THE T2K EXPERIMENT AT J-PARC*

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(Received May 24, 2010)

The Tokai to Kamioka (T2K) is the second generation long baseline neutrino oscillation experiment. Its primary goal is to measure the last unknown mixing angle θ_{13} and determine precisely the value of Δm^2_{23} and θ_{23} oscillation parameters. The neutrino beam from J-PARC high intensity proton synchrotron travels 295 km to Super-Kamiokande detector. The status of the project and its expected physics results are presented.

PACS numbers: 14.60.Pq, 14.60.Lm, 95.30.Cq, 95.55.Vj

1. Introduction

Since the discoveries of neutrino oscillations by the Super-Kamiokande (SK) [1] and SNO [2] Collaborations neutrino studies have revolutionized our ideas about leptons in the Standard Model of elementary particles. The neutrino mixing $\nu_\mu \leftrightarrow \nu_\tau$ explaining the atmospheric observations in SK was later confirmed by two long-baseline accelerator experiments. First, the K2K Collaboration observed ν_μ disappearance using the neutrino beam from KEK traveling to SK detector 250 km away [3]. Then, MINOS Collaboration published its results [4], obtained using NuMI beam at Fermilab and Soudan detector 730 km away in Minnesota. The SK data also show some supporting evidence that muon neutrinos are transformed primarily into τ neutrinos [5].

A deficit of solar neutrinos has puzzled physicists since the first results of the Homestake chlorine experiment. However, the final proof of the oscillation of electron neutrinos into a combination of muon and tau neutrino states, $\nu_e \leftrightarrow \nu_{\mu\tau}$, was provided by the SNO experiment [6]. Recently, the

* Presented at the Cracow Epiphany Conference on Physics in Underground Laboratories and Its Connection with LHC, Cracow, Poland, January 5–8, 2010.

Borexino Collaboration reported the first direct observation of neutrinos from electron capture on ^{7}Be [7] and the results are consistent with the MSW [8] interpretation of previous solar neutrino experiments. The oscillation parameters which provide the explanation for solar neutrino data could be probed by reactor antineutrinos in a detector at sufficiently large distance. The measurements by KamLAND Collaboration found the evidence for $\overline{\nu_e}$ disappearance with the parameters consistent with the solar results [9] and allowed for precision determination of Δm^2_{12} and θ_{12} oscillation parameters.

Finally, the Mini-Boone Collaboration [10] has recently published the results of the experiment which was designed to check the observation of neutrino oscillations claimed by the LSND Collaboration [11] in 2001. The oscillation parameters obtained by LSND had implied an existence of a fourth neutrino mass state. The MiniBooNE found no evidence for $\nu_\mu \to \nu_e$ appearance in the LSND allowed region of parameters. The data obtained with $\overline{\nu_e}$ [12] are inconclusive with respect to $\overline{\nu_\mu} \to \overline{\nu_e}$ oscillations suggested by LSND.

Studies of NC interactions in SK, and MINOS experiments have also shown no evidence for transitions that would imply existence of a fourth mass state or sterile neutrinos [13, 14].

The exciting epoch of finding solutions to the neutrino puzzles has thus come to end and we now have the firm evidence for neutrino oscillations with three active neutrinos and three mass states. Still several of the oscillation parameters are either not well measured or not known at all. The next goal is to complete our understanding of neutrino mixing, to determine the ordering (or hierarchy) of the neutrino mass spectrum and to search for CP violation in the lepton sector. In order to achieve this we first need to determine the small parameter θ_{13}, which characterizes the strength of CP violating effects in neutrino oscillations and improve on precision of Δm^2_{23} and θ_{23} oscillation parameters. The first project designed to follow this agenda is a long baseline accelerator neutrino experiment T2K. In this report we present the status of the experiment and its expected physics results.

T2K Collaboration consists of more than 500 members from 62 institutions from 12 countries: Canada, France, Germany, Italy, Japan, Korea, Poland, Russia, Spain, Switzerland, UK and USA[1].

2. Oscillation parameters and probabilities

In view of the fact that LSND results have not been confirmed only 3-neutrino scenario is generally assumed. The three neutrino flavor eigenstates ν_α can be treated as combinations of three mass eigenstates ν_i using

[1] The complete list of the institutions can be found at `http://neutrino.kek.jp/t2k/T2KInstitutions.pdf`

a 3×3 unitary mixing matrix U

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i} \nu_i \,. \tag{1}$$

Consequently the neutrino mixing can be described by six real parameters: two independent differences of mass squared $\Delta m^2_{12} \equiv m_1^2 - m_2^2$ and $\Delta m^2_{23} \equiv |m_2^2 - m_3^2|$, three mixing angles ($\theta_{12}$, θ_{23} and θ_{13}), and a Dirac CP-violating phase $\delta_{\rm CP}$. Two Majorana phases are omitted here because they do not show up in oscillations (they affect only processes violating total lepton number).

Using the PDG parametrization [15] the MNS mixing matrix U of Eq. 1 can be written as a product of three rotations, each described by one of the mixing angles

$$\mathrm{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} , \tag{2}$$

where s_{ij} and c_{ij} stand for $\sin\theta_{ij}$ and $\cos\theta_{ij}$, respectively.

Two mass squared differences and two mixing angles are quite well determined [15]. The solar neutrino experiments and the KamLAND reactor measurements provide the following results: $\sin^2\theta_{12} = 0.87 \pm 0.03$ and $\Delta m^2_{12} = (7.59 \pm 0.20) \times 10^{-5}$ eV^2. The atmospheric neutrino studies and long baseline accelerator experiments provide the values: $\sin^2\theta_{23} > 0.92$ at 90% C.L. and $|\Delta m^2_{23}| = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 (we do not know the sign of Δm^2_{23}).

However, the θ_{13} mixing is only known to be small. The most restrictive limits on θ_{13} have been obtained by the CHOOZ reactor experiment [16] which searched for $\overline{\nu_e}$ disappearance. CHOOZ established an upper limit on the disappearance probabilities in function of Δm^2_{23}. A global analysis of all available oscillation data performed in Ref. [17] provided the upper limit $\sin^2 2\theta_{13} < 0.14$ at 90% C.L. for the best fit Δm^2_{23}.

As $\sin\theta_{13}$ is a dominant factor only in U_{e3} matrix element one needs transitions involving ν_e (or $\overline{\nu_e}$) and a distance to energy ratio L/E characteristic to atmospheric oscillation frequency determined by Δm^2_{23}. There are two types of such experiments: reactor $\overline{\nu_e}$ disappearance and accelerator long baseline $\nu_\mu \to \nu_e$ appearance. The $\nu_\mu \to \nu_e$ transition probability can be given by the following expansion [18] around the small parameters $\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$ and $\sin 2\theta_{13}$

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} T_1 + \alpha \sin 2\theta_{13} (T_2 - T_3) + \alpha^2 T_4 \,, \tag{3}$$

where

$$
\begin{aligned}
T_1 &= \sin^2\theta_{23}\frac{\sin^2[(A-1)\varDelta]}{(A-1)^2}\,,\\
T_2 &= \cos\delta_{\mathrm{CP}}\sin 2\theta_{12}\sin 2\theta_{23}\cos\varDelta\times\frac{\sin(A\varDelta)}{A}\frac{\sin[(A-1)\varDelta]}{A-1}\,,\\
T_3 &= \sin\delta_{\mathrm{CP}}\sin 2\theta_{12}\sin 2\theta_{23}\sin\varDelta\times\frac{\sin(A\varDelta)}{A}\frac{\sin[(A-1)\varDelta]}{A-1}\,,\\
T_2-T_3 &= \sin 2\theta_{12}\sin 2\theta_{23}\cos(\varDelta+\delta_{\mathrm{CP}})\times\frac{\sin(A\varDelta)}{A}\frac{\sin[(A-1)\varDelta]}{A-1}\,,\\
T_4 &= \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(A\varDelta)}{A^2}\,,
\end{aligned}
$$

and $\varDelta\equiv\frac{\Delta m^2_{31}L}{4E}$. The MSW matter effects [8] are taken into account by $A\equiv\frac{2EV}{\Delta m^2_{31}}$, where the potential seen by a neutrino passing through earth is $V=\pm\sqrt{2}G_{\mathrm{F}}N_e$ and G_{F} is the Fermi coupling constant, N_e is the number of electrons per unit volume.

The first term is dominant for not too small θ_{13}. The T_3 term contains $\sin\delta_{\mathrm{CP}}$ and thus is CP violating. At distances of only hundreds of km the fourth (solar) term will generally be small, however, for very small θ_{13} this is the only non-vanishing term. For antineutrinos δ_{CP} has to be replaced with $-\delta_{\mathrm{CP}}$ and V with $-V$ which can give rise to one of the possible degeneracies when matter effects can mimic the "true" CP violating effects. With A changing sign together with Δm^2_{31} matter effects provide sensitivity to mass hierarchy. It is seen that a non-zero value for θ_{13} is necessary to probe both the CP violation phase δ_{CP} and the ordering of neutrino mass states. An experiment can either compare the matter effects for neutrinos and antineutrinos or look for modifications of neutrino spectra after long path-lengths.

3. Off-axis neutrino beam

Neutrinos in the next decade will come from conventional beams *i.e.* ν_μs from meson decays produced by intense beams of protons. Important conditions of a sensitive search for $\nu_\mu\to\nu_e$ oscillations are: ν_μ beam of high intensity, a small contamination by ν_e and a narrow band neutrino spectrum. Detectors should also provide a good identification of ν_e interactions through secondary electrons produced in CC reactions. This is necessary for efficient reduction of π^0 background, coming from dominant ν_μ interactions, especially NC processes where a produced π^0 may sometimes look like an electron.

Both K2K and MINOS detectors were positioned along the neutrino beam axis. Future experiments are, however, designed for off-axis beams [19]. The advantage of the off-axis beam is a smaller spread of neutrino energies and smaller contamination with ν_e. With much reduced tail of higher energies the background coming from NC interactions with visible energy in SK similar to the $\nu_\mu \to \nu_e$ signal is much smaller. The advantage of using a beam at an angle θ from the axis of focused pions comes from pion decay kinematics. Energies of neutrinos, $E_\nu = \frac{0.43 E_\pi}{1+\gamma_\pi \theta_{\pi\nu}{}^2}$, emitted at an angle $\theta_{\pi\nu}$ different from zero are much less dependent on original pion energy E_π.

In Japan a powerful ν_μ beam has been built in Tokai, at J-PARC (Japan Proton Accelerator Research Complex) laboratory [21]. The beam design aims at 0.75 MW power for 30 GeV protons from main ring proton synchrotron PS. Protons are extracted from main ring with superconducting magnets which bend the beam almost 90° towards the target.

The T2K neutrino spectra for different off-axis angles are displayed in Fig. 1. It can be seen that the off-axis configuration offers an almost monochromatic neutrino beam. It is then possible to tune the peak neutrino energy to enhance the oscillation probability for a given distance of the far detector from source. Ultimately, the angle of 2.5 deg off axis was chosen.

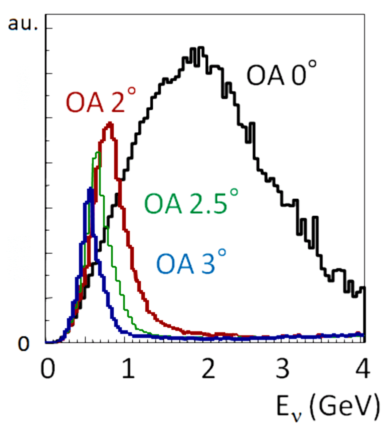

Fig. 1. Neutrino energy spectra at SK at different off-axis angles, 3°, 2.5°, 2° and on-axis.

4. Layout of the experiment

The schematic view of the experiment is displayed in Fig. 2. The major components are the intensive 2.5° off axis ν_μ beam, the near ND280 detector and the Super-Kamiokande detector 295 km away [20, 21]. To control the beam, muon monitors are located 140 m downstream from the target.

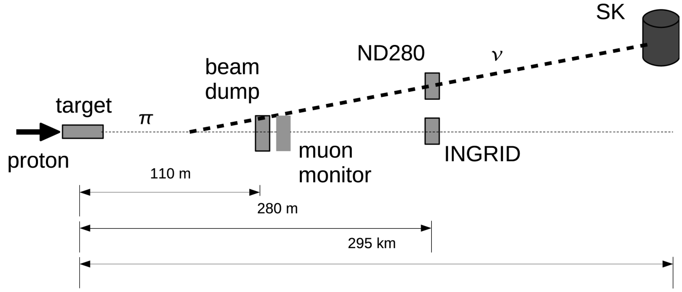

Fig. 2. Layout of T2K neutrino beam and detectors.

The proton beam is shot onto the target, a 90 cm graphite rod of 26 mm diameter, cooled with high pressure helium. Produced positive mesons are colimated by a system of 3 magnetic horns. They are driven by pulsed current of up to 320 kA, synchronized with the proton beam timing. To maximize the pion collection efficiency, the target is located inside the first horn magnet. The mesons decay in the helium filled tunnel about 100 m long. The main source of ν_μ are the pion decays $\pi^+ \to \nu_\mu + \mu^+$. The ν_e contamination is estimated at 0.4% at the peak neutrino energy around 0.7 GeV and 1% of the whole beam neutrinos. A contamination by ν_e comes at lower energies mostly from muon decays $\mu^+ \to \overline{\nu_\mu} + e^+ + \nu_e$ and from $K^+ \to \pi^0 + e^+ + \nu_e$ decays at higher energies. A contamination by $\overline{\nu_\mu}$ is expected to be at a level of a few percent.

To monitor the beam intensity, profile and direction, the surviving muons from pion decays are measured at the end of the decay channel by ionization chambers and array of Si photodiodes. They provide information on the same parameters for the accompanying neutrinos and allow to control the proton beam direction with an accuracy better than 1 mrad on spill by spill basis. Such a precision is important because a small shift in the beam direction results in shift of the neutrino spectrum peak of 2%/mrad [22]. The beam spills separated by 3.5 s are currently composed of six 58 ns bunches [23].

The construction of the J-PARC accelerator complex was completed in 2008 and the beamline of the neutrino facility in March 2009.

5. Tasks of near detectors

The idea of long baseline experiments is to compare the observed event rates in a far detector, $N_{\rm far}^{\rm obs}$, with expected rates , $N_{\rm far}^{\rm exp}$, which are optimally based on measurements in a near detector $N_{\rm near}^{\rm obs}$. In absence of oscillations the event rates depend on the neutrino flux $\Phi(E_\nu)$ and cross-section $\sigma(E_\nu)$:

$\frac{dN}{dE_\nu} = A \times \Phi(E_\nu) \times \sigma(E_\nu)$, where A accounts for exposure and detection efficiencies. Measured event rates provide then only a product of flux and cross-section. Therefore, one approach is to use the same processes in the near and far detector and then the expected rate depends primarily on the ratio: $R(E_\nu) = \frac{\Phi_{\rm far}(E_\nu)}{\Phi_{\rm near}(E_\nu)}$. The R ratio dependence on neutrino energy comes from two factors. First, energy spectrum slightly depends on neutrino directions and solid angles for far and near detectors are quite different. Secondly, and more importantly, if front detectors are located close to target compared to the decay pipe length, the neutrino source is point-like for the far detector but extended for the near one. Therefore, in order to find $R(E_\nu)$ one needs a reliable beam simulation. To achieve this a good knowledge is needed of double differential cross-sections of meson productions in proton interactions on target. The NA61/SHINE at CERN experiment has been designed to study 30 GeV proton interactions using carbon target, in particular a replica T2K target. First results are presented in Ref. [31].

The easiest process to reconstruct (and quite frequent at T2K energies) is quasi-elastic (QE) scattering: $\nu_\mu n \to \mu^- p$. Therefore, for oscillation studies the QE interaction rates $N^{\rm obs}_{\rm far}(E_\nu)$ will be compared with the expected given by: $R(E_\nu) \times N^{\rm obs}_{\rm near}(E_\nu)$ taking into account detection efficiencies in both detectors.

For precision measurements one needs to take into account all possible background processes. The most important of them will be measured using water targets in the near detectors and their rates extrapolated to the far detector. However, for some of them, *e.g.* for $\nu N \to \nu N \pi^0$ the neutrino energy reconstruction is not possible and only event rates integrated over the neutrino spectra can be used. To cross check their expected rate in the far detector some model expectations can be useful [24]. However, one then needs a determination of the flux $\Phi_{\rm far}(E_\nu)$. This can be obtained from $R(E_\nu) \times \Phi_{\rm near}(E_\nu)$. The $\Phi_{\rm near}(E_\nu)$ flux can be derived from the rate of QE events, for which the cross-section is known best. The absolute value of QE cross-section depends primarily on the axial mass, $M_{\rm A}$. The axial mass can be determined from the shape of differential cross-section $\frac{d\sigma}{dQ^2}$ for muons. The flux $\Phi(E_\nu)$ then can be determined with an accuracy derived from the $M_{\rm A}$ accuracy. The beam simulation upgraded by NA61 results can be used to cross check the flux measurement.

An important source of background for $\nu_\mu \to \nu_e$ appearance are QE interactions of the ν_e admixture in the beam. To determine this background a good separation of muon and electron QE events in the near detector is needed.

For those purposes a system of ND280 detectors was constructed 280 m downstream of the target.

6. T2K detectors

The ND280 front detector complex [25, 26] is situated in a 36 m deep concrete pit. Its schematic view is displayed in Fig. 3. It consists of an on-axis INGRID detector and a set of off-axis detectors located along the direction toward the SK far detector.

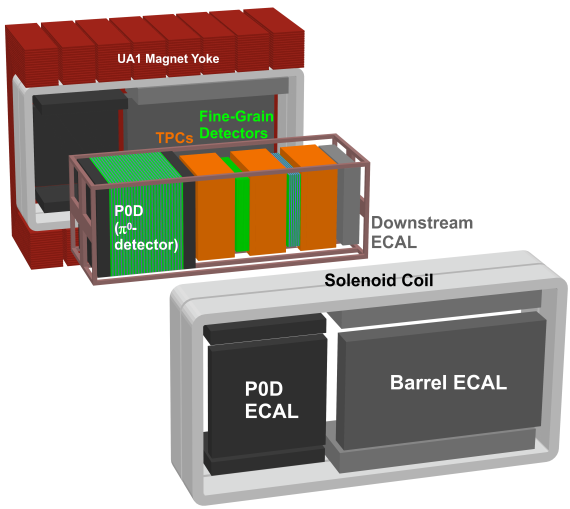

Fig. 3. The off-axis near detector system shown with one side of the UA1 magnet. The inner detectors are supported by a basket and consist of the P0D upstream, followed by the *Tracker*, and the dowstream ECAL. They are surrounded by the side ECALs. The slits of the yokes are equipped with SMRD counters.

INGRID consists of 16 modules arranged in 7 vertical and 7 horizontal modules aligned in the form of a cross perpendicular to the beam direction and two off-axis modules. Each module has dimensions of $(1.2\times1.2\times1.3)$ m^3 and consists of 11 plastic scintillator planes alternating with 10 thick iron layers. Each plane has 24 rectangular scintillator bars, each of dimensions of $(5\times120.3\times1)$ cm^3. INGRID task is to monitor stability of the neutrino beam, its direction and profile. It will be also used to measure cross-sections of QE interactions. It can determine the beam direction well within 1 mrad and notice beam shifts at the target of the order of 1 mm on a day-to-day basis. Fig. 4 shows the neutrino beam profile measured from the INGRID detector (Monte Carlo simulation). The first event was recorded in November 2009.

The off-axis detectors are located in a reused UA1/NOMAD magnet yoke donated by CERN. A coil provides magnetic field of 0.2 T in the inner volume of $(3.5 \times 3.6 \times 7)$ m^3.

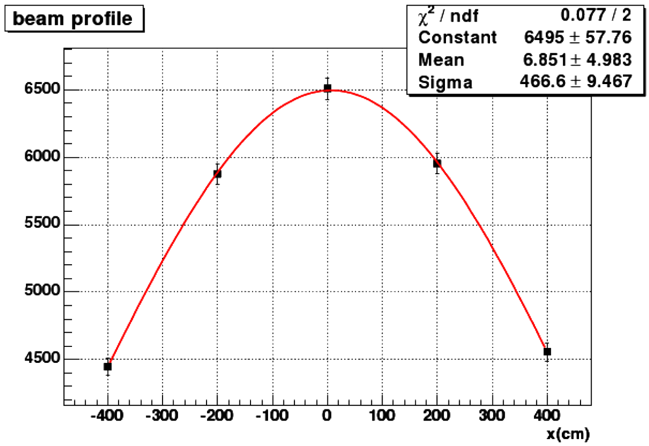

Fig. 4. Neutrino beam profile measured with the INGRID detector (Monte Carlo simulation) [25].

The first detector placed upstream is P0D. It is dedicated to measurement of the main background coming from NC π^0 production. P0D consists of scintillator planes alternated with lead plates (in the front and rear parts) or water tanks (in the central part). A scintillator plane consists of 2 layers, each composed of extruded polystyrene 17×35.5 mm^2 triangular bars doped with a scintillator. The P0D is surrounded by electromagnetic calorimeters ECAL to enhance gamma conversions.

Downstream from P0D there is *Tracker*, which is composed of two FGDs (Fine Grained Detectors) and three gas TPCs. The major task of the *Tracker* is to allow accurate reconstruction of CCQE interactions. FGDs are composed of planes of scintillating bars with dimensions $(0.96 \times 0.96 \times 184.3)$ cm^3. The granularity allows to record proton recoils. Second FGD contains water tanks. Two target materials make it possible to determine cross-sections on carbon and oxygen separately. The TPCs will provide good momentum measurement and separation of muons and electrons.

Some of the slits of the magnet yoke are equipped with scintillator counters forming the SMRD (Side Muon Range Detector). The details of SMRD counters can be found in Ref. [27,29]. Their purpose is to measure ranges of longer muon tracks leaving the *Tracker* and to reconstruct cosmic ray muons. The latter provide veto of external muons and triggering to calibrate internal detectors.

All the plastic scintillator detectors are equipped with wavelength shifting (WLS) fibers which transport light toward Hamamatsu photosensors MPPC (a total of 60 000) [28]. In case of P0D and *Tracker* only one end of each bar is read out and the other end is mirrored. The ND280 complex was installed in 2009.

The Super-Kamiokande, 50 kt water Čerenkov detector (22.5 kt fiducial volume), is well tested during more than a decade of data taking (see Ref. [30] for details). All front-end electronics and on-line systems are renovated. A GPS based system selects events correlated with T2K beam spills. At the full intensity of 750 kW about 700 CC ν_μ interactions are expected per year. SK provides a very good separation between muon and electron rings. In order to reconstruct the energy spectrum of neutrinos arriving to SK the QE interactions are used. At T2K energies the recoil protons are under Cherenkov threshold and thus only the measured energies and directions of muons or electrons can be used to reconstruct neutrino energy, E_ν. In the calculation one has to neglect Fermi motion of the initial nucleons, which is a major source of the δE_ν uncertainty amounting to about 80 MeV. The energy scale is known to 2%.

7. Expected sensitivities

Physics data taking started in January of 2010. The beam intensity will be gradually increased. Here we present expected sensitivities for 5 years of running at full beam power of 750 kW (or 8×10^{21} p.o.t. at 30 GeV of proton energy). The expected signal and background for ν_e appearance is given in Table I for two assumed values of $\sin^2 2\theta_{13}$ (the first one being close to CHOOZ limit).

TABLE I

Number of events in Super-Kamiokande in the reconstructed E_ν range of 0.35 to 0.85 GeV for 2 assumed values of $\sin^2 2\theta_{13}$ and 5 years running at designed intensity.

	$\sin^2 2\theta_{13} = 0.1$	$\sin^2 2\theta_{13} = 0.01$
Signal events	143	14
Background from beam ν_e	16	16
Background from ν_μ	10	10

The sensitivity to $\sin^2 2\theta_{13}$ is plotted in Fig. 5 for normal hierarchy and the following oscillation parameters: $\sin^2 2\theta_{12} = 0.8704$, $\sin^2 2\theta_{23} = 1.0$, $\Delta m^2_{12} = 7.6 \times 10^{-5}\text{eV}^2$, $\delta_{\text{CP}} = 0$. The curves are shown for systematic errors of 5%, 10% and 20%. It is seen that for $\Delta m^2_{23} = 2.4 \times 10^{-3}\text{eV}^2$ the experiment should be sensitive to $\sin^2 2\theta_{13}$ as low as 0.006, which means more than an order of magnitude improvement with respect to current limit.

The evolution of the sensitivity to $\sin^2 2\theta_{13}$ with exposure is plotted in Fig. 6.

Finally, the study of the ν_μ disappearance should allow a more precise determination of $\sin^2 2\theta_{23}$ and Δm^2_{23}. It is expected that the following precision can be achieved: $\delta(\sin^2 2\theta_{23}) = 0.01$ and $\delta(\Delta m^2_{23}) = 1 \times 10^{-4}$ eV^2.

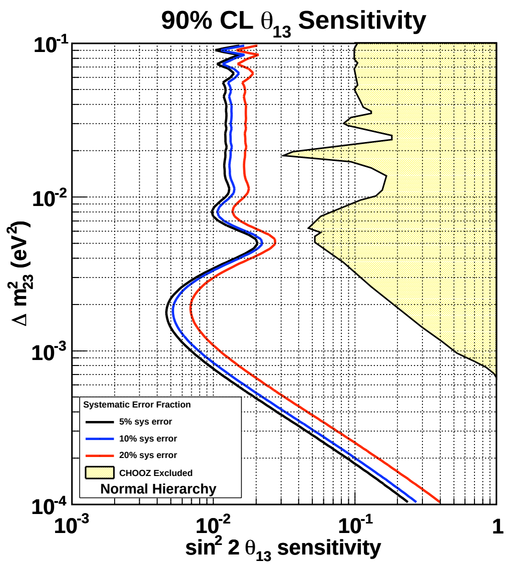

Fig. 5. T2K sensitivity to $\sin^2 2\theta_{13}$ at the 90% C.L. as a function of Δm^2_{23} for systematic errors of 5%, 10% and 20%. Beam is assumed to be running at 750 kW for 5 years (or equivalently, 8×10^{21} p.o.t.). The region which has already been excluded at 90% C.L. by the CHOOZ reactor experiment [16] is also shown.

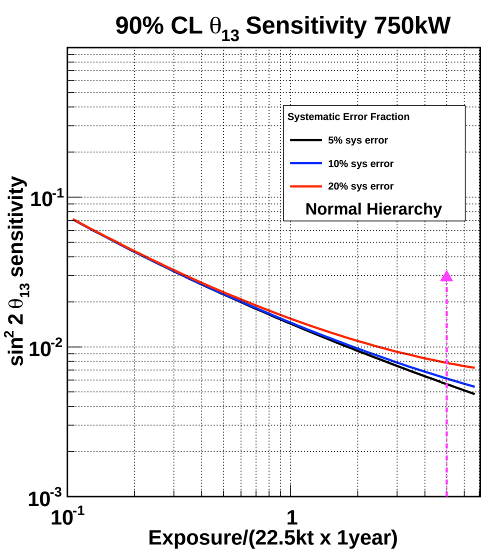

Fig. 6. Evolution with exposure of T2K sensitivity to $\sin^2 2\theta_{13}$ at the 90% C.L. for systematic errors of 5%, 10% and 20%. Beam is assumed to be running at 750 kW. The dashed arrow indicates a 5-year run.

8. Summary and outlook for future

T2K, the first oscillation experiment of the second generation of neutrino oscillation studies has just started to take data. In November 2009 the first interaction in the INGRID on-axis detector was recorded. In December 19, 2009 the first neutrino interaction in P0D with tracks through all central detectors was observed. Finally, on February 24, 2010 the first beam correlated event was observed in Super-Kamiokande. It is expected that about 100 kW $\times\ 10^7$ s of data will be accumulated in 2010. If θ_{13} is close to the CHOOZ limit we can expect about 5 $\nu_\mu \to \nu_e$ events with insignificant background.

At 30 GeV the 100 kW power is obtained with repetition cycle of 3.5 s, 6 bunches per spill and 1.2×10^{13} protons per bunch [35]. The beam power will be gradually improved by reducing the repetition cycle, increasing the number of bunches to 8 and doubling the number of protons per bunch [35].

Currently two reactor experiments [32, 33] are constructed to study $\overline{\nu_e}$ disappearance and measure θ_{13} exploiting the fact that for distances smaller than 10 km a dominant oscillation effect might come from θ_{13}. The Double Chooz experiment [32] with a pair of detectors will provide sensitivity to $\sin^2 2\theta_{23} > 0.03$.

Determination of θ_{13} mixing angle is essential to search for CP violation in neutrino sector and for establishing the neutrino mass hierarchy in future experiments. Reactor experiments are not able to measure δ_{CP}, $\mathrm{sign}(\Delta m^2_{23})$ nor to improve accuracy on $|\Delta m^2_{23}|$ and $\sin^2 2\theta_{23}$. This will be the task of accelerator experiments, initiated by powerful, conventional beams, and later probably of neutrino factories or beta beams. However, it has been noticed [34] that the three-neutrino analysis of long-baseline experiments can lead to an eight-fold degeneracy in the oscillation parameters. In particular matter effects can mimic CP-violation in vacuum. In order to lift the degeneracies multiple detectors and multiple experiments are needed for studies of $\nu_\mu \to \nu_e$ appearance. In USA a new long-baseline accelerator experiment NOνA is constructed [36]. It will use an upgraded NuMi beam from main injector at Fermilab.

For the second phase of J-PARC beam an upgrade of linac and RCS ring is planned which would allow to achieve a few MW of proton beam power. A possibility to construct more than 100 kt far detectors is discussed [35]. Considered locations are Kamioka mine, Okinoshima island and Korea.

The author acknowledges the support by the Ministry of Science and Higher Education project DWM/57/T2K/2007. The author would like to express gratitude to the organizers for the kind invitation and their hospitality.

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