THE LATEST T2K NEUTRINO OSCILLATION RESULTS AND THE FUTURE OF THE T2K AND HYPER-KAMIOKANDE EXPERIMENTS*

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T2K is an accelerator neutrino experiment conducted in Japan, which studies neutrino oscillations: muon (anti)neutrinos disappearance and electron (anti)neutrinos appearance at a distance of 295 km. It has already provided world-best measurements of the two oscillation parameters: θ_{23} mixing angle and $\delta_{\rm CP}$ phase, describing the CP symmetry conservation/violation for neutrinos, as well as many neutrino cross-section measurements. T2K is now heading towards its phase II (T2KII), which goal is to confirm CP symmetry violation at the 3σ level. The successor of the T2K experiment will be the Hyper-Kamiokande (HK) experiment. The HK physics program includes confirmation of CP violation at the 5σ level, searching for proton decay and cosmic neutrino studies. The start of T2KII and HK is scheduled for 2023 and 2027, respectively. The latest T2K neutrino oscillation results and the status of the work performed for T2KII and HK, as well as their physics program, are presented in this document.

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1. Neutrino oscillations

Neutrino oscillations [1] is a quantum mechanical phenomenon in which a neutrino of one flavour changes to a neutrino of a different flavour during travelling in space. It results from the fact that neutrino flavour eigenstates $(\nu_e, \nu_\mu, \nu_\tau)$ are a mixture of mass eigenstates (ν_1, ν_2, ν_3). This mixing is described by the mixing matrix U, called Pontecorvo–Maki–Nakagawa–Sakata matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} . \tag{1}$$

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Matrix U is usually parametrized with four parameters: three mixing angles $(\theta_{12}, \theta_{13}, \theta_{23})$ and the $\delta_{\rm CP}$ phase

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

where $c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$, and $\delta = \delta_{\rm CP}$.

Neutrino oscillation probabilities depend on:

- 6 theoretical parameters: 3 mixing angles θ_{ij}, $\delta_{\rm CP}$ phase, and 2 mass square differences between neutrino mass eigenstates ($\Delta m^2_{ij} = m^2_i - m^2_j$, where m_i is a mass of the mass state ν_i),
- 2 parameters which can be set experimentally: neutrino energy E and the distance L (baseline) travelled by the neutrino at which oscillations are measured.

The simplified oscillation probabilities with CP-violating term included, but without matter effects are

$$P(\nu_\mu \to \nu_\mu) \approx 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}\left(1 - \cos^2\theta_{13}\sin^2\theta_{23}\right)\sin^2 X_{32}\,, \tag{3}$$

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2 X_{32} \mp \frac{\Delta m^2_{21}L}{4E} 8J_{\rm CP}\sin^2 X_{32}\,, \tag{4}$$

where

$$X_{ij} = \frac{\Delta m^2_{ij}L}{4E}\,,$$
$$J_{\rm CP} = \frac{1}{8}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\sin\delta_{\rm CP} = 0.033\sin\delta_{\rm CP}\,.$$

The muon neutrino survival probability (Eq. (3)) is the same for neutrinos and antineutrinos. If the $\delta_{\rm CP}$ phase is different than 0 and π radians, the formula for the probability of electron neutrino appearance (Eq. (4)) is different for neutrinos and antineutrinos (the second term, with $J_{\rm CP}$, is with $-$ for neutrinos and $+$ for antineutrinos) that would break CP symmetry in the neutrino oscillations.

The current values of the oscillation parameters are as follows [1–3]:

$$\sin^2\theta_{12} = 0.307 \pm 0.013\,,$$
$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ {\rm eV}^2\,,$$
$$\sin^2\theta_{23} = 0.546 \pm 0.021\ (\text{normal order}: m_1 < m_2 < m_3)\,,$$
$$\sin^2\theta_{23} = 0.539 \pm 0.022\ (\text{inverted order}: m_3 < m_1 < m_2)\,,$$

$$
\begin{aligned}
\Delta m^2_{32} &= (2.453 \pm 0.033) \times 10^{-3}\ \text{eV}^2\ (\text{normal order})\,, \\
\Delta m^2_{32} &= (-2.536 \pm 0.034) \times 10^{-3}\ \text{eV}^2\ (\text{inverted order})\,, \\
\sin^2\theta_{13} &= 2.20 \pm 0.07\,, \\
\delta_{\text{CP}} &= -1.89 + 0.70 - 0.58\ (\text{normal order})\,, \\
\delta_{\text{CP}} &= -1.38 + 0.48 - 0.54\ (\text{inverted order})\,. \qquad (5)
\end{aligned}
$$

2. T2K experiment

The T2K experiment (Tokai to Kamioka) [4] is a long-baseline neutrino oscillation experiment conducted in Japan in two places: in the J-PARC complex in Tokai village, where the neutrino beam is produced, and in the Kamioka area, where the beam properties after oscillations are measured in the far detector (Fig. 1).

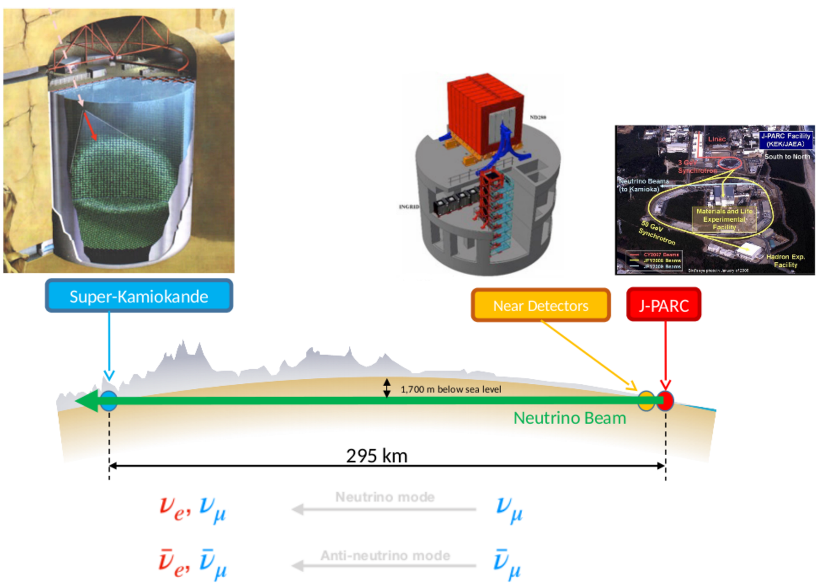

Fig. 1. T2K experiment overview.

An intense beam of either muon neutrinos or muon antineutrinos is produced in J-PARC (Japan Proton Accelerator Research Complex). The proton beam, propelled by a set of three accelerators to the energy of 30 GeV, hits the graphite target and produces a bunch of secondary particles, mainly pions and kaons. Depending on the direction of the current in the set of three horns, either positive or negative secondary particles are focused and directed into the decay volume. Positive pions and kaons decay predominantly to muon neutrinos and the negative ones to muon antineutrinos

(Fig. 2). After 280 m, the beam goes through a set of near detectors, where beam properties before oscillations are measured and a variety of neutrino interactions are studied. After another 295 km, the distance corresponding to the first oscillation maximum for the T2K beam energies, the beam goes through the far detector Super-Kamiokande.

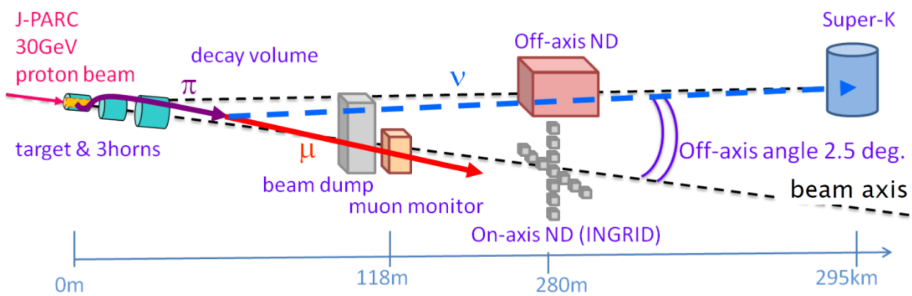

Fig. 2. Neutrino beam production scheme.

T2K experiment uses the so-called off-axis beam. That means that one of the near detectors (ND280 detector) and the far detector Super-Kamiokande are located 2.5° off the neutrino beam axis. Due to the kinematics of two-body decays, the higher the off-axis angle is, the narrower is the neutrino energy spectrum, and the peak energy is lower. The T2K off-axis angle was chosen to maximise the oscillation probabilities at the far detector (Fig. 3).

T2K has 3 near detectors (Fig. 4). Each of them is located at a different off-axis angle:

— INGRID is located on-axis. It is a not magnetized detector, predominantly made of iron and plastic scintillator (an active material). Its main goal is the monitoring of the beam position and intensity.

— ND280 is 2.5° off-axis. It is a magnetized spectrometer composed of different subdetectors, made of plastic scintillator layers interleaved with different inactive materials (water, iron, lead), and three vertical Time Projection Chambers (TPC). Two Fine-Grained Detectors, FGD1 and FGD2, are located in-between TPC detectors and are made of scintillator and water-scintillator layers, respectively. FGDs and TPCs constitute the tracker of the ND280 detector. The Pi-Zero Detector (P0D) is located upstream (with respect to the neutrino beam) of the tracker. Its scintillator layers are interleaved with drainable water bags and brass sheets in the central part of P0D and with lead layers in its upstream and downstream part. Electromagnetic Calorimeter (ECal) surrounds P0D and the tracker, and is made of a scintillator sandwiched with lead. The gaps in the magnet yoke closing the detector are instrumented with the scintillator plates building the Side Muon Range Detector (SMRD). ND280 measures the beam content before oscillations and studies neutrino interactions.

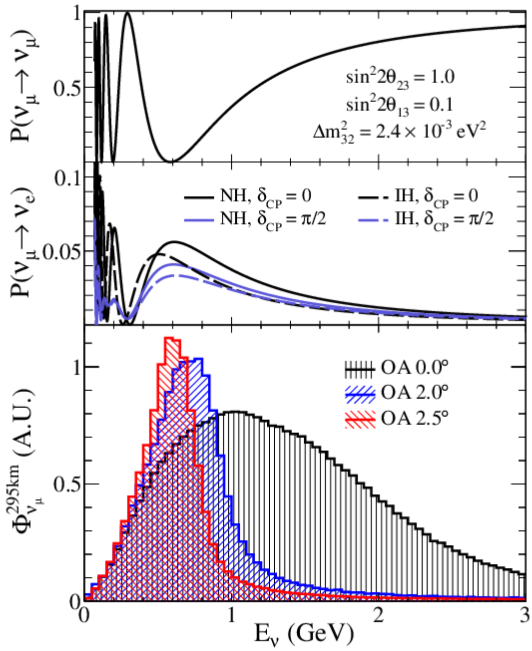

Fig. 3. T2K neutrino beam energy spectrum for different off-axis angles, and the muon neutrino survival and electron neutrino appearance probabilities as a function of neutrino energy.

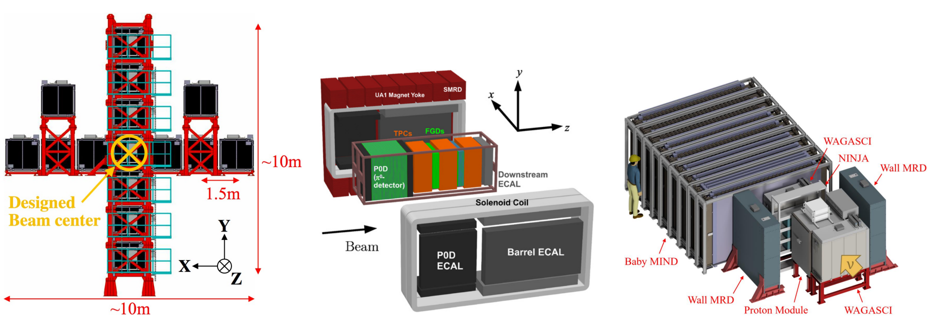

Fig. 4. T2K near detectors INGRID, ND280, and WAGASCI-BabyMIND.

— WAGASCI-BabyMIND [5] is 1.5° off-axis. It consists of subdetectors made of plastic scintillator, water, and iron. Its BabyMIND part is magnetized. The detector registers neutrino interactions for a different energy range and started physics data taking with a full setup in November 2019.

The far detector Super-Kamiokande [6] is a 50 kiloton water Cherenkov detector instrumented with about 13 000 photomultiplier tubes (Fig. 5). Originally, it was filled with ultra-pure water, but recently it was doped with gadolinium [7] which will enhance neutron capture and thus neutrino–antineutrino discrimination, as it is not possible to use the charge of the produced lepton to discern them, because the detector is not magnetized. A particle travelling faster than light in the medium (here water) produces a ring of the so-called Cherenkov light. Electrons and muons produce rings of a different shape, sharp for muons and fuzzy for electrons, as electrons scatter more easily due to their smaller mass. In this way, muon and electron neutrinos undergoing Charged Current (CC) interactions, with $W^{\pm}$ boson exchange in which charged lepton of the same flavour is produced, can be distinguished. Tauons are too heavy to be produced by neutrinos from the T2K beam, thus ν_τ component cannot be detected.

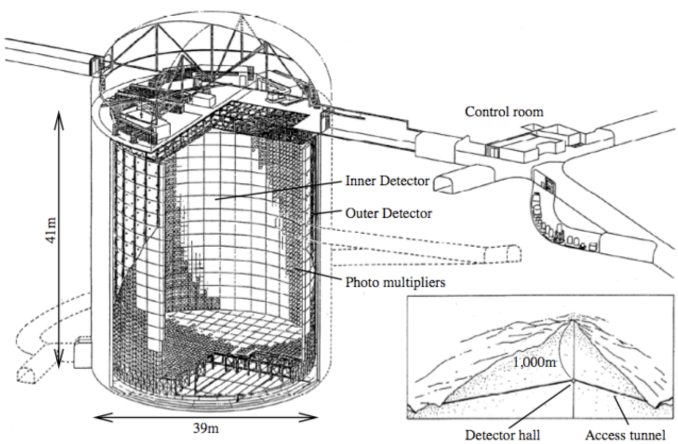

Fig. 5. Super-Kamiokande detector scheme [4].

2.1. Latest neutrino oscillation results in T2K

The main signal reaction in the far detector is CC Quasi-Elastic (CCQE) interaction, for which it is possible to calculate neutrino energy E_ν based only on the produced lepton momentum p_l and its angle θ_l with respect to the incoming neutrino

$$E_\nu = \frac{m_p^2 - m_n^2 - m_l^2 + 2m_n E_l}{2(m_n - E_l + p_l \cos\theta_l)}\,, \qquad E_l = \sqrt{m_l^2 + p_l^2}\,, \tag{6}$$

where m_p — proton mass, m_n — neutron mass, m_l — lepton mass. This formula is accurate when the interaction occurs on a free nucleon at rest. This is usually not the case in Super-Kamiokande, thus a good neutrino interaction model taking into account nuclear effects is essential to correctly estimate neutrino energy spectrum.

T2K uses five samples in the oscillation analysis in the SK detector: 1 muon-like ring (1Rμ) and 1 electron-like ring (1Re) for both neutrino and antineutrino modes, and 1 electron-like ring 1 decay-electron ring (1Re1de) in neutrino beam mode only. The decay electron is an electron from $\pi \to \mu \to e$ decays. 1Rμ and 1Re samples are intended to contain mainly CCQE interaction, while 1Re1de is intended to contain mainly CC interactions with 1 π^+ meson. Neutrino flux and cross-section measurements provided by the ND280 near detector already allow to reduce a systematic error in oscillation analysis from 11–13% to 3–6% for 1Rμ and 1Re samples.

The oscillation results presented below are improved with respect to the analysis in [2, 3], were presented for the first time in [8], and are still preliminary.

The ratio of the oscillated muon neutrino energy spectrum measured in Super-Kamiokande from 1Rμ samples to the expected spectrum in the case of no oscillations (Fig. 6) gives us the muon neutrino survival probability, which allows extracting θ_{23} angle and Δm^2_{23} (Fig. 7).

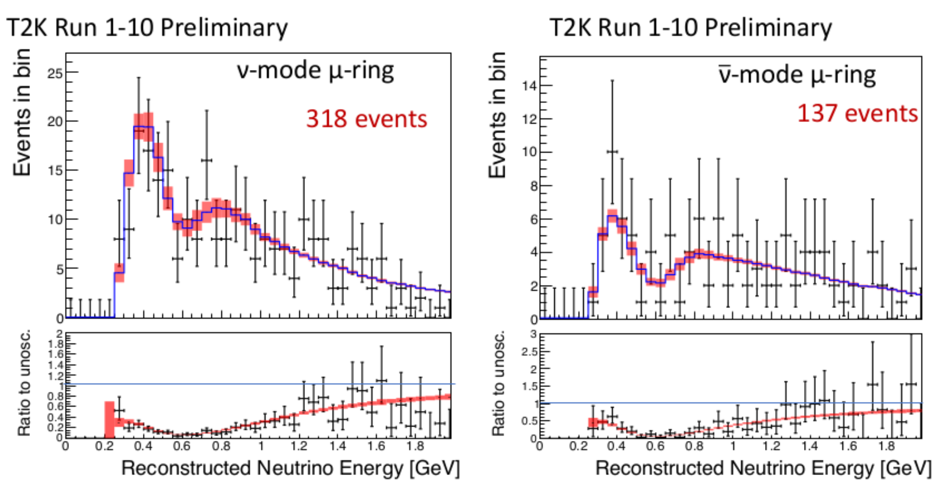

Fig. 6. Number of 1Rμ events (muon-like candidates) and its ratio to the expected unoscillated spectrum in the Super-Kamiokande detector for the neutrino (left) and antineutrino (right) beam mode [8].

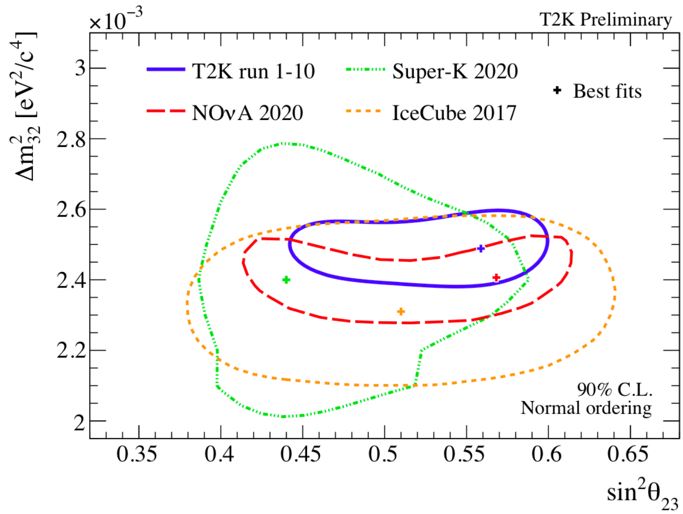

Fig. 7. Comparison of 90% confidence levels for Δm^2_{32} and θ_{23} for normal ordering for different experiments [9–11].

Electron neutrino and antineutrino appearance probabilities largely depend on the $\delta_{\rm CP}$ phase which affects these probabilities in opposite directions (the $\delta_{\rm CP}$values which enhance ν_e appearance probability decrease the appearance probability for $\bar{\nu}_e$ and *vice versa*). Thus, comparing the measured appearance probabilities for ν_e and $\bar{\nu}_e$ (Figs. 8 and 9), T2K was able to provide the first, as so far the best, constraint on the $\delta_{\rm CP}$ phase, with the best fit value close to the maximal CP-violation and excluding CP-conserving values at the 95% level (Eq. (5), Fig. 10).

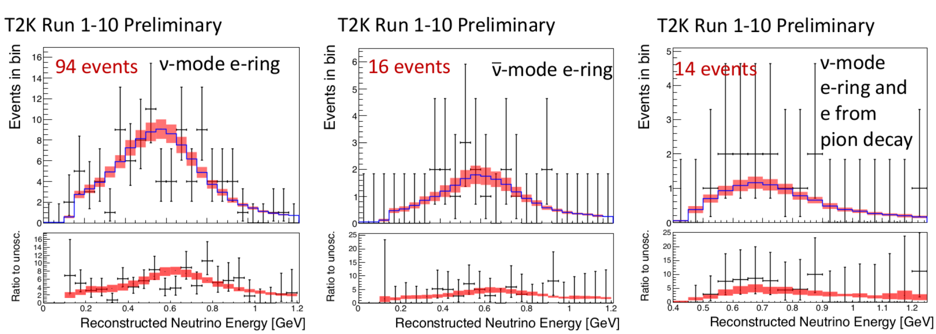

Fig. 8. Number of 1Re and 1Re1de events (electron-like candidates) and their ratio to the expected unoscillated spectrum in the Super-Kamiokande detector for the neutrino (left, right) and antineutrino (middle) beam mode [8].

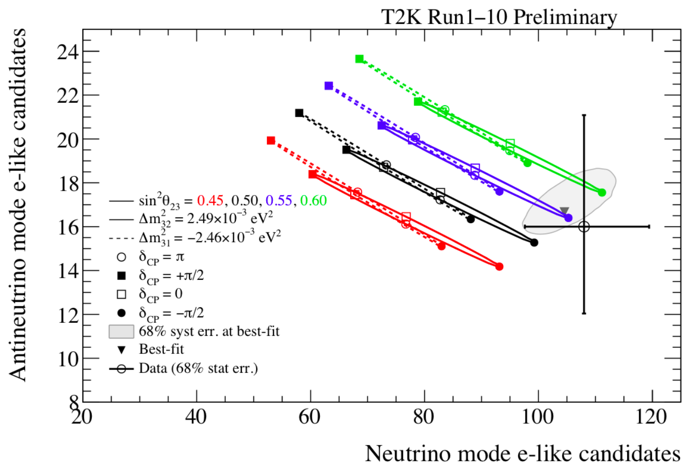

Fig. 9. Expected number of 1Re events for the neutrino *versus* antineutrino beam mode as a function of $\sin^2\theta_{23}$, neutrino mass ordering, and δ_{CP} values together with the measured value, best fit value, and 68% contour [8].

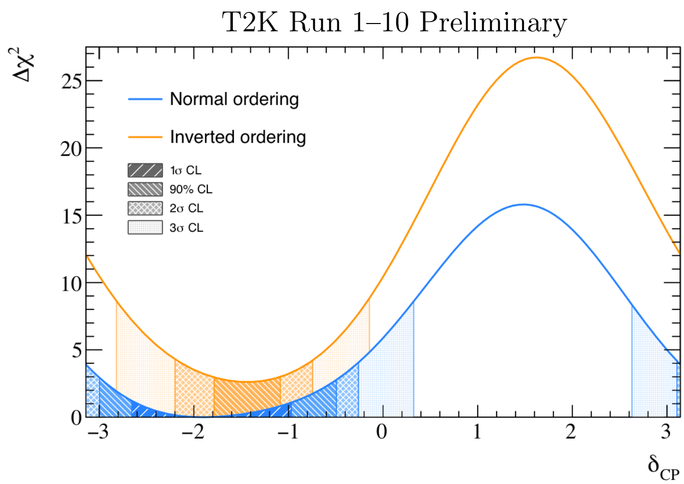

Fig. 10. χ^2 distribution in the δ_{CP} parameter range for fit to the T2K data including the constraint on θ_{13} from the reactor experiments, measuring a disappearance of the ν_e flux from nuclear reactors [8].

2.2. T2K — phase II

T2K phase II of data taking will last from 2023 till 2026 and it will be able to confirm at the 3σ level if the CP symmetry is violated in the neutrino oscillations, if the violation is close to maximal. Preparation for it involves the upgrade of the neutrino beam and ND280 near detector and benefiting from the doping of the SK detector with gadolinium.

The accelerator and neutrino beamline upgrade [12] includes an upgrade of power supplies, focusing horn, enhancement of cooling capacity *etc.* This will allow to increase the number of protons per pulse from 2.6×10^{14} to 3.2×10^{14} and shorten the time between pulses from 2.48 s to 1.16 s, and thus steadily rise the proton beam power from the current 500 kW to 1.3 MW, increasing the neutrino beam intensity. Enlarging the current in the magnetic horns focusing secondary particle from 250 kA to 320 kA will increase both the neutrino beam intensity and its purity, as more secondary particles with a right sign and less with a wrong sign will enter the decay volume.

Within the ND280 detector upgrade (Fig. 11), one of its subdetector, the Pi-Zero Detector (P0D), will be replaced with a new tracker consisting of:

— a highly granulated plastic scintillator target Super Fine-Grained Detector (SuperFGD, SFGD) made of circa 2 millions $1\,\mathrm{cm}^3$ plastic scintillator cubes with quasi-3D readout [13],

— SFGD will be sandwiched between two horizontal TPCs (High-Angle TPC, HATPC) complementary to the current, vertical TPCs; HATPC characterise with thinner walls (easier to cross for low momentum particles) and a better spacial resolution thanks to the usage of the novel readout detectors — Encapsulated Resistive Anode Micromegas (ERAM) [13, 14],

— these detectors will be surrounded by six planes of Time-Of-Flight (TOF) detector enabling the ability to distinguish between outgoing and incoming particles, as well as enhancing particle identification based on their velocity [13].

This new setup will allow reconstructing particles with much lower energies (for protons the detection threshold will decrease from 450 MeV to 300 MeV) produced at any angle and thus performing more sophisticated studies of neutrino interactions, including *e.g.* nuclear effects.

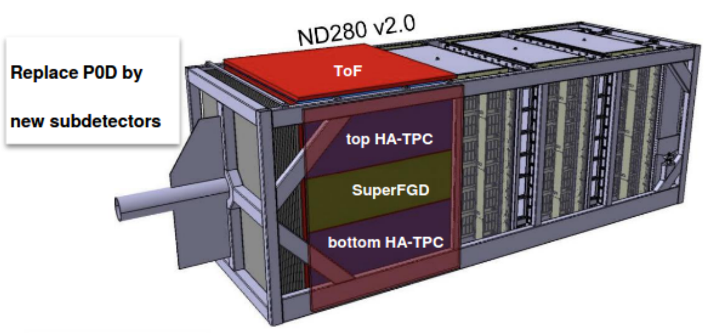

Fig. 11. Scheme of the inner part of the ND280 detector after the upgrade.

Neutron capture by gadolinium nucleus followed by its deexcitation allows to discriminate neutrino from antineutrino interactions in SK [7] as neutrons are mainly produced in antineutrino interactions

$$\begin{aligned} \nu_l + n &\rightarrow l^- + p\,, \\ \bar{\nu}_l + p &\rightarrow l^+ + n\,. \end{aligned} \tag{7}$$

In 2020, the first loading of gadolinium (0.011% of Gd) was done, which lead to 50% neutron capture efficiency. This year the second loading is planned to get 0.03% Gd concentration and 75% n capture efficiency, and the planned final concentration is 0.1% (90% n capture efficiency). It is expected that Super-Kamiokande with gadolinium will be able to discern electron antineutrino signal from Relic SuperNovas (RSN) from the background.

3. Hyper-Kamiokande experiment

Hyper-Kamiokande experiment [15] will start in 2027, after the closing of the T2K experiment. It will use the same beamline and set of near detectors as T2KII, but apart from that, it will have a new far detector with ten times bigger fiducial volume, also called Hyper-Kamiokande. Building of the Intermediate Water Cherenkov Detector (IWCD) at a distance of around 1–2 km is also considered.

The Hyper-Kamiokande far detector will be located at the same distance and at the same off-axis angle as the SK detector. SK contains 50 kton of water and $\sim$ 13 000 photomultipliers on its walls, while HK will contain 260 kton of water and $\sim$ 33 000 photomultipliers. Currently, the excavation of tunnels to the future HK cavern is ongoing.

IWCD detector [16] will be a 50 m high and 10 m wide cylinder filled with water with a 6 m high and 8 m wide movable frame with photomultipliers, scanning the neutrino beam for the off-axis angle from 1° to 4° while moving from the bottom to the top of the cylinder. The detector will be able to study neutrino interaction with water for different energy ranges and thus improve our knowledge about neutrino interactions on water in a function of the neutrino energy.

3.1. Hyper-Kamiokande physics programme

Hyper-Kamiokande physics program [15] involves studies of:

- neutrino oscillations,
- proton decay searches,
- indirect dark matter detection,
- neutrinos from astrophysical sources,
- geoneutrinos.

Accelerator neutrino oscillations will allow to measure precisely Δm^2_{32} and θ_{23} angle, and confirm at the 3 and 5σ levels if CP symmetry is violated for the 76% and 57% of possible $\delta_{\rm CP}$ values, respectively (Fig. 12). Atmospheric neutrino oscillations will be used to study the neutrino mass ordering, as the sign of the mass square difference influences only oscillations in the matter and, for atmospheric neutrinos, the baseline in the matter is up to the Earth diameter. For solar neutrino oscillations, the tension between Δm^2_{21} measured in the reactor and solar oscillations will be studied. It will be checked if this tension can be explained by the so-called electron neutrino regeneration in the Earth, which would be visible as a day–night asymmetry. The so-called upturn — the solar neutrino survival probability in the transition energy region between vacuum and matter-dominated neutrino oscillations (Fig. 13) — will be also studied, which will allow testing different oscillation models.

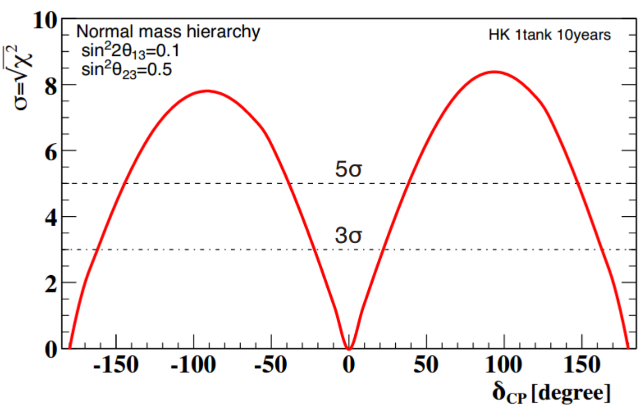

Fig. 12. σ distribution in the $\delta_{\rm CP}$ parameter range after 10 years of data taking by HK [15].

Hyper-Kamiokande will continue the proton decay searches, which was the primary physics goal of the KamiokaNDE (Kamioka Nucleon Decay Experiment) experiment. The main channels studied will be $p \to e^+ + \pi^0$ and $p \to \bar{\nu} + K^+$ decays. $p \to e^+ + \pi^0$ is a favoured mode in many Grand Unification Theory (GUT) models. In HK, it is an almost background-free sample (Fig. 14), as all the decay products are visible in the detector allowing to measure their invariant mass and total momentum, which should be low (cut < 250 MeV), especially for the decay of a free proton from hydrogen (cut < 100 MeV). $p \to \bar{\nu} + K^+$ channel occurs in the supersymmetric GUT models. In the water Cherenkov detector, this channel is more complicated, as the kaon is below the Cherenkov detection threshold and must be identified based on its decay products. After 10 years of data taking, HK will be able to increase the lifetime limit (or to observe a decay) in the $p \to e^+ + \pi^0$ ($p \to \bar{\nu} + K^+$) mode from the current 1.6×10^{34} (0.7×10^{34}) to 7.8×10^{34} (3.2×10^{34}) years [15, 18].

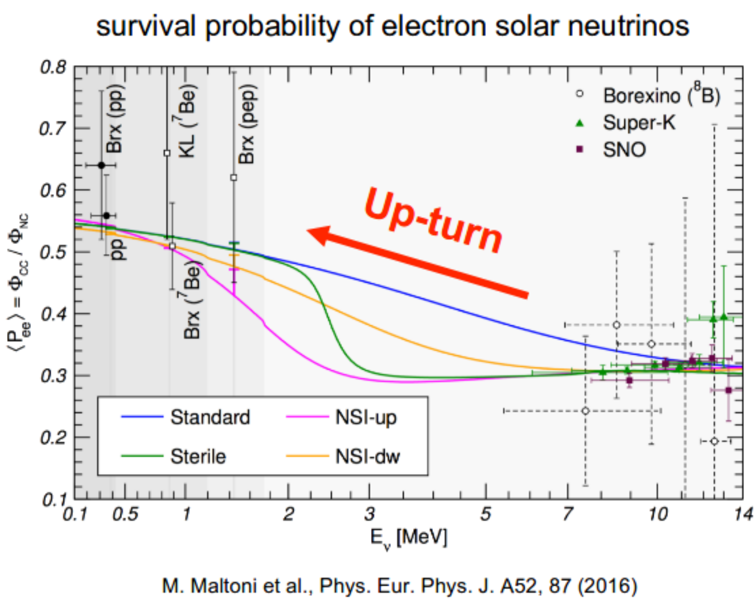

Fig. 13. Survival probability of electron solar neutrinos as a function of neutrino energy [17].

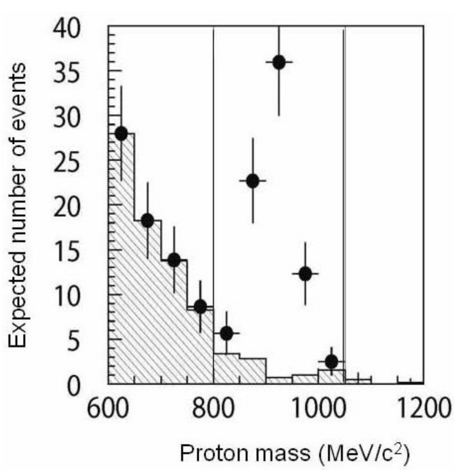

Fig. 14. Reconstructed proton mass distribution after 10 years of data taking in HK assuming the current lower limit as proton lifetime. Dots — signal and background, hatched histogram — background [18, 19].

The HK physics programme involves neutrino astro- and geophysics. HK, benefiting from its large mass, will search for the dark matter particle annihilation signal in the galactic centre, in the Sun and in the Earth (gravitational binding potentials), which should be visible as an excess of neutrinos from these directions over the atmospheric neutrino background. HK will be able to study neutrinos from both nearby and Relic SuperNovas (RSN). For nearby supernovas, the large statistics (over 50 000 events for a Supernova in the galactic centre) will allow obtaining the time and energy spectrum of the neutrinos and thus better understand the mechanism of explosion. RSN neutrino signal should be visible between solar and atmospheric background (Fig. 15). RSN flux measurement will allow studying the history of star and black hole formation. For solar neutrinos, HK will search for *hep* ($^3\mathrm{He} + p \to {}^4\mathrm{He} + e^+ + \nu_e$) solar neutrinos predicted by the Standard Solar Model, a correlation between Sun activity and neutrino flux, and for neutrinos produced by solar flares. Hyper-Kamiokande will also study neutrinos from other astrophysical sources such as gamma-ray bursts, newborn pulsars or gravitational wave sources. HK provides the directional information of detected neutrinos, thus it can be used in multi-messenger observation. The studies of neutrinos from radionuclides decays in the Earth (geoneutrinos), which are useful in the analysis of the Earth's chemical composition, are also planned.

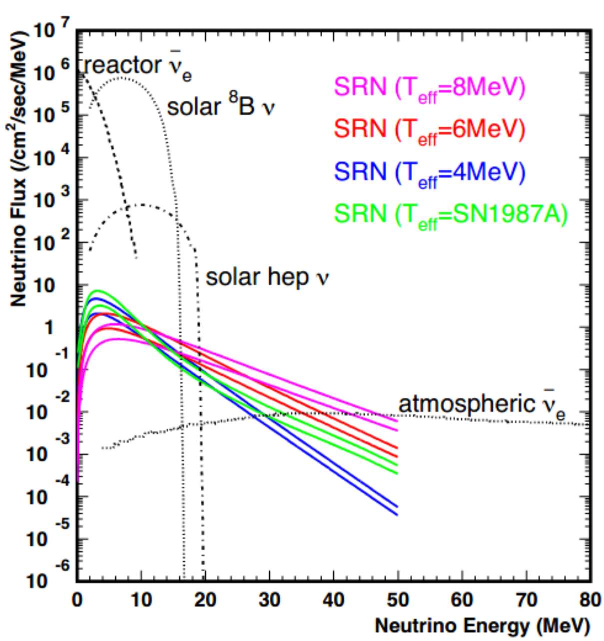

Fig. 15. Components of neutrino flux [15].

4. Summary

T2K is one of the world-leading neutrino oscillation experiments, which already provided the best constraint on the θ_{23} mixing angle and δ_{CP} phase, as well as many cross-section measurements for muon and electron neutrinos and antineutrinos. Phase II of the T2K experiment will last from 2023 to 2026 and will use the upgraded neutrino beam and near detector ND280, and the SK gadolinium doping to confirm at the 3σ if the CP symmetry is conserved or violated in the neutrino oscillations. The Hyper-Kamiokande experiment — the T2K successor — plans to start in 2027. It will use the same beam and the set of near detectors as T2KII, but with five times larger and eight times more efficient far detector Hyper-Kamiokande and the intermediate detector IWCD. Its goal is the confirmation at the 5σ level of the CP symmetry conservation/violation in the neutrino oscillations, the world-best proton decay searches, the dark matter searches, and the studies of neutrinos from astrophysical sources and from the Earth.

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REFERENCES

[1] Particle Data Group (P. Zyla *et al.*), «Review of Particle Physics», *Prog. Theor. Exp. Phys.* **2020**, 083C01 (2020).

[2] K. Abe *et al.*, «Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations», *Nature* **580**, 339 (2020); *Erratum ibid.* **583**, E16 (2020).

[3] K. Abe *et al.*, «Improved constraints on neutrino mixing from the T2K experiment with protons on target», *Phys. Rev. D* **103**, 112008 (2021).

[4] K. Abe *et al.*, «The T2K experiment», *Nucl. Instrum. Methods Phys. Res. A* **659**, 106 (2011).

[5] A. Blondel *et al.*, «The WAGASCI experiment at J-PARC to measure neutrino cross-sections on water», *PoS* **(EPS-HEP2015)**, 292 (2015).

[6] Y. Fukuda *et al.*, «The Super-Kamiokande detector», *Nucl. Instrum. Methods Phys. Res. A* **501**, 418 (2003).

[7] K. Abe *et al.*, «First gadolinium loading to Super-Kamiokande», *Nucl. Instrum. Methods Phys. Res. A* **1027**, 166248 (2022).

[8] P. Dunne, «Latest neutrino oscillation results from T2K», pleanry talk at the XXIX International Conference on Neutrino Physics and Astrophysics, June 22–July 2, 2020, `https://doi.org/10.5281/zenodo.4154355`

[9] A. Himmel, «New oscillation results from the NOvA experiment», pleanry talk at the XXIX International Conference on Neutrino Physics and Astrophysics, June 22–July 2, 2020, https://doi.org/10.5281/zenodo.4142045

[10] M.G. Aartsen *et al.*, «Measurement of Atmospheric Neutrino Oscillations at 6–56 GeV with IceCube DeepCore», *Phys. Rev. Lett.* **120**, 071801 (2018).

[11] Y. Nakajima, «Recent results and future prospects from Super-Kamiokande», pleanry talk at the XXIX International Conference on Neutrino Physics and Astrophysics, June 22–July 2, 2020, https://doi.org/10.5281/zenodo.4134680

[12] K. Abe *et al.*, «J-PARC Neutrino Beamline Upgrade Technical Design Report», arXiv:1908.05141 [physics.ins-det].

[13] K. Abe *et al.*, «T2K ND280 Upgrade — Technical Design Report», arXiv:1901.03750 [physics.ins-det].

[14] D. Attié *et al.*, «Characterization of resistive Micromegas detectors for the upgrade of the T2K Near Detector Time Projection Chambers», *Nucl. Instrum. Methods Phys. Res. A* **1025**, 166109 (2022).

[15] Hyper-Kamiokande Proto-Collaboration (K. Abe *et al.*), «Hyper-Kamiokande Design Report», arXiv:1805.04163 [physics.ins-det].

[16] S. Bhadra *et al.*, «Letter of Intent to Construct a nuPRISM Detector in the J-PARC Neutrino Beamline», arXiv:1412.3086 [physics.ins-det].

[17] M. Maltoni, A.Y. Smirnov, «Solar neutrinos and neutrino physics», *Eur. Phys. J. A* **52**, 87 (2016).

[18] S. Mine, «Recent nucleon decay results from Super Kamiokande», *J. Phys.: Conf. Ser.* **718**, 062044 (2016).

[19] «Proton Decay Searches: Hyper-Kamiokande», http://www.hyper-k.org/en/physics/phys-protondecay.html