Status of the T2K experiment

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Abstract. The Tokai-to-Kamioka long-baseline neutrino experiment will study neutrino oscillations using an intense neutrino beam produced at a newly constructed accelerator at J-PARC in Japan. This presentation describes an overview of the experiment and its physics potential, the construction status of the experimental apparatus and the timescale for initial operation.

1. Introduction

The Tokai-to-Kamioka long-baseline neutrino experiment (T2K) is a next-generation neutrino oscillation experiment in Japan to intensively search for the undiscovered electron neutrino appearance oscillation and to measure precisely the disappearance oscillation of muon neutrinos. The proton beam from a newly constructed 50 GeV proton synchrotron at J-PARC will be used to produce an intense narrow-band off-axis neutrino beam toward the Super-Kamiokande detector at a distance of 295 km. By selecting the off-axis angle at 2.5 degrees, the neutrino beam directed towards the Super-Kamiokande detector will have a narrow energy spread with the peak at the oscillation maximum for the 295 km distance, i.e. $\sim$600 – 700 MeV. The reconstructed energy distributions for muon neutrinos to be observed at Super-Kamiokande, with three different Δm^2_{23} assumed, are shown in figure 1 (left), illustrating T2K's great sensitivity to a small variation in the oscillation parameters. With an integrated beam intensity of 5×10^{21} protons on target (POT), the T2K experiment will be capable of determining the oscillation parameters relevant to the muon neutrino disappearance with high precision of $\sim 10^{-4}$ eV$^2/c^4$ and $\sim 10^{-2}$ for Δm^2_{23} and $\sin^2 2\theta_{23}$, respectively, as shown in figure 1 (middle). The measurement of electron neutrino appearance in the same data sample is expected to improve the sensitivity to $\sin^2 2\theta_{13}$ by an order of magnitude compared to the current upper limit.

2. Experimental apparatus

The T2K beamline layout at J-PARC is shown in figure 2. Protons will be accelerated step-by-step by the 400 MeV Linac, the 3 GeV Rapid Cycle Synchrotron (RCS) and Main Ring Synchrotron to 30 GeV (in the initial phases of the experiment) and then be extracted to the neutrino beamline. The extracted protons will be bent by 90 degrees toward the Super-Kamiokande direction by superconducting magnets and led to the target station. The hadron production target is enclosed by the first of a set of three electromagnetic horns. Positively

[1] The T2K collaboration consists of about 400 members from 65 institutes in 12 countries — Canada, France, Germany, Italy, Japan, Poland, Russia, South Korea, Spain, Switzerland, UK and USA.

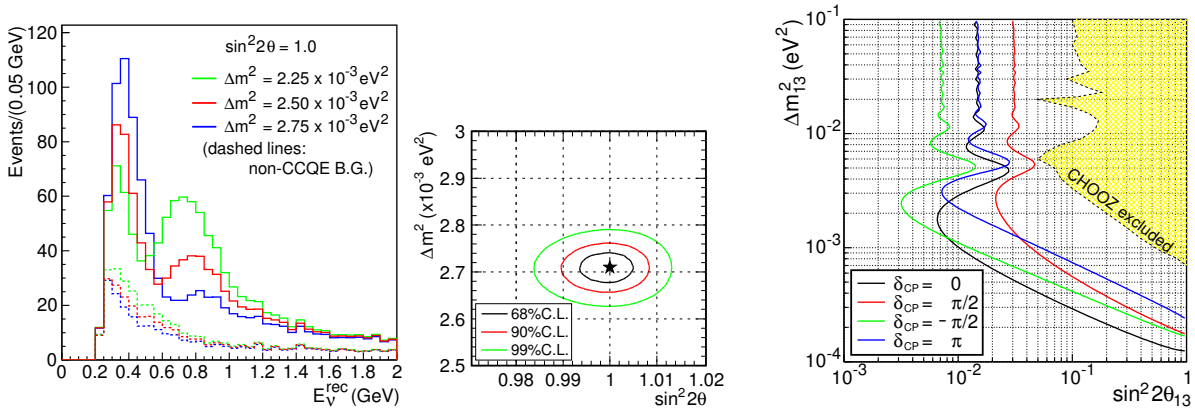

Figure 1. The T2K experimental reach for the oscillation parameters with an integrated beam intensity of 5×10^{21} POT. (Left) Reconstructed energy spectra of muon neutrinos to be observed at Super-Kamiokande for three different Δm^2_{23} values. (Middle) Expected statistical uncertainties in Δm^2_{23} v.s. $\sin^2 2\theta_{23}$ space. (Right) An estimated sensitivity to $\sin^2 2\theta_{13}$ as a function of Δm^2_{13} for CP violation phases $\delta_{\rm CP} = 0$, $\pi/2$, $-\pi/2$ and π.

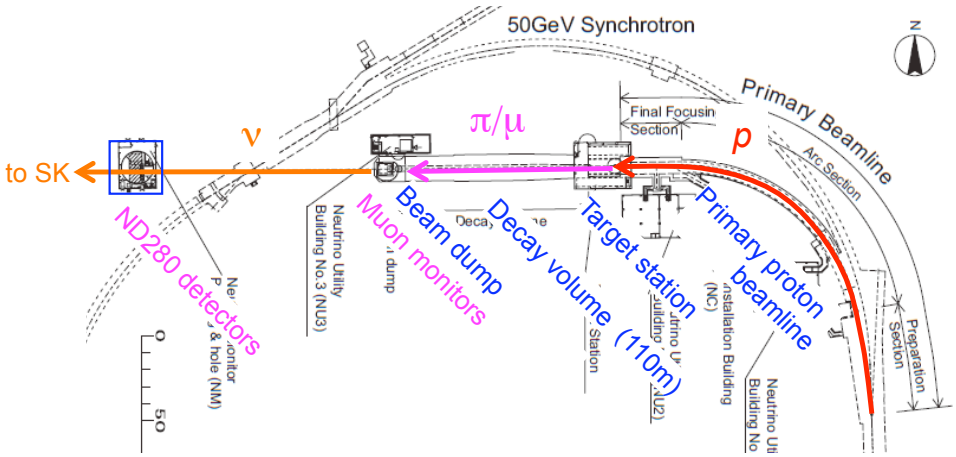

Figure 2. The layout of the T2K beamline, showing the location of primary proton beamline, target station, decay volume, beam dump, muon monitors and near neutrino detectors.

charged secondaries, mainly pions, produced by protons colliding in the target will be focused to the forward direction by the horn system and then enter a 110 m long decay volume. Pions decay into neutrinos that travel in the earth to the Super-Kamiokande detector.

Since the neutrino flux and energy spectrum depend on the neutrino beam direction, various beam monitors will be installed to track the beam direction. A number of beam intensity and profile monitors will be placed along the primary proton beamline to monitor the proton transportation through it and to determine the final beam direction. It is crucial to position the proton beam at the center of the target for target safety and since the neutrino direction is sensitive to where the protons hit the target. In order to track it, an Optical Transition Radiation (OTR) beam monitor will be installed in front of the target. Muon monitors will be installed immediately after the beam dump to track the profile center of muons from pion decays. An on-axis neutrino monitor will be installed in a pit located 280 m downstream of the target in order to track the profile center of the neutrino beam itself. Also located at the

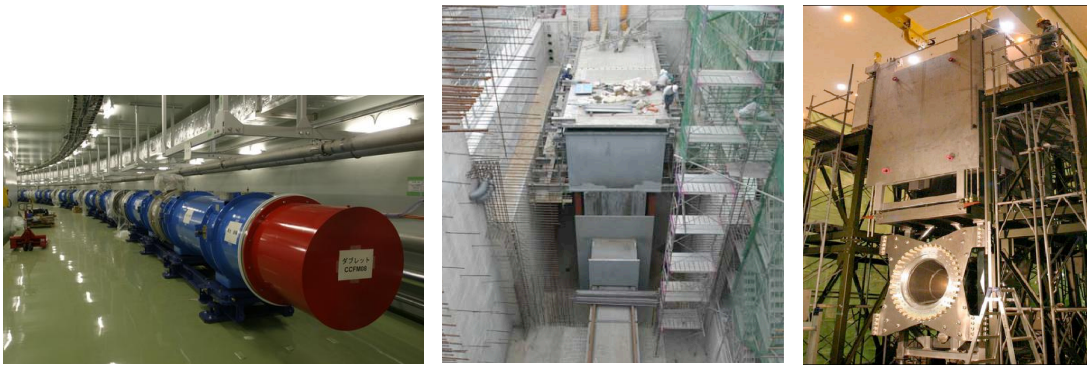

Figure 3. Pictures of the superconducting magnets installed in the beamline (left), the helium vessel placed in the target station area (center) and the horn system mocked up at KEK (right).

280 m location will be an off-axis neutrino detector to measure the properties of the neutrino beam to the Super-Kamiokande, such as fluxes, species and energy spectra. The off-axis detector will also measure neutrino interaction cross-sections and kinematics, which are indispensable for studying the neutrino oscillations and understanding the background to the measurements.

3. Construction status of accelerators, neutrino beamline and beam monitors

The construction of the J-PARC accelerator complex began in 2001. The civil construction and the installation of accelerator components for the Linac, the RCS and the Main Ring have all been finished. The accelerator group has been working intensively on their commissioning. The Linac was successfully commissioned and proton acceleration to 181 MeV, which is the nominal beam energy in the initial phase, achieved in January 2007 with good beam stability. In October 2007, the RCS was successfully commissioned to accelerate protons to 3 GeV and extract them from the ring. By now, 4.4×10^{12} protons have been accelerated in 25 Hz single-bunch mode, which corresponds to 100 kW operation in terms of the number of particles accelerated per bunch. The accelerator group are working on commissioning the Main Ring Synchrotron and they achieved a major milestone in May 2008: 3 GeV protons were injected from the RCS to the Main Ring, captured by the RF system and successfully circulated. The accelerator group is aiming to accelerate the beam to 30 GeV in December 2008.

As for the neutrino beamline, the civil construction started in April 2004 and the tunnel was completed in December 2006. Most of the superconducting magnets for the arc section have been completed and about half of the magnets have already been placed in the beamline (figure 3, left). Normal conducting magnets for the preparation and the final focusing sections are also being installed. A huge helium vessel for the target station has been manufactured and installed (figure 3, center). It passed vacuum leak tests in November 2007. The surface building of the target station is under construction. The upstream 2/3 of the decay volume has already been completed. The rest will be completed by August 2008. All graphite hadron absorber modules for the beam dump at the end of the decay volume have already been assembled and are ready for installation scheduled for October 2008.

The hadron production target is made of a helium-cooled graphite core encapsulated in a Ti-alloy container. The target to be used for day-1 operation was delivered and helium flow tests were successfully performed at the full flow rate. Prototypes of the first and third electromagnetic horns underwent long-term tests with full current of 320 kA. No major failure was observed after a million pulses. The full setup of horn system using the third horn was mocked up at KEK to verify its remote maintenance procedures (figure 3, right). The first and third horns have already been delivered to Tokai in order to be ready for day-1 operation. They will be installed

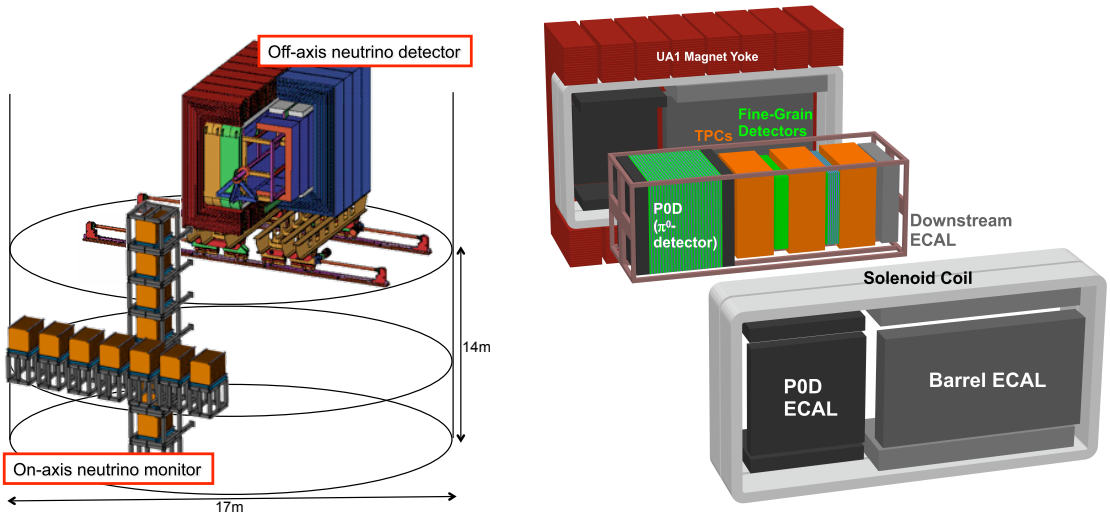

Figure 4. A schematic view of the near neutrino monitors in the detector pit (left) and the off-axis neutrino detector with more detail (right).

in the target station in August 2008 and then will undergo pulsation tests.

There are a number of beam monitors to be installed in the primary beamline: five current transformers for beam intensity, twenty-one electro-static monitors for beam positions, nineteen segmented secondary emission monitors for beam profile, 50 beam loss monitors, and an optical transition radiation (OTR) beam monitor for the position and profile immediately in front of the target. Most of them have been assembled, tested and calibrated. The installation work is in progress and scheduled to finish by October 2008.

As for the muon monitors, which measure the profile of muons from pion decays at immediately downstream of the beam dump using ionization chambers and semiconductor detectors (Si or Diamond), their prototype detector modules were assembled and underwent performance tests. The final modules will be assembled and installed in a detector pit by the end of 2008.

All the beamline components will be installed in place and commissioned by March 2009. The 30 GeV proton beam will be extracted from the Main Ring to the neutrino beamline to deliver the first neutrino beam in April 2009.

4. Near neutrino detectors and their construction status

As previously mentioned, two detector systems will be located at 280 m downstream of the target: an on-axis neutrino monitor to track the center of the neutrino beam profile and an off-axis detector to measure the properties of the neutrino beam to the Super-Kamiokande detector. Figure 4 (left) shows a schematic view of the near neutrino monitors. The on-axis monitor is a grid of detectors consisting of iron-scintillator stacks. Individual modules measure the rate of neutrino interactions occurring inside and the grid of the measurements gives vertical and horizontal spreads of the neutrino beam.

Figure 4 (right) shows a schematic view of the off-axis neutrino detector. It has two main types of detector systems: a tracker and a pi-zero detector. They are housed in a dipole magnet giving a magnetic field of 0.2 T in it. The magnet yoke is re-used from the UA1 and then NOMAD experiments previously conducted at CERN. Two fine-grained detectors (FGD) made of stacks of scintillator bars and three time projection chambers (TPC) form the tracker part, which is optimized to precisely study charged-current neutrino interactions. FGDs give target

Figure 5. Pictures of the near detector experimental hall construction. Excavation of the pit (left) and the UA1 magnet yoke installation (right).

mass for neutrino interaction and detect charged particles scattered out of the vertex. One of them has layers of water target between scintillator layers. TPCs measure momenta of tracks emerging from the FGDs. Electromagnetic calorimeters (ECAL) made of stacks of lead sheets and scintillator layers surround the tracker to identify electromagnetically showering particles originating from the FGD and measure their energies. A side muon range detector (SMRD) consists of scintillator slabs inserted in gaps of the magnet yoke. The SMRD measures the energy of sideways-going muons by the range through the yoke. The pi-zero detector (PØD) consists of planes of scintillator bars and thin lead sheets with water targets in between. The PØD is optimized to detect neutral-current π^0 production.

It is important for the detector to be capable of distinguishing the charged-current quasi-elastic (CCQE) interaction from other interactions since CCQE is used to estimate the neutrino energy spectrum. Other interactions are backgrounds to this measurement. The FGDs are capable of detecting relatively short tracks and the decay chain of $\pi \to \mu \to e$, where the π comes from non-CCQE interactions. In addition, the FGD plus TPC system measures final state kinematics of the neutrino interactions, which can be used to check the consistency with CCQE expectation on an event-by-event basis. The ECAL detects photons from π^0 decay, which effectively vetoes π^0 producing non-CCQE interactions. These features allow the study of the CCQE interaction and its backgrounds from various points of view.

Two major sources of background to the study of electron neutrino appearance are electron neutrinos contaminating the beam and a π^0 misidentified as an electron. The rates of these two backgrounds have to be estimated at the off-axis detector. The TPC and ECAL provide independent measurements for electron identification, which will be employed to study the beam-ν_e rate. The PØD will also be able to detect a showering electron, thus providing a complementary measurement. For the neutral-current π^0 production, the PØD will provide the primary measurements on its rate with high statistics while the tracker will also be capable of identifying the π^0 events, again for complementarity. The neutrino interaction rate on water must be estimated, since the neutrino interaction target in the Super-Kamiokande detector is water. The PØD and the second FGD module will have water targets in them, allowing the study of the neutrino-water interactions.

The construction of the near detectors is under way. The excavation of the detector pit was finished in March 2008 (figure 5, left). The UA1 magnet were refurbished and shipped from CERN to J-PARC. Its assembly and installation work started in April 2008 (figure 5, right). It will be finished by June 2008. The infrastructure and the surface building for the near detector hall will be completed by the end of 2008. Construction of individual detectors is also in progress around the world. The on-axis neutrino monitor will be completed and installed in the pit by the

end of 2008. It will be commissioned to be ready for the first neutrino beam in April 2009. Half of the scintillator slabs for SMRD will be assembled, tested and then installed in the magnet yoke by spring 2009, while the rest will be installed in summer 2009. The FGD, TPC, ECAL and PØD will be completed and shipped to Japan by summer 2009. They will be installed and commissioned through the summer and fall of 2009 to start their data taking at the end of 2009.

5. Status of the Super-Kamiokande detector

In 2006, the Super-Kamiokande detector was back to full capability after the accident in 2001, and it has been taking data as 'SK-III' since then. In order to further enhance its performance, the readout electronics and online data acquisition system will be fully upgraded in 2008. This will enable data taking with higher speed, less dead time and wider dynamic range. New electronics using ASICs has been developed for the last few years and it is now in mass production. The installation of the electronics is scheduled in summer to fall 2008. After this electronics installation, the Super-Kamiokande detector will resume data taking as 'SK-IV.'

6. Hadron production measurements at CERN

Besides measuring the neutrino fluxes at the near neutrino detectors, another effort to constrain the fluxes has been made using hadron production measurements at the CERN-SPS. The knowledge of the kinematics of hadrons produced by protons hitting the target enables the estimation of the absolute flux of any neutrino species at any distance from the origin since the kinematics of the decays of hadrons that produce neutrinos is well known and the geometry of the horn system and decay volume is well defined. The NA61 experiment (the SHINE experiment) measures hadron production by employing the same proton energy and the same production target as used in the T2K experiment. The momentum and angular acceptance for the secondary particles to be measured also matches the acceptance of the T2K horn magnets which focus particles forward. The experiment is capable of distinguishing π and K, so that the beam-ν_e flux from K decay can be estimated. The first data taking period in October 2007 collected $\sim$500,000 interactions with a 2 cm thick target and $\sim$180,000 interactions with a replica T2K target (90 cm long). Data analysis is in progress. Further data taking is scheduled in 2008.

7. Summary

The T2K experiment will be an exciting opportunity to extend our knowledge of neutrino oscillation and explore possibilities toward new physics. The new accelerators at J-PARC have been successfully commissioned on schedule, so far. It is planned to accelerate protons to 30 GeV in December 2008. The neutrino beamline and beam monitors are being prepared to deliver the first neutrino beam in April 2009. The near neutrino detectors are so designed to make the measurements necessary to study neutrino oscillations unambiguously with the Super-Kamiokande detector. They are being manufactured and will be installed in 2009. Intensive neutrino data taking and analysis will take place in following years.

I would like to thank the organizers for inviting me to give this presentation at the XXIII International Conference on Neutrino Physics and Astrophysics, and for their work to prepare interesting conference.