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Neutrino oscillations

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The existence of neutrino oscillations was confirmed 25 years ago. Since that time, a lot of experiments have been performed with different sources of neutrinos and detection techniques. Now, we know the values of the neutrino mixing angles with quite good precision, yet there are still questions to be answered, such as the neutrino mass ordering, CP-violation in the neutrino sector, or the existence of sterile neutrinos. This article summarizes the current knowledge of neutrino oscillations and presents recent results from selected experiments as well as some perspectives for the future.

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1. Introduction

The deficit of solar and atmospheric neutrinos was observed for many years, and it was finally explained by two experiments: Super-Kamiokande [1] and SNO [2] over 20 years ago. Since that time, many experiments have utilized different sources of natural and human-made neutrinos and various experimental techniques to better study this phenomenon.

Most of the existing experimental results can be explained by the mixing of three neutrino mass and flavour eigenstates, described by the Pontecorvo-Maki-Nakagawa-Sakata matrix [3], usually parametrized using three mixing angles θ_{12}, θ_{23}, θ_{13} and one CP-violating phase δ_{CP}. The angle θ_{12} has been determined in the solar [4, 5] and reactor experiments [6], and θ_{23}—in atmospheric [7, 8] and accelerator experiments [9–11]. The third mixing angle, θ_{13}, can be measured by the observation of the $\bar{\nu}_e$ disappearance in the short-baseline reactor experiments, or by the observation of the $\nu_\mu \to \nu_e$ oscillation in the long-baseline accelerator experiments, as described below.

Today, we know all the neutrino mixing angles with quite good precision [12], but there are still several questions to be answered, like the neutrino mass ordering, the octant of the θ_{23} angle or the CP-symmetry violation in the neutrino sector. There are also some experimental results which suggest the existence of so-called sterile neutrinos: hypothetical neutrinos not coupling to $W^\pm$ and Z^0 bosons. Since mixing between active and sterile neutrinos may occur, they would affect the oscillations of active neutrino flavours.

2. Reactor experiments

The nuclear reactors emit large numbers of electron antineutrinos from the β decays of the products of nuclear fission. They can be detected via the inverse beta decay ($\bar{\nu}_e + p \to e^+ + n$); after which the positron promptly annihilates and the neutron can be captured by a nucleus, providing a delayed signal. The energy range of reactor neutrinos is a few MeV.

2.1 Measurement of θ_{13}

Although θ_{13} is now the most precisely known mixing angle, it was measured as the last one. For a long time, only the upper limit was known, set by the CHOOZ experiment [13]. The first hint that θ_{13} is not zero came in 2011 from the long-baseline experiment T2K [14], but the 5σ confirmation was provided several months later by the Daya Bay collaboration [15], followed by another reactor experiment, RENO [16].

The Daya Bay experiment was located in China. Six commercial nuclear reactors produced an intensive flux of $\bar{\nu}_e$, which was measured by detectors in two near (about 400 m from the nearest reactor) and one far (at a distance of about 1.5 km) underground halls. Each of the two near stations contained two identical liquid scintillator detectors doped with gadolinium, and four such detectors were located in the far station. Using the near and far detectors allowed to compare the measured event rates at different baselines and suppress the correlated uncertainties.

In 2023, Daya Bay published results for 3158 days of data-taking, with over 5.5 million collected events (the largest sample of reactor $\bar{\nu}_e$). They provided the most precise measurement of the θ_{13} angle: $\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$ (2.8% precision) and also measured the mass splitting $\Delta m^2_{32} = 2.466(-2.571) \pm 0.060 \cdot 10^{-3}$ eV^2 with 2.4% precision [17].

Daya Bay performed also numerous measurements of the $\bar{\nu}_e$ flux and the flux evolution. Those results are very important for the understanding of the "reactor anomaly" (see Section 5.1).

2.2 JUNO

The reactor antineutrinos can also be used to determine the mass ordering. The $\bar{\nu}_e$ survival probability depends on both Δm^2_{31} and Δm^2_{32}, so the oscillation probabilities differ slightly for normal and inverted orderings. However, to distinguish between these two oscillation patterns, an experiment with excellent energy resolution is required.

The JUNO experiment, currently under construction in China, is planned to obtain the resolution of 3% / $\sqrt{E}$ (MeV) [18]. The detector will have an active mass of 20 kton of liquid scintillator, contained in a 35.4 m diameter acrylic sphere, which will be immersed in a veto Water Cherenkov detector. The active volume will be observed by two independent systems of highly efficient 20" and 3" photomultipliers (with photon detection efficiency over 25%), providing 78% of photo-coverage. JUNO will be equipped with an advanced calibration system allowing to study the energy scale, the detector response non-uniformity and the energy non-linearity.

The neutrinos will come from 10 nuclear cores located in two power plants at a distance of 53 km. A liquid scintillator detector TAO will also be installed close to one of the power plants, providing measurement of unoscillated neutrino flux.

JUNO plans to reach 3σ sensitivity for the mass hierarchy determination after 6 years of data-taking (with the exposure of 26.6 GWth) and provide also the measurements of Δm^2_{21} and $\sin^2\theta_{12}$ with precision better than 1%.

3. Measurements of atmospheric neutrinos

Atmospheric neutrinos originate from the decays of secondary particles (mostly pions) produced in the collisions of high-energy primary cosmic rays with the atmosphere. They cover a wide range of energies (from sub-GeV to TeV) and distances between their production and detection points, which can be estimated from their directions.

The experiments studying atmospheric neutrinos are sensitive to θ_{23}, Δm^2_{32}, and the mass ordering, which can be determined using neutrinos of energies 6–12 GeV, thanks to the matter effect in the Earth's core [19]. In the case of normal (inverted) ordering, one should observe the enhancement of $\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$) oscillations.

3.1 Super-Kamiokande

The most famous and oldest of the atmospheric neutrino experiments in operation is Super-Kamiokande (SK), located in Japan. SK is a cylindrical water tank containing 50 ktons of ultra-pure water (since 2020 doped with salts of Gadolinium [20]) observed by over 11 000 photomultipliers. The detector has excellent μ/e identification capability, and its energy resolution is at the level of about 10% for two-body kinematics.

In 2022, SK showed the new results obtained for the full "pure-water" phase, expanded fiducial mass (from 22.5 to 27.2 kt) and higher exposure (484 kt year in total). Also, for the latest phases of data-taking (SK IV-V periods, years 2008-2019), neutron tagging and a new multi-ring event classification based on BDT were applied, resulting in enhanced $\nu/\bar{\nu}$ separation.

The analysis of the oscillations was performed for (a) atmospheric neutrino data only, (b) with external constraints on θ_{13} from reactor results, and (c) with additional "T2K model"+T2K public $\nu/\bar{\nu}$ data [21].

All the analyses prefer the normal ordering of neutrino masses. Reported computed χ^2_{IO-NO} is 5.23 in case (a) and rises to 8.54 for case (c). Using atmospheric data only gives the best value of $\sin^2\theta_{23} = 0.45^{+0.06}_{-0.03}$ (assuming NO), while adding the T2K model and constraints shifts the preferred value of θ_{23} to the upper octant: $\sin^2\theta_{23} = 0.51^{+0.04}_{-0.04}$.

Recently, SK also presented new results of the search for ν_τ appearance due to the oscillations. The direct observation of τ lepton is not possible in SK; therefore, the analysis was performed using neural network event selection for upward-going events, where the contribution from ν_τ events is expected. Using full "pure-water" data and expanded fiducial volume, the no-ν_τ-appearance hypothesis was excluded at 4.8σ.

3.2 IceCUBE and KM3NeT

The IceCube detector is located at the South Pole and was primarily designed to observe ultra-high-energy neutrinos from space. The detection is made by a grid of digital optical modules in a volume of about 1 km^3 deep in the ice. For the studies of atmospheric neutrinos, a region with denser instrumentation, called DeepCore, is used.

IceCube published the results of an improved analysis of data corresponding to a livetime of 8 years [22]. The preferred value for θ_{23} mixing angle lies in the upper octant: $\sin^2\theta_{23} = 0.51 \pm 0.05$; and $\Delta m^2_{32} = (2.41 \pm 0.07) \cdot 10^{-3}\ \mathrm{eV}^2$, assuming the normal ordering. The results are similar and competitive with other existing measurements. Recently, a Convolutional Neural Network was introduced to reconstruct neutrino interactions in DeepCore, allowing for enhanced sensitivity. The first results used data corresponding to a livetime of 9.3 years and are consistent with those reported previously [23].

Another experiment using a natural medium is KM3NeT, under construction in the Mediterranean Sea. One of the sites of the experiment, called ORCA, will be a dense array of multi-photomultiplier digital modules, able to observe atmospheric neutrinos. The planned number of vertical strings anchored to the sea floor, each equipped with 18 modules, is 115, while 18 are already deployed.

KM3NeT published the first studies of atmospheric neutrinos for data taken with six strings. The results are consistent with other atmospheric experiments [24].

4. The long-baseline experiments

The experiments with a long-baseline use a muon neutrino or antineutrino beam produced at the accelerators. A primary beam of protons hits the target, and new particles are produced in the collisions. The hadrons emerging from the target, mostly pions and kaons, are then focused by magnetic horns, which select the particles of the desired charge and momentum range and direct them into the decay volume, where the mesons decay, producing muon neutrinos (with a small admixture of electron neutrinos coming from decays of kaons and tertiary muons). By switching the direction of the current in the horns, positive or negative mesons can be focused, thus obtaining neutrino or antineutrino beam.

Usually, several hundred meters from the target, where the effects of the oscillations can be neglected, a near detector is located. The data collected by the near detector can be used to constrain the uncertainties related to the flux and cross sections and thus improve the sensitivity of the experiment. The far detector is located several hundred kilometers from the target. Long-baseline experiments can study ν_μ disappearance and ν_e appearance and collect data with beam of neutrinos or antineutrinos. Thanks to that, they are sensitive to the θ_{23} octant, size of δ_{CP} and the mass ordering (for larger baselines).

Currently, two long-baseline experiments are operating: T2K (Tokai-to-Kamioka), located in Japan, and NOvA, located in the US. They are briefly described below, and the most important differences are summarized in Table 1.

	T2K	NOvA
baseline	295 km	810 km
peak energy	0.6 GeV	2 GeV
rate change due to CPV	32%	22%
rate change due to matter effects	9%	29%

Table 1: Comparison of basic properties of T2K and NOvA experiments.

Both experiments use the so-called off-axis neutrino beam, where the angle between the neutrino beam axis and the direction towards the far detector is non-zero. In the decay of a parent pion, if the neutrino is emitted at a non-zero angle, the energy of the neutrino is limited, even for the high-energy parent pions. This results in a more narrow energy spectrum, which can be tuned to the maximum oscillation probability by selecting the optimal off-axis angle.

4.1 T2K

T2K uses a beam of muon (anti)neutrinos produced at the Japan Particle Accelerator Research Centre (J-PARC) and a series of detectors located at J-PARC and in Kamioka, 295 km away [25].

The near detectors at JPARC, at a distance of 280 m from the target, consist of INGRID, an on-axis detector, and two other detectors placed off-axis. One of them, called ND280, is a multi-purpose detector equipped with a magnetic field. The part used in the oscillation analysis is the tracker, which consists of two Fine Grained Detectors (FGDs), one of which is made of scintillator and the other one contains also layers of water. FGDs are sandwiched between Time Projection Chambers (TPCs). They allow for particle momentum and charge reconstruction, and identification using the measurement of energy loss. The far detector for T2K is Super-Kamiokande, described previously. In the analysis, the CC $(\bar{\nu}_\mu)\nu_\mu$ events collected in ND280 and the CC $(\bar{\nu}_\mu)\nu_\mu$ and $(\bar{\nu}_e)\nu_e$ events from far detectors are used.

In the recent analysis, T2K increased the number of samples from ND280, introducing photon and proton tagging of events, which provided additional constraints or tests of the cross-section models used. In the far detector, a new sample of μ-like events was added, where a charged current interactions with the production of one pion is found.

T2K uses parametrized models of the neutrino flux, neutrino interactions and response of the ND280 and SK detectors. Two methods are used for extracting the oscillation parameters from the data: the frequentist approach, in which first the values of the parameters are tuned to the data events samples collected in ND280, and the oscillation fit to the far detector data is performed with the simulated prediction reweighted to the best values of flux and cross section parameters; and the Bayesian approach, based on the Markov Chain Monte Carlo method, in which the event samples from ND280 and the far detector are fitted simultaneously.

In the oscillation fit, the parameters of interest are θ_{13}, θ_{23}, $|\Delta m^2_{32}|$ and δ_{CP}. Other oscillation parameters that appear in the probability formula are taken from the Particle Data Group (PDG). The analysis is prepared for two cases: θ_{13} being a free parameter, or fixed at the value from reactor measurements. The fit is performed using the binned likelihood fit, which compares the data with the Monte Carlo predictions [26].

4.2 NOvA

The NOvA experiment, located in the US, makes use of the upgraded NuMI beam from Fermilab. NOvA detectors are placed 14 mrad off-axis, with the near one at a distance of 1 km from the target and the far one 810 km away. The peak energy of the off-axis beam is 2 GeV.

Both near and far detectors are functionally identical. They consist of planes of horizontal and vertical extruded PVC cells filled with liquid scintillator mixed into oil. The light in each tube is collected by looped wavelength-shifting fibers read-out by avalanche photodiodes. The total mass of the far detector is 14 kton, with the active mass being 65% of that.

The neutrino flavor identification is performed using a convolutional neural network. The CC interactions of muon and electron neutrinos and antineutrinos are selected in both near and far detectors. The true neutrino energy distribution is estimated from the spectrum measured in the near detector. It is then multiplied by Far-to-Near ratio and oscillation probability. The predicted true energy distribution in the far detector is converted into the reconstructed energy spectrum and compared to the data.

Recently, NOvA announced a new analysis of the same data as the latest publication [27], but using the Bayesian approach. The results are consistent with the published frequentist analysis.

4.3 Comparison of results

In the case of the analysis with θ_{13} value constrained by the reactor experiments, both experiments prefer the θ_{23} in the upper octant; however, the lower octant is still included in the confidence (and credible) intervals (within 68% C.L. in case of T2K). If θ_{13} is a free parameter (or if its value would be larger), the data favour the lower octant.

As for the CP violation, T2K prefers the values of δ_{CP} close to maximal violation, while the CP-conserving values (0 and π) are excluded at the level of 90%. There is also a weak preference for normal mass ordering with the region around $\delta_{CP} = \pi/2$ excluded at 3σ. This result is driven mostly by the observed excess of ν_e and deficit of $\bar{\nu}_e$ events.

NOvA, on the other hand, sees both ν_e and $\bar{\nu}_e$ appearance and such observation disfavors such combinations of the mass ordering and δ_{CP} hypotheses which predict large asymmetry. Thus, NOvA excludes the region around $\delta_{CP} = 3\pi/2(-\pi/2)$ for normal ordering at about 2σ, while in the case of inverted ordering, the values around $\delta_{CP} = \pi/2$ are excluded at $> 3\sigma$ level.

Both experiments also performed the fit of the Jarlskog invariant, which is independent of PMNS matrix parametrization. The CPV preferences are stable for different prior distributions (flat in δ_{CP} or in $\sin\delta_{CP}$) and the conclusions from the δ_{CP} fits remain valid also for these analyses.

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Summarizing, if the hypothesis of inverted ordering is true, both experiments show consistent preference for the δ_{CP} to be in the $3\pi/2(-\pi/2)$ region, but in the other case, there is some tension between them. However, one has to remember that current results are statistically limited and no strong conclusions should be drawn.

T2K and NOvA collaborations decided to perform a joint oscillation analysis, the results of which are expected very soon. Both experiments also continue to analyse their data separately, and new results with increased statistics are expected in 2024.

Both experiments will continue to take data during the next few years and also upgrade their experimental setup to reach the 3σ sensitivity for CPV (T2K) and mass ordering (NOvA). The beam power will be increased (to over 900 kW for NOvA and 750 kW and later 1.3 MW for T2K). It was already mentioned that T2K far detector, SK, is now doped with salts of Gadolinium (allowing to detect the presence of neutrons in an event), but also the near detector ND280 is undergoing a significant upgrade. The π^0 detector is replaced with a new scintillator detector called SuperFGD sandwiched horizontally between two new High Angle TPCs. The system will be surrounded by Time-Of-Flight planes. Such a configuration will significantly increase the angular acceptance, and the detection threshold will be much lower [28].

4.4 Future projects: Hyper-Kamiokande and DUNE

T2K and NOvA will continue to run over several years. In the future, two more long baseline experiments are planned: DUNE in the US [29] and Hyper-Kamiokande in Japan [30].

The megawatt-class neutrino beam for DUNE will be produced at Fermilab. The beam will have a broad spectrum of the order of a few GeV, covering the full oscillation period (first and second oscillation maxima) in order to help in breaking the degeneracy between matter effects and CP violation. The far detector station, located at a distance of 1300 km, will consist of four 17-kton detector modules (in total, over 40 kton of fiducial mass), large time projection chambers filled with liquid argon (LAr). The experiment will also utilize a set of near detectors, including movable and on-axis ones.

In phase I, the experiment will run with a beam power of 1.2 MW and two far detector modules, while several years later, in phase II the power will be increased to over 2 MW, and two additional modules will be installed. There is also a plan to upgrade the near detectors.

The Hyper-Kamiokande project will be a successor of SK, using the same known technology of water Cherenkov detectors. The water tank with a fiducial mass of 186 kton will be instrumented with improved photomultipliers, having better photon efficiency and timing resolution than those used in SK. The detector will be located at the same baseline and off-axis angle as SK in the T2K experiment.

Apart from using the upgraded ND280 of T2K experiment (further upgrades are in considerations), the plan is to add an intermediate water Cherenkov detector at a distance of 1-2 km to improve the systematic error suppression. The detector would be movable, thus able to measure the beam neutrinos at different off-axis angles.

The beam will be produced in J-PARC using the same beamline as for T2K, but with a megawatt-class beam and stronger focusing in the magnetic horns.

Thanks to its large baseline, DUNE will be able to determine the mass ordering with over 5σ already during phase I (within 2 years). The exact sensitivity depends on the true values of δ_{CP} and is highest for the maximal violation, suggested by T2K results. The improvement is also expected for the determination of θ_{23} octant.

If mass ordering is known, Hyper-Kamiokande has excellent sensitivity to CP violation. It will be able to exclude CP conservation within 2-3 years, if the true value $\delta_{CP} = -\pi/2$. If mass ordering would be still unknown, the combination of atmospheric and beam neutrinos will help to determine it.

After 10 years of operation 5σ sensitivity should be obtained for 50% of δ_{CP} values in DUNE and 60% in Hyper-Kamiokande.

4.5 Effort to suppress systematic errors

The new experiments are expected to gather much more events, so better control of the systematic uncertainties becomes more and more crucial. In particular, it is important to improve the knowledge of ν_e cross-section, nuclear initial state, final state interactions.

A lot of cross-section measurements are already underway or planned: performed by long-baseline near detectors (including movable near detectors in DUNE and HK), MINERvA, MicroBooNE. The measurement of the transverse kinematic imbalance variables seems very promising in providing direct constraints on nuclear effects, as discussed in [31].

As for the improvement of the beam-related uncertainties, the measurements of the hadron production, in particular with replica targets, are very valuable (i.e. NA61/SHINE measurements). Also, there is ongoing effort on new concepts for neutrino beams (ESSnuSB [32], nuSTORM [33]); and monitored/tagged beams (ENUBET [34], NuTAG [35]). Finally, there are new developments in future neutrino detectors (LiquidO [36], Theia [37]), with improved performance and energy resolutions.

5. Sterile neutrinos

The sterile neutrinos hypothesis was introduced to explain existing experimental results that did not fit the 3-flavours oscillation framework. Several short baseline beam and reactor experiments observed signals suggesting the existence of the oscillations with Δm^2 of the order of 1 eV^2.

The anomalies and the recent results from ongoing experiments aiming at the discovery of sterile neutrinos are presented below.

5.1 Reactor Antineutrino Anomaly (RAA)

Reactor Antineutrino Anomaly (RAA) is the deficit of measured $\bar{\nu}_e$ compared to reactor flux prediction. In 2011, when the experiments designed for θ_{13} measurements were built, an effort was made to produce a new flux prediction, which turned out to be about 5% higher than previous estimations and fluxes measured by earlier reactor experiments. The discrepancy was at the level of approximately 3σ.

The methods and improvements in reactor flux modelling are nicely summarized in [38]. The authors compare various predictions with numerous measurements of the evolution of the antineutrino rate with the fuel composition performed by Daya Bay and other reactor experiments in the last few years. They showed that those data disfavour models with higher flux predictions;

thus the significance of RAA was reduced to about 1.1σ. The best models are compatible with no oscillations at short baselines.

5.2 Gallium anomaly

The gallium anomaly is related to ν_e event rates from ^{51}Cr and ^{37}Ar sources used to calibrate solar neutrino detectors filled with gallium, which were found to be smaller than expected. The significance of this effect was at the level of 2.9σ.

In 2022, the BEST (Baksan Experiment on Sterile Transitions) experiment announced the results of the measurements of neutrino flux from a 3.4 MCi ^{51}Cr source in two nested volumes of gallium. The deficit of ν_e was found to be over 5σ, however, no L/E measurement was done [39].

If the effect observed by BEST is due to oscillations, such a strong signal would imply large mixing. This is, however, contrary to the results from reactor experiments, which disfavour the parameter region allowed by theGallium anomaly, and to the solar upper bound. The region of high values of Δm^2_{41} is also in strong tension with cosmology limits and disfavoured by the KATRIN experiment [40].

5.3 LSND and MiniBooNE

The anomalous signals observed in LSND and MiniBooNE experiments are related to (anti)ν_e appearance in (anti)ν_μ beam and their significance is 3.8σ and 4.8σ, respectively.

There were several hypotheses trying to explain the Low Energy Excess (LEE) observed by MiniBooNE, like the wrong modelling of rare NC Δ radiative decay ($\Delta \to N\gamma$).

The MicroBooNE experiment, based on LAr TPC technology, is part of the multi-detector facility using the same neutrino beam produced by Booster at Fermilab. MicroBooNE performed four independent studies of possible LEE origin: three with assumptions of electrons from ν_e interactions and different hadronic final states; and one with the hypothesis of photons from Δ radiative decay. The results reject electrons as the sole LEE explanation at $> 97\%$ C.L. [41] and disfavour Δ radiative decay as a sole source of LEE at 94.8% C.L. [42].

The data from the inclusive electron search were used to test the (3+1) sterile neutrino hypothesis, but no evidence of sterile neutrino oscillation was found [43].

The Short-Baseline Neutrino Program in Fermilab is still developing. The detector closest to the neutrino source, SBND, is expected to start data taking early next year, while the most distant one, ICARUS, is already collecting data. In the future, multi-detector oscillation analyses are expected to be performed, which should shed more light on the problem of sterile neutrinos.

6. Summary

Neutrino physics entered the era of precise measurements. Most parameters are known with a precision of a few %. Therefore, controlling the systematic uncertainties becomes crucial. There are many efforts to suppress the systematic effects, like cross-section measurements, using movable near detectors in LBL experiments, new detection techniques and concepts of controlled beams.

The unknowns in neutrino physics are targeted by many experiments, utilizing natural and artificial sources of neutrinos and various detectors. Also, joint analyses between experiments are performed.

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Many planned experiments are already under construction and are supposed to start collecting data before 2030. The ongoing and planned efforts allow to hope that at least some of the pending questions will find answers in the next decade.

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References

[1] Y. Fukuda et al. (Super-Kamiokande), Phys. Rev. Lett. 81, 1562 (1998).

[2] Q.R. Ahmad et al. (SNO), Phys. Rev. Lett. 87, 071301 (2001).

[3] Z. Maki, M. Nagakawa and S. Sakata, Prog. Theor. Phys. 28, 870 (1962).

[4] B. Aharmim et al. (SNO), Phys. Rev. C72, 055502 (2005).

[5] K. Abe et al. (Super-Kamiokande), Phys. Rev. D 94, 052010 (2016).

[6] A. Gando et al. (KamLAND), Phys. Rev. D88, 3, 033001 (2013).

[7] K. Abe et al. (Super-Kamiokande), Phys. Rev. D 97, 072001 (2018).

[8] M.G. Aartsen et al. (IceCube), Phys. Rev. Lett. 120, 071801 (2018).

[9] K. Abe et al. (T2K), Phys. Rev. D 103, 112008 (2021).

[10] P. Adamson et al. (MINOS), Phys. Rev. Lett. 125, 131802 (2020).

[11] M.A. Acero et al. (NOvA), Phys. Rev. D 106, 032004 (2022).

[12] Particle Data Group, PTEP 2022, 083C01 (2022).

[13] M. Apollonio et al. (CHOOZ), Eur. Phys. J. C27 331 (2003).

[14] K. Abe et al. (T2K), Phys. Rev. Lett. 107, 041801 (2011).

[15] F.P. An et al. (Daya Bay), Phys. Rev. Lett. 108, 171803 (2012).

[16] J.K. Ahn et al. (RENO), Phys. Rev. Lett. 108, 191802 (2012).

[17] F.P. An et al. (Daya Bay), Phys. Rev. Lett. 130, 161802 (2023).

[18] F. An et al. (JUNO), J. Phys. G43:030401 (2016).

[19] L. Wolfenstein, Phys. Rev. D 17, 2369 (1978); S.P. Mikheyev and A.Y. Smirnov, Sov. J. Nucl. Phys. 42, 913 (1985).

[20] K. Abe et al. (Super-Kamiokande), Nucl. Instrum. Meth. A 1027, 166248 (2022).

[21] M. Posiadała-Zezula, PoS ICHEP2022 573 (2022).

[22] R. Abbasi et al. (IceCube), Phys. Rev. D 108, 012014 (2023).

[23] S. Yu, J. Micallef, PoS ICRC2023 1143 (2023).

[24] L. Nauta et al., PoS ICRC2021 1123 (2022).

[25] K. Abe et al. (T2K), Nucl. Inst. Meth. A 659, 106 (2011).

[26] K. Skwarczyński, PoS ICHEP2022 606 (2022).

[27] M.A. Acero et al. (NOvA), Phys. Rev. D 106, 032004 (2022).

[28] K. Abe et al. (T2K), *T2K ND280 Upgrade - Technical Design Report*, arXiv:1901.03750 [physics.ins-det].

[29] B. Abi et al. (DUNE), Eur. Phys. J. C 80, 978 (2020).

[30] K. Abe et al. (Hyper-Kamiokande), arXiv: 1805.04163 [physics.ins-det].

[31] X-G. Lu et al., Phys. Rev. C 94, 015503 (2016).

[32] A. Alekou et al., Eur. Phys. J. ST. 231, 3779 (2022).

[33] L. Alvarez Ruso et al., arXiv:2203.07545.

[34] A. Longhin, L. Ludovici, F. Terranova, Eur. Phys. J. C 75 155 (2015); arXiv:2308.09402.

[35] M. Perrin-Terrin, Eur. Phys. J. C 82, 465 (2022).

[36] LiquidO Consortium, Nature Com.Phys. 4, 273 (2021).

[37] M. Askins et al., Eur. Phys. J. C 80, 416 (2020).

[38] C. Giunti, Y.F. Li, C.A. Ternes, Z. Xin, Phys, Lett. B 829, 137054 (2022).

[39] V.V. Barinov et al., Phys. Rev. Lett. 128, 232501 (2022); V.V. Barinov et al., Phys. Rev. C 105, 065502 (2022).

[40] M. Aker et al. (KATRIN), Phys. Rev. D 105, 072004 (2022).

[41] P. Abratenko et al. (MicroBooNE), Phys. Rev. Lett. 128, 241801 (2022).

[42] P. Abratenko et al. (MicroBooNE), Phys. Rev. Lett. 128, 111801 (2022).

[43] P. Abratenko et al. (MicroBooNE), Phys. Rev. Lett. 130, 011801 (2023).