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CURRENT AND FUTURE NEUTRINO EXPERIMENTS*

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The article presents a review of selected results from neutrino experiments, concerning the mass measurements and studies of neutrino oscillations with various neutrino sources. Some of the projects planned to start in the near future are also presented.

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1. Introduction

Since the discovery of the neutrino oscillations in 1998 [1], many of the parameters appearing in the neutrino mixing matrix have been measured. Some of them are known with quite high precision like θ_{13}, but the other need better measurements. There are also still questions, for which only some hints exist.

The oscillation probabilities depend also on the mass squared differences, which can be measured in the oscillation experiments, but the absolute neutrino mass scale has to be determined in a different kind of experiments. Additionally, it is still not known which of the neutrino mass states is the heaviest one: ν_3 (so-called "normal mass hierarchy", NH) or ν_2 ("inverted mass hierarchy", IH). This, however, can be found in the oscillation experiments thanks to the existence of the effects related to an extra interaction experienced by the electron neutrino component in the passage through matter, which modifies the oscillation probabilities and is sensitive to the mass hierarchy.

The violation of the CP symmetry in the lepton sector is a very important question. There are some hints on the value of the CP violation phase coming from the T2K experiment [2] but the statistical significance is still small. There are also additional phases in the neutrino mixing matrix if neutrinos are Majorana particles. Those phases do not affect oscillation probabilities but the nature of the neutrinos can be determined if the neutrinoless double beta ($0\nu\beta\beta$) decay would be found in dedicated experiments.

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Finally, there are some experimental signals, which may suggest the existence of so-called sterile neutrinos — the hypothetical neutrinos which do not couple to $W^{\pm}$ and Z^0 bosons. Still, they should affect the oscillations as the mixing between active and sterile neutrinos may occur. There are many ongoing projects aimed at the discovery of the sterile neutrinos.

The current best-fit values of the oscillation parameters are summarized in Table I and the following sections present selected experiments which published their results in the last year or are planned in the future.

TABLE I

The best-fit values of the oscillation parameters obtained from a global fit to the current neutrino oscillation data (taken from [3]).

Parameter	Best-fit value
Δm^2_{21}	7.37×10^{-5} eV$^2/c^4$
Δm^2_{31} (NH)	2.56×10^{-3} eV$^2/c^4$
Δm^2_{23} (IH)	2.54×10^{-3} eV$^2/c^4$
$\sin^2\theta_{12}$	0.287
$\sin^2\theta_{23}$ (NH)	0.425
$\sin^2\theta_{23}$ (IH)	0.589
$\sin^2\theta_{13}$ (NH)	0.0215
$\sin^2\theta_{13}$ (IH)	0.0216
δ_{CP} (NH)	1.38π
δ_{CP} (IH)	1.31π

2. Non-oscillation experiments

2.1. Direct mass measurements in KATRIN

The absolute scale of neutrino masses can be obtained by the observation of the electron spectrum in the beta decay (or electron capture) of nuclei, neutrinoless double beta decay or from the cosmological observations [4]. Each of those methods provides different observable: the incoherent sum of neutrino masses $m^2_\beta = \sum_i |U_{ei}|^2 m^2_i$, the coherent sum $m^2_{\beta\beta} = |\sum_i U_{ei} m_i|^2$, and the sum $\sum_i m_i$, respectively, where i goes over the light neutrino mass eigenstates. However, the two latter methods are strongly model-dependent, as opposed to the measurement of the electron spectrum in the beta decay.

The information about the neutrino mass can be extracted from the observation of the endpoint of the β electron spectrum, where the rate of events is extremely small. Therefore, one needs to use a high activity radioactive source and a detector with excellent energy resolution.

In 2018, a new experiment will start taking data with the tritium source. KATRIN (Karlsruhe Tritium Neutrino) will use the magnetic adiabatic collimation with an electrostatic filter (MAC-E filter). The gaseous molecular tritium source of the activity of 170 GBq will be located in the solenoidal magnetic field of 3.6 T. The β electrons, emitted isotropically, will be transformed into a beam and transported to the region of low magnetic field, while their momentum components perpendicular to the field will be adiabatically converted to parallel motion, as shown in Fig. 1. A system of cylindrical electrodes is located in the low field volume (main spectrometer, 10 m in diameter), creating the electrostatic retarding potential, which can be passed only by the electrons with the energies over certain threshold, while all others are reflected. The electrons which crossed the barrier are reaccelerated, refocused and counted on the other side of the spectrometer. KATRIN can thus measure the β spectrum in an integrating mode by varying the retarding potential.

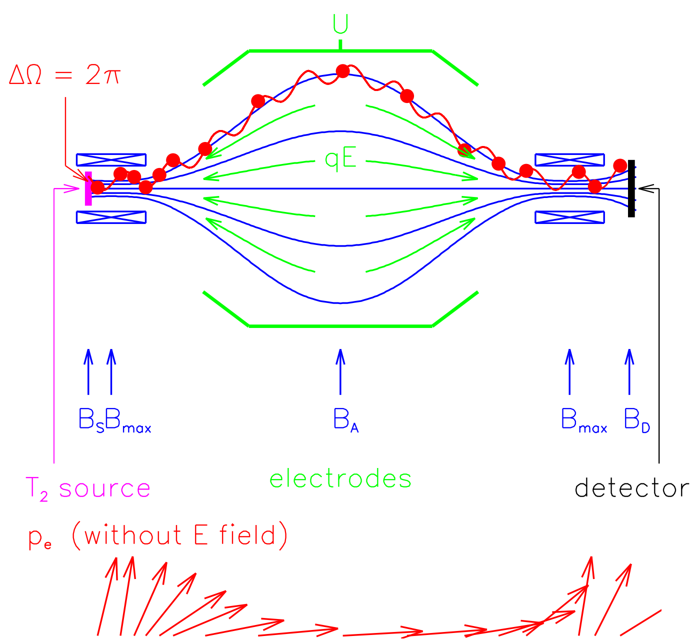

Fig. 1. The principle of the MAC-E filter. The upper drawing shows the experimental setup and the bottom one the momentum transformation. Image taken from [5].

The expected sensitivity to neutrino mass is 0.2 eV$/c^2$ after three years of data taking. KATRIN is able to measure the mass with precision of 5σ if it is above 0.35 eV$/c^2$. Further increase in the sensitivity requires much larger spectrometers, therefore there are several proposed methods to measure the β electron energy, such as using the cyclotron radiation emission spectroscopy in PROJECT 8 [6] or the calorimetric measurements with holmium-163 source (ECHO, HOLMES, NuMECS) [7].

2.2. Search for neutrinoless double beta decay in GERDA

The neutrinoless double beta decay ($0\nu\beta\beta$) is allowed only if neutrinos are Majorana particles and the lepton number is not conserved

$$(A,Z) \rightarrow (A,Z+2) + 2e^- \,.$$

The (A,Z) isotope half-life of $0\nu\beta\beta$ decay is related to the $m_{\beta\beta}$ through the following relation:

$$\left(T_{1/2}\right)^{-1} = G g_{\mathrm{A}}^4 \left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2 \,,$$

where G is the two-body phase-space factor, known with good accuracy, M means the nuclear matrix element, having large uncertainties, and g_{A} is the axial coupling constant of the nucleon.

There are many experiments using the decays of various candidate isotopes (such as ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe) and with various experimental techniques. In this paper, one of the most precise recent results reported by GERDA experiment will be presented [8].

The GERDA experiment uses two types of germanium detectors directly immersed in an active liquid argon shield. The germanium monocrystals are enriched in ^{76}Ge isotope to about 87%, and the total mass of germanium is currently about 36 kg. In such a configuration, the radioactive source is simultaneously the detector improving greatly the efficiency. The cryostat is placed inside the water tank which provides the passive shield. The veto system is completed by the plastic scintillator panels. The experiment is located in the underground Gran Sasso laboratory.

The sum of the daughter electron energies, corresponding to the mass difference of the parent and daughter nuclei, is measured and reconstructed. If the $0\nu\beta\beta$ decay occurs, it will be visible as a peak at the end of the spectrum for double beta decays with neutrinos ($2\nu\beta\beta$). For germanium-76, the energy region where the signal is expected is 2039 keV.

In 2017, GERDA published the results obtained for data from phase I+IIa (total exposure of 34.4 kg yr), showing the limit for the $0\nu\beta\beta$ half-life $T_{1/2} > 5.3 \times 10^{25}$ yr (90% C.L.). For nuclear matrix elements range 2.8–6.1, such a limit can be converted to the limit for the mass $m_{\beta\beta}$ <0.15–0.33 eV$/c^2$.

New preliminary results for the total exposure of 46.7 kg yr were shown in TAUP 2017 conference and the corresponding limits are: $T_{1/2} > 8.0 \times 10^{25}$ yr and $m_{\beta\beta}$ <0.12–0.27 eV$/c^2$ (90% C.L.) [9].

GERDA continues to take data and the expected limit to be reached in the mid of 2018 is $T_{1/2} = 10^{26}$ years (if no signal will be observed). For the future, there are plans for a ton-scale experiment using germanium-76 which could reach the sensitivity of 10^{28} years and $m_{\beta\beta}$ range of 10–20 meV/c^2 [10].

3. Reactor neutrino experiments in China

The reactor antineutrinos are emitted in large numbers from the β decays of the products of nuclear fission. The energies of such antineutrinos are of the order of few MeV. The detection is performed via the inverse beta decay

$$\bar{\nu}_e + p \to e^+ + n \,,$$

after which the positron quickly annihilates and the neutron can be captured by a nucleus. In the detection process, the coincidence between the prompt signal of positron annihilation and delayed signal from the deexcitation of the nucleus after neutron capture is used to select the signal events.

Historically, the detection of reactor neutrinos proved the existence of those particles [11]. More recently, they were used for the precise measurement of the θ_{13} mixing angle. Although the first hint that the last unmeasured mixing angle is not zero came in 2011 from the long-baseline experiment T2K [12], the 5σ confirmation was done by the Daya Bay Collaboration [13] followed by other reactor experiment RENO [14].

The Daya Bay experiment is located in China. Six commercial nuclear reactors produce intensive flux of antineutrinos, measured by detectors inside three underground halls. Each of two near stations (about 400 m from the nearest reactor) contains two identical liquid scintillator detectors doped with gadolinium and four such detectors are located in the far station at the distance of about 1.5 km. Using the near and far detectors allows to compare the measured antineutrino rates at different baselines and suppress the correlated uncertainties.

In 2017, Daya Bay published results of the 1230 days of data-taking. Using over 2.5 million events, they obtained the most precise measurement of the θ_{13} angle: $\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(\text{stat.}) \pm 0.0019(\text{syst.})$ [15]. The measured survival probability of the electron antineutrinos is shown in Fig. 2.

The reactor neutrinos can be also used to determine the mass hierarchy. The formula for the electron oscillation survival probability depends on both Δm^2_{31} and Δm^2_{32}, therefore the oscillation pattern is slightly different for normal and inverted hierarchy hypotheses. An experiment planned to determine the mass hierarchy, called JUNO, is planned to start in 2020 in China [16].

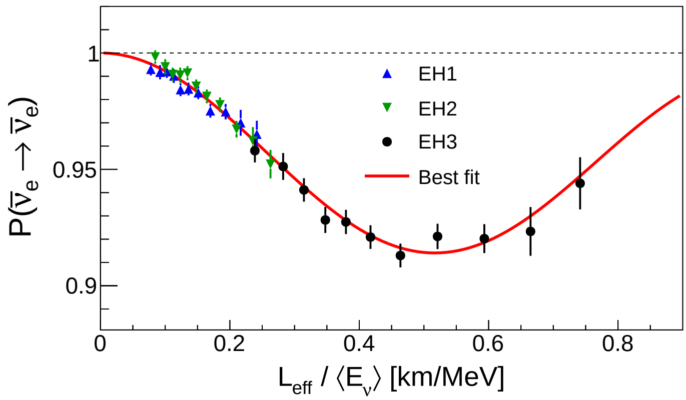

Fig. 2. The probability of the $\bar{\nu}_e$ survival as a function of the effective propagation distance $L_{\rm eff}$ over the average neutrino energy, measured in the Daya Bay experiment. EH1, EH2 and EH3 denote the results obtained from the detectors located in two near and one far hall, respectively. Image taken from [15].

JUNO will have the active mass of 20 kton of liquid scintillator, observed by two independent photomultiplier systems. The neutrinos will come from two nuclear power plants (10 cores in total) at the distance of 53 km. In order to observe the subtle effect of mass hierarchy, the experiment has to obtain 3% energy resolution at 1 MeV. JUNO plans to reach 3σ sensitivity for the mass hierarchy determination after 6 years of data-taking and provide also the measurements of Δm^2_{21} and $\sin^2\theta_{12}$ with precision better than 1%.

4. Observations of solar neutrinos

The solar neutrinos are the electron neutrinos produced in the fusion reactions in the Sun. Depending on particular nuclear reaction, the various contributions to the total solar neutrinos flux can have continuous or monoenergetic spectrum, but they are all of the order of few MeV. There are various techniques used in the detection of solar neutrinos, which have different energy threshold, such as radiochemical method, Cherenkov or scintillation light.

The deficit of solar neutrinos measured on Earth was observed since 60s and explained by the SNO experiment [17], which measured the flux of neutrinos of all flavours, while the previous experiments measured mainly the electron neutrino component. The deficit of electron neutrinos can be explained with the resonant flavour transition in the dense matter of the Sun due to the Mikheyev–Smirnov–Wolfenstein (MSW) effect [18].

For solar neutrinos, the resonant enhancement of neutrino mixing in solar matter is expected to happen for energies above 5 MeV, while the vacuum oscillations dominate below 1 MeV. Therefore, it is interesting to perform the full spectroscopy of solar neutrinos to observe both regimes and the transition region.

Such a measurement was done by the Borexino experiment located in underground Gran Sasso laboratory. Borexino observed the elastic scattering of neutrinos on electrons in liquid scintillator. The detector contains 270 ton of organic scintillator (100 ton of fiducial mass) shielded by 1000 tons of liquid buffer. The experiment has low threshold of about 70 keV, ultra-low radioactive background and excellent background control and simulation.

The Borexino experiment observed the flux of ^{8}B neutrinos and also detected for the first time the ^{7}Be and *pep* neutrinos, as well as *pp* neutrinos, providing almost full solar neutrino spectroscopy. The ν_e survival probability obtained by Borexino is shown in Fig. 3 verifying the MSW pattern.

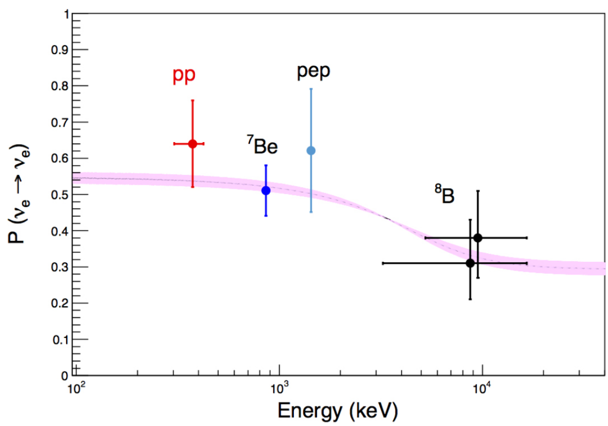

Fig. 3. (Colour on-line) Electron neutrino survival probability measured in Borexino for various solar neutrino flux components. The grey/pink band denotes the MSW predictions. Image taken from [19].

Borexino searches also for neutrinos produced in CNO solar cycle, which may provide information about the metallicity of the Sun.

The effect of matter can be observed also for neutrinos passing through the Earth as the day–night asymmetry. For the density of Earth, the so-called regeneration of electron neutrino component is expected for energies above 7 MeV, where the ^{8}B flux component dominates. In fact, a 3.3% day–night asymmetry for ^{8}B neutrinos was observed in water Cherenkov detector Super-Kamiokande (with 2.0σ significance) [20], while Borexino found no asymmetry for lower energy ^{7}Be neutrinos [21], confirming the hypothesis of matter effects.

5. Atmospheric neutrino studies

The atmospheric neutrinos originate mostly from the decays of pions produced in the collisions of high-energy primary cosmic rays with the atmosphere. Also some of the daughter muons decay in the atmosphere, producing the component of electron (anti)neutrinos. The energy range of atmospheric neutrinos is wide, from sub-GeV to TeV.

Most of the atmospheric neutrino experiments are water Cherenkov detectors, where the Cherenkov light produced by the daughter charged lepton and/or pions emerging from the neutrino interaction is detected by photomultipliers. The distance between the neutrino production and detection point (baseline) can be determined with quite good accuracy from the direction of the charged lepton.

The most famous among the atmospheric neutrino experiments is Super-Kamiokande, a huge detector located in Japan which discovered the neutrino oscillations in 1998 [1]. Super-Kamiokande (SK) is a cylindrical water tank containing 50 ktons of ultra-pure water (fiducial mass 22.5 kton) observed by over 11 000 photomultipliers. The detector has the capability to separate μ-like and e-like events using the properties of the Cherenkov ring and its energy resolution is at the level of about 10% for two-body kinematics.

Since the discovery of neutrino oscillations, the detector is still taking data and producing results. SK performs the measurements of the oscillation parameters $|\Delta m^2_{32}|$ and θ_{23}, studies of the solar neutrino flux and search for dark matter and proton decay. SK looks also for the ν_τ appearance in atmospheric neutrino oscillations. Although the direct observation of τ lepton is not possible in SK, the advanced statistical analysis with neural network was performed for upward direction events, where the contribution from ν_τ events is expected, looking for the hadronic decays of τ. The no-τ-appearance hypothesis has been excluded with 4.6σ statistical significance [22]. The result is dominated by statistical uncertainty, so it will probably be improved when more data are collected.

Thanks to the matter effects in Earth, the atmospheric neutrinos can also be used for determination of the mass hierarchy. In this case, in the region of 6–12 GeV, the oscillations are expected to be enhanced for neutrinos in case of normal hierarchy (for antineutrinos in case of inverted hierarchy) producing strong alteration of the oscillation pattern both for ν_μ and ν_e event samples.

There are two neutrino detectors which are planning to look for this effect and both of them will use a natural medium: ice or sea water.

The IceCube detector is located at the South Pole and was primarily designed to observe ultra-high energy neutrinos from the space in the energy range from 100 GeV till 10 PeV. It uses downward-looking photomultipliers enclosed in glass spheres and deployed on strings into holes in the ice, 1.5–2.5 km deep. For the observations of atmospheric neutrinos, a region of ice called DeepCore was more densely instrumented, lowering the threshold to about 10 GeV, which allowed to provide the measurement of oscillation parameters $|\Delta m^2_{32}|$ and θ_{23} [23] (see Fig. 4). For the determination of mass hierarchy, more strings with photomultiplier modules will be added in the core (PINGU project with threshold below 5 GeV [24]), starting in 2018 and planned to be completed after 4 years.

The sea water will serve as a medium in ORCA detector (Oscillation Research with Cosmics in the Abyss), a part of the KM3NeT project in the depths of Mediterranean Sea [25]. ORCA will be a dense array of multi-photomultiplier digital modules, able to observe atmospheric neutrinos. The completion is expected in 2020. Depending on the true values of the oscillation parameters, both experiments claim to be able to determine the mass hierarchy with 3σ significance within 3 (ORCA) or 4 (PINGU) years of data-taking.

6. Long-baseline experiments in Japan and the US

The long-baseline experiments utilize neutrino beams created at the accelerators. A beam of high-energy protons hits a target producing large numbers of pions and kaons, which are focused by magnetic horns and directed into a decay volume. Usually, the horns can focus positive or negative mesons, resulting in neutrino or antineutrino beam, respectively. Such a beam consists mostly of muon (anti)neutrinos from pion decays, contaminated with some percent of electron (anti)neutrinos from decays of kaons and secondary muons.

Currently, there are two experiments using neutrino beams, namely T2K in Japan and NOvA in the US. Both of them use the so-called off-axis beam, which means that the beam axis is directed few miliradians away from the far detectors. Thanks to the kinematics of pion decay, such configurations allow to obtain quasi-monochromatic beam and tune the peak energy to the region where the expected oscillation effect is maximal for a given baseline. The comparison of the properties of both experiments is shown in Table II.

T2K experiment started to take data in 2010. The beam is produced in the J-PARC laboratory on the eastern shore of Japan and directed towards Super-Kamiokande detector 295 km away. 280 m from the target a set of near detectors is located. One of the near detector, called INGRID, is placed on-axis and measures the intensity, position and profile of the beam. The off-axis detector, called ND280, is a multipurpose detector with magnetic field, allowing to measure precisely various final states of neutrino interactions. The data collected in ND280 are used for the tuning of the parametrized models used in the simulations of neutrino beam and interactions, thus allowing for great suppression of related systematic uncertainties.

TABLE II

Basic information on T2K and NOvA experiments.

	T2K	NOvA
Baseline	295 km	810 km
Off-axis angle	2.5°	0.84°
Peak energy	≈ 600 MeV	≈ 2 GeV
Far detector mass	50 kton	14 kton
(Fiducial)	22.5 kton	10.3 kton

The events selected in the far detector are one-ring fully contained events, enriched with charged current quasi-elastic interactions, for which the neutrino energy can be reconstructed from the kinematics of the daughter charged lepton (under assumption of no Fermi motion of the target nucleon). In the oscillation analysis, four such samples are used: ν_μ and ν_e for data taken with neutrino beam, and $\bar{\nu}_\mu$ and $\bar{\nu}_e$ for antineutrino data. Recently, an additional sample with a pion produced in charged current ν_e interaction was included in the analysis. All the samples are used in a simultaneous fit to obtain the values of θ_{23}, $|\Delta m^2_{32}|$, θ_{13} and δ_{CP}.

T2K provided the most precise measurement of θ_{23} mixing angle. The 90% C.L. allowed region for oscillation parameters $\sin^2\theta_{23}$ and $|\Delta m^2_{32}|$ is shown in Fig. 4 together with the values obtained from atmospheric and other long-baseline experiments.

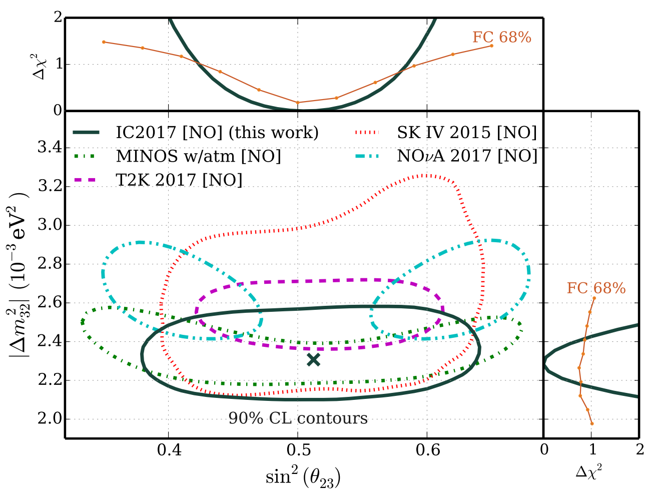

Fig. 4. Allowed regions for oscillation parameters $\sin^2\theta_{23}$ and $|\Delta m^2_{32}|$ obtained in atmospheric and long-baseline experiments. Image taken from [23].

The newest results from T2K were shown in summer 2017 for doubled data statistics for neutrino beam and improved data analysis [26]. Using the reactor constraints on θ_{13} the allowed region for δ_{CP} has been restricted to $[-171°; -34°]$ ($[-88°; -68°]$) at 95% C.L. (see Fig. 5) and the CP-conservation hypothesis is excluded at 2σ level. The T2K data also slightly prefer the normal mass hierarchy and the upper octant of θ_{23}.

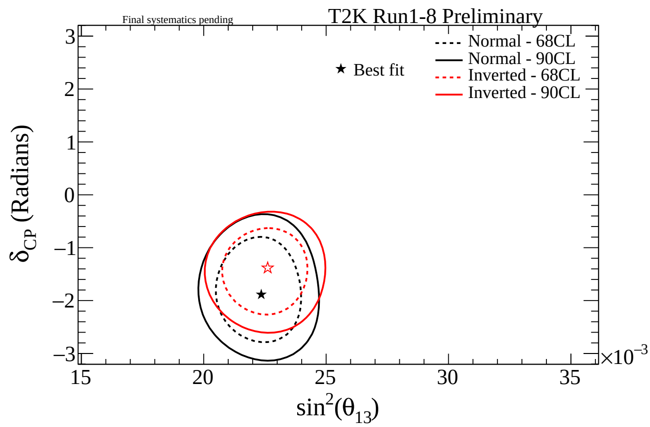

Fig. 5. Allowed regions for oscillation parameters $\sin^2\theta_{13}$ and δ_{CP} obtained in T2K experiment with the reactor constraints included. Image taken from [26].

The NOvA experiment is located in the US. The neutrino beam is produced in Fermilab and the far detector is placed at the distance of 810 km. The near and far detectors are built in the same technology: extruded plastic cells filled with oil and liquid scintillator with the read-out provided by wavelength-shifting fibers and avalanche photodiodes. The neutrino energy is estimated from the lepton track length and visible hadronic energy. The selection of ν_e events is based on the computer vision and deep learning methods.

From the spectrum measured in the near detector, the true neutrino energy distribution is estimated. It is then multiplied by far-to-near ratio and oscillation probability. The predicted true energy distribution in the far detector is then converted into the reconstructed energy spectrum and compared to data. To observe ν_e appearance, the near detector candidates are used to predict the background from the intrinsic ν_e beam component and any excess over the prediction is interpreted as ν_e appearance.

In 2016, NOvA announced the results for ν_μ disappearance where the maximal mixing was rejected with 2.6σ significance [27]. However, in January 2018, new results were shown, obtained for 50% more data and many improvements in the analysis, including the neutrino interactions modelling, detector simulation and joint fit of ν_μ and ν_e event samples. The new analysis prefers nearly maximal mixing and is much more consistent with other experiments [28].

The analysis of ν_e appearance with the constraints from reactor experiments and from ν_μ disappearance data allowed to reject the combination of inverted mass hierarchy and lower octant of θ_{23} for all values of $\delta_{\rm CP}$ with over 93% C.L. [29]. The allowed regions for $\sin^2\theta_{23}$ and $\delta_{\rm CP}$ are shown in Fig. 6.

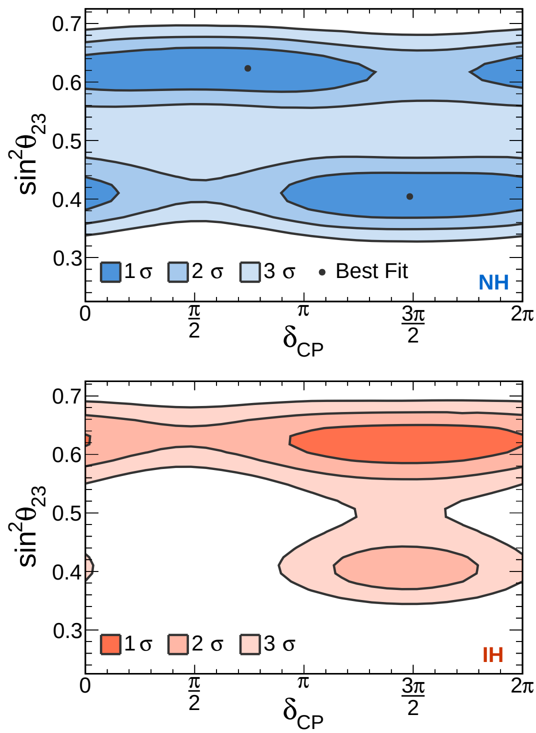

Fig. 6. Allowed regions for oscillation parameters $\sin^2\theta_{23}$ and $\delta_{\rm CP}$ obtained in NOvA experiment for normal (top) and inverted (bottom) mass hierarchy hypotheses. Reactor constraint on $\sin^2\theta_{13}$ is included. Image taken from [29].

T2K and NOvA will continue to run over next several years, collecting data with neutrino and antineutrino beams. Taking into account the planned exposure and detector improvements planned in T2K, they can have up to 3σ sensitivity for rejection of CP conservation hypothesis. In the future, two more long-baseline experiments are planned, which are designed to reach 5σ sensitivity: DUNE in the US [30] and Hyper-Kamiokande in Japan [31].

DUNE will be a large liquid argon (LAr) time projection chamber. LAr is a dense target for neutrino interactions, providing ionization and scintillation signal. The technique allows for particle identification based on energy loss and range, in particular for excellent photon/electron separation.

The megawatt-class neutrino beam for DUNE will be produced in Fermilab. The beam will have broad spectrum of the order of few GeV, covering the first and second oscillation maxima in order to help in breaking the degeneracy between matter effects and CP violation. The far detector station, consisting of four 17-kton detectors (over 40 kton of fiducial mass) will be located at the distance of 1300 km.

The detector installation is expected in 2021 and the start of physics run in 2024 with 20 kton of LAr. The beam will be ready in 2026. The 770 ton LAr ProtoDUNE prototypes are now under construction at CERN and will be tested on beam in 2018.

The Hyper-Kamiokande project will be a successor of SK, using the known technology of water Cherenkov detectors. Two vertical tanks of fiducial mass of 190 kton each will be instrumented with improved photomultipliers, having twice better photon efficiency and timing resolution than those currently used in SK. The detectors will be located close to SK, at the same baseline and off-axis angle as SK in T2K experiment. There is also a proposal to locate one of the tanks in Korea, to extend the baseline and sensitivity to matter effects. Another possible extension is to add an intermediate water Cherenkov detector at the distance of 1–2 km to improve the systematic errors suppression.

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

7. Search for sterile neutrinos

The sterile neutrinos were introduced to explain some experimental results, which did not fit to 3-flavours oscillation framework. The observations of several short-baseline beam and reactor experiments suggested the existence of the oscillations with Δm^2 much higher (of the order of 1 eV^2/c^4) than measured for solar and atmospheric neutrinos .

Sterile neutrinos cannot be observed by interactions, but they affect the oscillations through mixing. There are many ongoing projects aiming at the discovery of sterile neutrinos, but most of them showed no signal of sterile neutrinos up to now (see, for example, [32]). In particular, the lower than predicted number of $\bar{\nu}_e$ events seen in reactor experiments can be probably explained by the wrong modelling of reactor fuel evolution [33].

One of the experiments planned for the close future is CeSOX [34]. It will use the Borexino detector and PBq radioactive source. The source will be placed under the detector and emit the electron antineutrinos from the beta decay chain of ^{144}Ce–^{144}Pr which will be detected via inverse beta decay reaction. If the sterile neutrinos exist, the expected oscillation length for the $\Delta m^2 \approx 1$ eV$^2/c^4$ is smaller than the detector size (about 7 m) and larger than its spatial resolution (about 15 cm). Therefore, the very short-baseline oscillations can be measured using two different method: the distortion of the energy spectrum and the interaction rate as the function of the distance from the source $L_{\rm rec}$ as shown in Fig. 7.

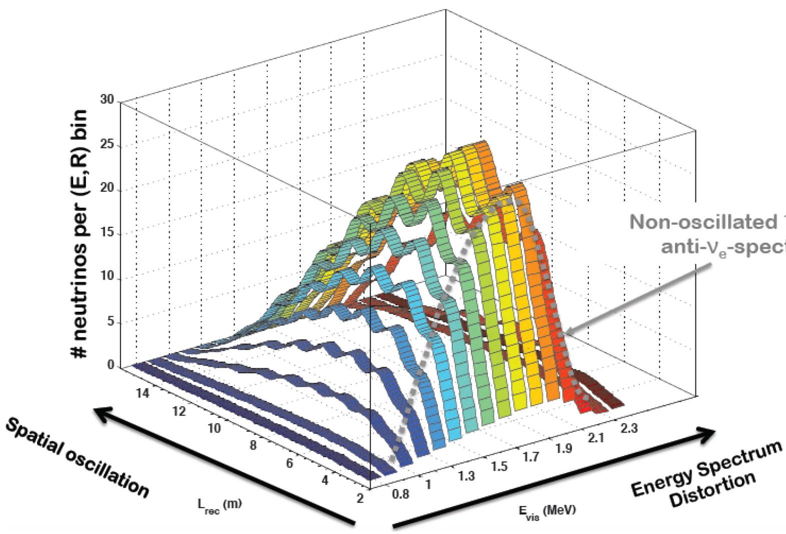

Fig. 7. Oscillation pattern expected for $\bar{\nu}_e$ in CeSOX project. Image taken from [35].

The source will be delivered to the laboratory of Gran Sasso in April 2018 and the physics run will last for 18 months with the expected number of event of the order of 10 000.

8. Summary

The neutrino experiments provided already many interesting and complementary measurements concerning the neutrino masses and oscillations. However, there are still questions which need to be answered. Many physicists work in many projects worldwide, using the neutrinos from natural and artificial sources and various detection techniques. The ongoing and planned experiments allow to hope that at least some of the pending questions will find answers in the next decade.

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