sterile}}$ solution to the atmospheric neutrino anomaly. The search for $\nu_\mu \rightarrow \nu_{\text{sterile}}$ with a small mixing angle is still an interesting topic that can be addressed by the T2K experiment. The analysis method is based on the neutral current measurement in the SK detector, a clear signature of which is single π^0 production. The analysis is performed in a similar way to the previous ones:

- 22.5 kton fiducial volume cut is applied.
- The visible energy is selected between 100 and 1500 MeV.
- Events are selected for two e-like rings.
- Events are selected with no decay electrons to further suppress the CC background.

The event suppression by the cuts is shown in Table 4. The purity of the final NC sample is 83%, with 255 total expected events for an exposure of 5×10^{21} POT.

The sensitivity to the fraction of ν_s in $\nu_\mu \rightarrow \nu_\tau$ oscillation is shown in Fig. 20 (left) as a function of Δm^2 and $\sin^2 2\theta_s$. The best limit, $\sin^2 2\theta_s \leq 0.2$, will be obtained for $\Delta m^2 \approx 3 \times 10^{-3} \text{eV}^2$. The effect of systematic uncertainties is shown in Fig. 20 (right), where the sensitivity to $\sin^2 2\theta_s$ is plotted as a function of the exposure time for two values of systematic error on the NC prediction: 5 and 10%. A 10% error already dominates the measurement after the first year (10^{21} POT). The main systematic error for this analysis is a limit on the knowledge of the NC π^0 production, similar to the ν_e appearance analysis.

Table 4. The expected number of neutrino events in 5×10^{21} POT for ν_τ appearance analysis without oscillation. The third and fourth columns show the comparison for the two cases where the oscillation is purely due to ν_τ or due to ν_s . The numbers are computed assuming $\sin^2 2\theta_{23} = 1.0$ and $|\Delta m_{23}^2| = 2.7 \times 10^{-3} \text{eV}^2$.

	ν_μ CC	$\nu_\mu + \nu_\tau$ NC $\nu_\mu - > \nu_\tau$	ν_μ NC $\nu_\mu - > \nu_s$	ν_e
Generated in fiducial volume	3,173	3,239	1,165	236
(1) $100 \text{ MeV} \leq E_{\text{vis.}} \leq 1500 \text{ MeV}$	184	724	429	109
(2) Two e-like rings	31	281	125	19
(3) No decay electron	9	255	104	14

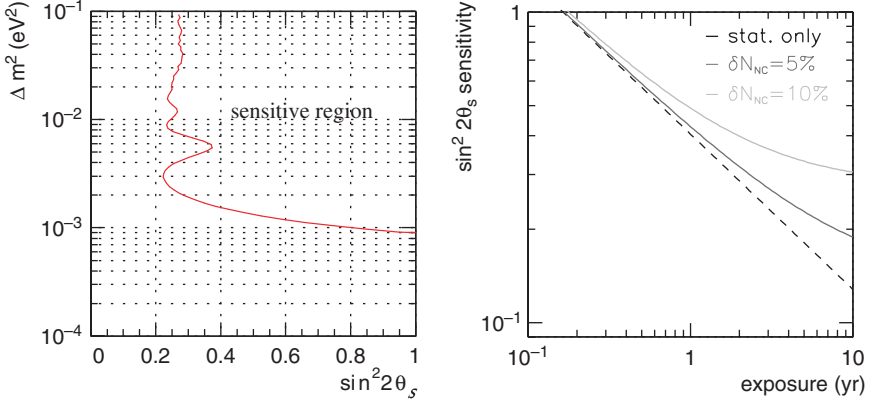


Fig. 20. (*Left*) Sensitivity to the ν_s fraction in the $\sin^2 2\theta_s$ versus Δm^2 plane with 5×10^{21} POT. (*Right*) The sensitivity as a function of exposure with different uncertainties in the background estimation.

3.4 Search for the CP Violation in the Lepton Sector – Future Project

Now that the large mixing angle solution of the solar neutrino deficit is confirmed by KamLAND, the chance of discovering CP violation is good providing that θ_{13} and δ_{CP} are not suppressed too much. The CP asymmetry is calculated as follows:

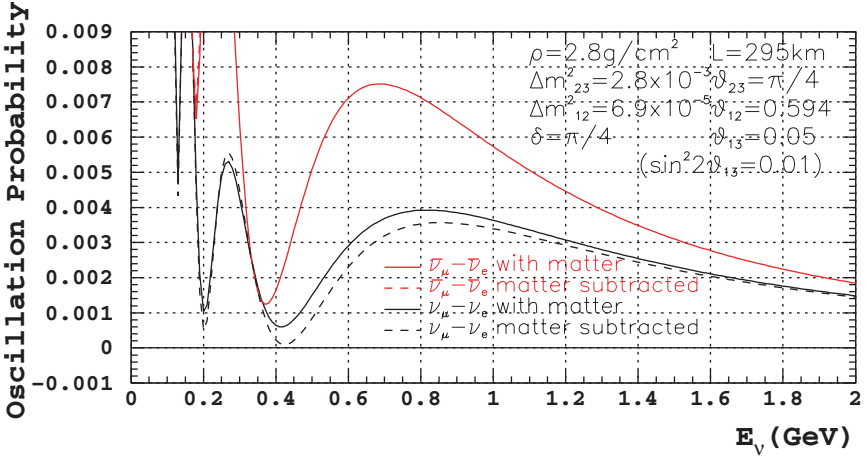


Fig. 21. Oscillation probabilities for $\nu_\mu \rightarrow \nu_e$ (*upper*) and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (*lower*). The *solid curves* include asymmetry due to matter effect. For the *dashed curves*, the matter effect is subtracted and the differences between $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ are all due to CP effect.

$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} = \frac{\Delta m_{12}^2 L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin \delta. \quad (11)$$

By choosing a low-energy neutrino beam at the oscillation maximum ($E \sim 0.75$ GeV and $L \sim 295$ km for T2K), the CP asymmetry is enhanced as $1/E$. Taking the best-fit values of KamLAND, $\sin^2 2\theta_{12} = 0.91$ and $\Delta m_{12}^2 = 6.9 \times 10^{-5}$, 1/10 of the CHOOZ limit for $\sin^2 2\theta_{13} = 0.01$, and $\delta = \pi/4$ (half of the maximum CP angle), A_{CP} becomes as large as 40% as shown in Fig. 21. The matter effect, which creates fake CP asymmetry, increases linearly with the neutrino energy. Because of the use of low-energy neutrinos, the fake asymmetry due to the matter effect is small for the T2K experiment. Further upgrade of the J-PARC beam intensity up to 2–4 MW, and a mega-ton class neutrino detector would enable to explore the CP phase as small as $\sim 10^\circ$.

4 Summary

The neutrino beam produced at J-PARC will be the world's most intense neutrino beam in GeV region when the J-PARC accelerator complex succeeds to accelerate the protons at the designed intensity. Super-Kamiokande is already the world's largest neutrino detector. With this combination of the beam and far detector, the Tokai-to-Kamioka long-baseline neutrino oscillation experiment, T2K, is aiming for the discovery of finite θ_{13} and most precise measurement of θ_{23} and Δm_{23}^2 . If the nature gives sufficiently large θ_{13} , discovery of the CP violation in the lepton sector may lie in the future of the project.

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