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Long-baseline neutrino accelerator experiments: results and prospects

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Contents

Abstract. Recent results from long-baseline neutrino experiments are presented. Prospects for determining the mass hierarchy and observing CP violation in neutrino oscillations are discussed.

1. Introduction

Neutrino physics is one of the most dynamic and unpredictable domains of elementary particle physics, and its rapid development is proceeding along the course of brilliant ideas put forward by Bruno Pontecorvo in the 1950–1960s. First and foremost, this concerns the hypothesis of $\nu \to \bar{\nu}$ neutrino oscillations formulated by Pontecorvo [1, 2] in 1957 by analogy with $K^0 \to \bar{K}^0$ oscillations. In 1968, Pontecorvo, together with Gribov, made the assumption that a neutrino produced with a certain flavor can change its flavor (violate its lepton number) with a probability depending on the distance from its source [3]. The understanding that right and left neutrinos cannot take part in weak interactions permitted Pontecorvo to introduce the concept of 'sterile' neutrinos.

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During the past 15–20 years, many fundamental results have been obtained in neutrino physics, the most important being the discovery of neutrino oscillations predicted by Pontecorvo. This result was the first direct experimental proof of the model. As follows from the existence of oscillations, neutrinos have a small nonzero mass, they mix, and lepton numbers are not conserved. This contradicts provisions of the Standard Model, according to which there are three sorts (flavors) of active neutrinos, which are massless particles that cannot change their flavor in the process of propagation with the speed of light, i.e., cannot mix.

Neutrino oscillations are described by the so-called Standard Neutrino Model, in which three sorts of active neutrinos, ν_e, ν_μ, ν_τ, with left chirality, are related by a unitary matrix U [4] (the Pontecorvo–Maki–Nakagawa–Sakata or PMNS matrix) to mass states ν_1, ν_2, ν_3 with the corresponding masses m_1, m_2, m_3. In general, the elements of this matrix are complex quantities. The standard parameterization of matrix U involves three mixing angles θ_{12}, θ_{23}, θ_{13} and three physical CP-odd phases. The probability of neutrino oscillations depends on the three mixing angles, two square mass differences $\Delta m_{21}^2 = m_2^2 - m_1^2$ and $\Delta m_{32}^2 = m_3^2 - m_2^2$, and the Dirac CP-odd phase δ. The two Majorana phases present in the matrix U do not affect oscillations of the neutrino flavor.

2. Present-day status of neutrino oscillations

Impressive progress has been achieved in measurements of the oscillation parameters since the actual discovery of oscillations: $\sin^2 \theta_{12} = 0.857 \pm 0.024$, $\sin^2 (2\theta_{23}) > 0.95$ at a 90% confidence level (CL), $\Delta m_{21}^2 = (7.50 \pm 0.20) \times 10^{-5} \text{ eV}^2$, and $|\Delta m_{32}^2| = (2.32^{+0.132}_{-0.08}) \times 10^{-3} \text{ eV}^2$. From the above data, the accuracy of these parameters can be seen to amount to only several percent. It must be noted that the sign of Δm_{32}^2 is unknown, because the neutrino mass hierarchy has not been determined. Both the normal hierarchy, $m_3 \gg m_2 > m_1$, and the inverse one, $m_2 > m_1 \gg m_3$, are possible. The physics of

neutrino oscillations, neutrino experiments, and their results are discussed in detail in reviews [5–10].

The most significant recent result in neutrino physics is the measurement of the θ_{13} angle. Until recently, the θ_{13} angle had remained an unknown parameter; only its upper bound had been found in the Chooz experiment [11]: $\sin^2(2\theta_{13}) < 0.15$ (90% CL). Many theoretical models in which attempts were made to explain the experimental data and to propose mechanisms for neutrino mixing predicted a very small or even zero value for this angle. The first indication that the θ_{13} angle was not zero was obtained in 2011 in the T2K (Tokai-to-Kamioka) accelerator experiment [12]. This result was soon confirmed in another accelerator experiment, MINOS (Main Injector Neutrino Oscillation Search) [13]. The most accurate measurements of this angle were performed in 2012 in the reactor experiments Double Chooz [14], Daya Bay [15], and RENO (Reactor Experiment for Neutrino Oscillation) [16]. The value of θ_{13} averaged over three reactor experiments amounted to $9.1° \pm 0.6°$ [17]. In a short period of time (about two years), the θ_{13} angle was measured with a precision close to the precisions achieved for the two other mixing angles during a period of 15 years.

Thus, it turns out that none of the three mixing angles θ_{12}, θ_{23}, and θ_{13} of the PMNS matrix is equal to zero and that strong mixing occurs between the different neutrino flavors. The next important result consists in the discovery of muon neutrino oscillations into electron neutrinos [18] in the T2K experiment.
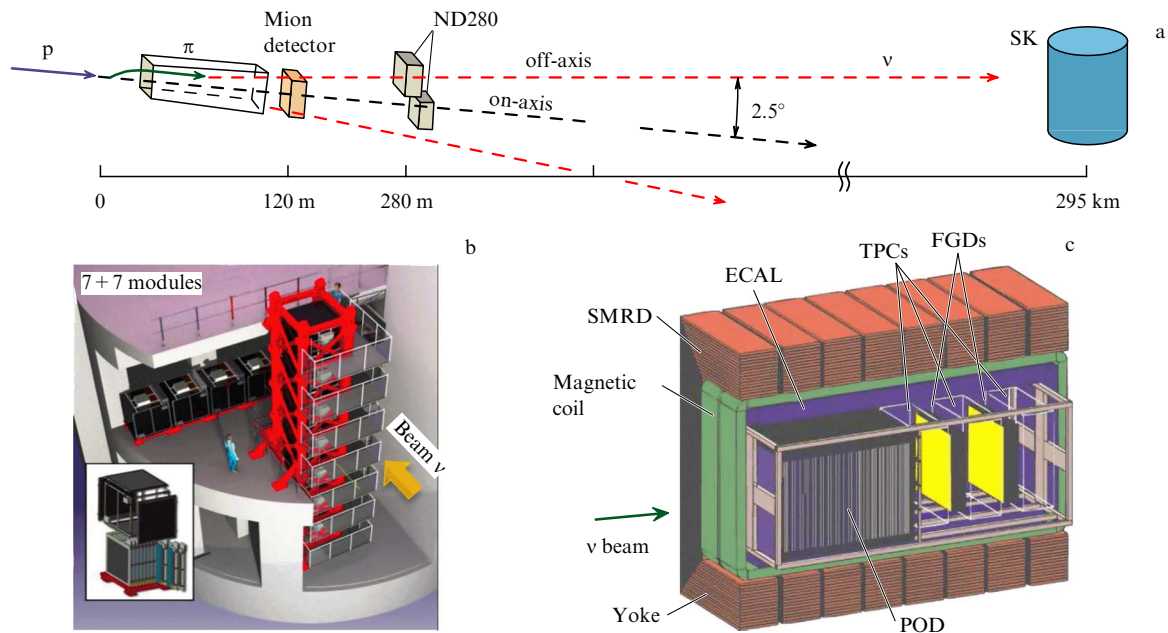
3. T2K experiment

The general layout of the T2K experiment is shown in Fig. 1. The main elements of the T2K setup [19, 20] include the neutrino channel based on the JPARC (Japan Proton Accelerator Research Complex) high-current accelerator, a complex of near neutrino detectors (ND280) situated in a mine at a distance of 280 m from the target, and the Super-Kamiokande far detector that is at a distance of 295 km from the target. The ND280 complex [21, 22], consisting of two neutrino detectors, is used for measuring the parameters of the neutrino beam close to the target (before oscillations occur) and for permanent control of its properties and measurement of the cross sections of neutrino interactions with nuclei. One of the detectors, INGRID (Interactive Neutrino GRID), is situated on the beam axis, i.e., at a zero angle with the proton beam direction, while the second near neutrino detector is at an angle of $2.5°$ on the axis connecting the decay volume and the Super-Kamiokande near detector. A quasimonoenergetic off-axis neutrino beam was used for the first time in the T2K experiment. As follows from the $\pi \to \mu + \nu$ decay kinematics, the neutrino energy E_ν in the case of small angles between the pion and neutrino momenta is independent of the pion energy E_π. The angle $2.5°$ was chosen so as to have the peak intensity of the neutrino energy spectrum tuned to the first oscillation maximum for $L = 295$ km and $|\Delta m_{32}^2| = 2.4 \times 10^{-3}$ eV^2. These conditions determine the characteristic neutrino beam energy in this experiment: $E_\nu = \Delta m_{32}^2 L / 2\pi \simeq 0.6$ GeV.

At present, the power of the JPARC 30-GeV proton beam amounts to 230 kW, which corresponds to an intensity of about 1.1×10^{14} protons per pulse, a pulse duration of about 3.0 μs, and fast extraction every 2.5 s of the beam impinging on the target. At energies corresponding to the maximum of the neutrino spectrum intensity, the admixture of electron neutrinos from the decay chain $\pi \to \mu \to e$ and kaon decays amounts to about 0.5% for the angle $2.5°$.
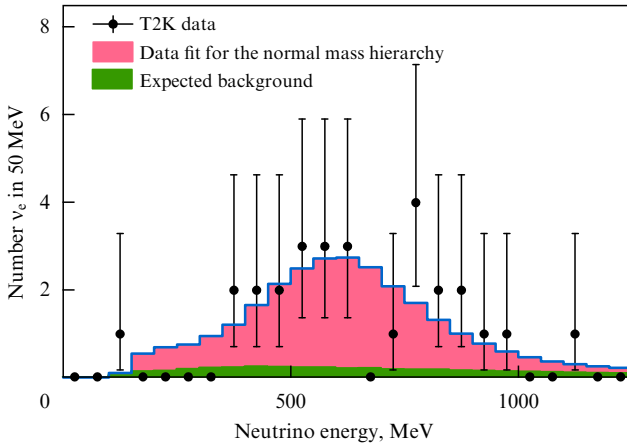
The Super-Kamiokande water Cherenkov detector [23] is used as a far detector that registers neutrinos in the energy range from 4.5 MeV to 1 TeV. The size, shape, and direction of the Cherenkov cone are used for event identification: an


Figure 1. Layout of T2K experiment. (a) The main elements of the setup: neutrino beam; neutrino beam monitor; ND280 near neutrino detector, situated at a distance of 280 m from the target; Super-Kamiokande (SK) far neutrino detector. (b) General view of the INGRID on-axis neutrino beam monitor. (c) Near off-axis neutrino detector comprising a neutral pion detector (POD), an electromagnetic calorimeter (ECAL), a muon range detector (SMRD), and a track detector consisting of three time-projection chambers (TPCs) and two highly segmented scintillation detectors (FGDs).

event can be single-ring muonlike (μ-like), single-ring electron-like (e-like), or multi-ring. The momentum resolution of the detector amounts to 2.4% for muons of the momentum 1 GeV/c.

Results of the T2K experiment. During the period between January 2010 and April 2013, the T2K experiment accumulated 6.4×10^{20} protons on the target (p.o.t.). Elements of the analysis of experimental data are described in detail in [24]. A total of 532 events from neutrinos that covered the 295 km distance from JPARC was detected by Super-Kamiokande. The energy of each of these events was fully measured by the inner detector in the absence of any signal in the outer detector. The expected background of atmospheric neutrinos amounted to 0.07 events. Of the 532 neutrino events, 28 were identified as electronlike — candidates for electron neutrinos [25]. The number of electron-like events expected in the absence of $\nu_\mu \to \nu_e$ oscillations ($\theta_{13} = 0$) should only

amount to 4.92 ± 0.55 for this measurement time. The energy distribution of the 28 events is shown together with the expected background in Fig. 2. The distribution of detected electrons over momenta and angles relative to the neutrino beam is shown in Fig. 3. Statistical analysis reveals the measured electron neutrino appearance effect, i.e., of $\nu_\mu \to \nu_e$ oscillations, to be 7.3σ. The probability of random statistical fluctuations resulting in the observed excess of electron neutrinos in the muon neutrino beam is extremely small, $< 10^{-12}$. This result is the first direct observation of muon neutrinos transforming into electron neutrinos, i.e., neutrino oscillations first revealed as the appearance of electron neutrinos in a pure muon beam, while in previous oscillation experiments, the disappearance of different sorts of neutrinos was measured.

The dependences of the *CP*-odd phase δ on $\sin^2 (2\theta_{13})$ for the normal and inverted mass hierarchies are shown in Fig. 4, where also shown is the value of $\sin^2 (2\theta_{13})$ obtained in reactor experiments [17]. It follows from the figure that a comparison of the value of $\sin^2 (2\theta_{13})$ obtained in reactor experiments with T2K data (if the measurement precision of $P(\nu_\mu \to \nu_e)$ and of the mixing angle θ_{23} is improved) can serve as a first step in searches for *CP* violation and even point to the existence of this effect in the most favorable case, for instance, if $\delta \simeq -\pi/2$.

The combination of this T2K result together with the value of θ_{13} obtained in reactor experiments has permitted

Figure 2. (Color online.) Energy distribution of the 28 electron neutrinos detected by the Super-Kamiokande far detector. The histograms show the fitting of the signal for the normal neutrino mass hierarchy (red) and the expected background (green).
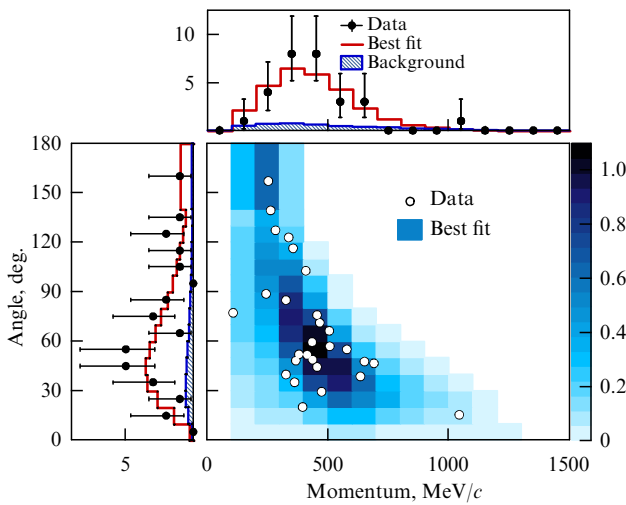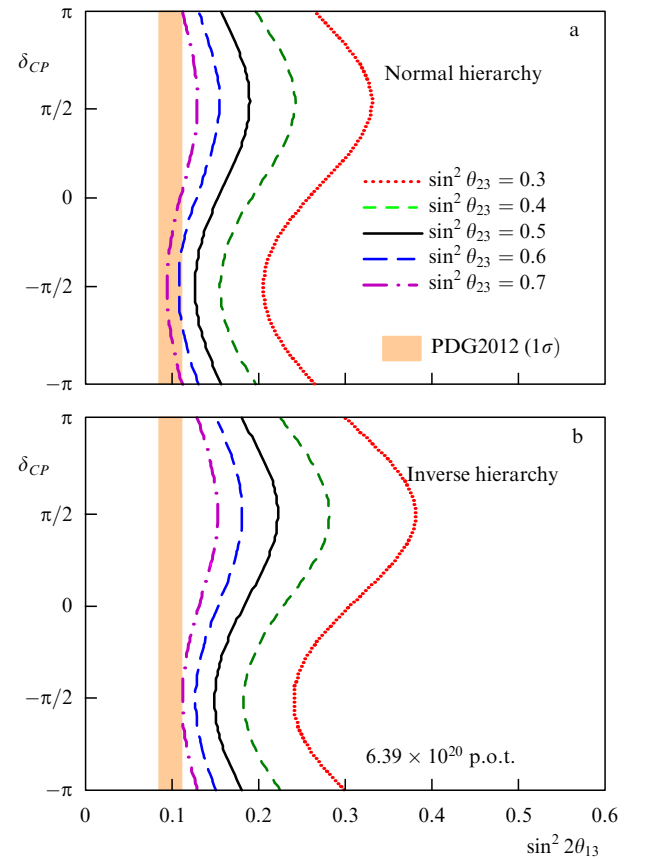
Figure 3. (Color online.) Distributions over momenta and angles relative to the neutrino beam direction of 28 electron events from quasielastic electron neutrino scattering. The rectangles in different colors show the distributions of electrons from registered electron neutrinos, obtained by Monte Carlo simulations for $\sin^2 (2\theta_{13}) = 0.150$, corresponding to the best data fit for the normal mass hierarchy and $\delta = 0$, $\Delta m_{32}^2 = 2.4 \times 10^{-3}$ eV^2 [18].

Figure 4. T2K results showing the dependence of δ on $\sin^2 (2\theta_{13})$ for several possible values of the mixing angle $\sin^2 \theta_{23}$ in the case of (a) the normal and (b) the inverted neutrino mass hierarchy. The solid black curve corresponds to the maximum mixing, $\theta_{23} = \pi/4$. Also shown is the value of $\sin^2 (2\theta_{13})$ obtained in reactor experiments (denoted as PDG2012).
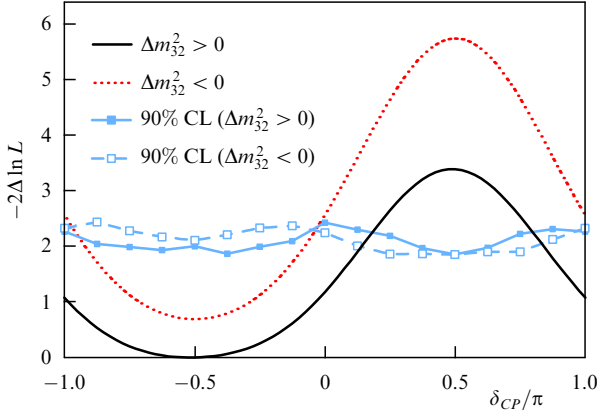
Figure 5. Dependence of the maximum-likelihood function $-2\Delta \ln L$ on δ [18]. The solid and dotted curves respectively show the 90% confidence probability level for normal and inverse mass hierarchies. The range of δ values above these curves is ruled out at a 90% CL.

obtaining the first experimental bounds for the CP-odd phase δ. The maximum-likelihood function $-2\Delta \ln L$ for all possible values of δ from $-\pi$ to π is shown in Fig. 5. The solid (dotted) curve shows the 90% CL for the normal (inverted) mass hierarchy. In the case of the normal mass hierarchy, the range of values $\delta = (0.19-0.80)\pi$ lying above the corresponding solid curve is excluded at a 90% CL. In the case of the inverted mass hierarchy (dotted curve), the values of δ in the intervals from $-\pi$ to -0.97π and from -0.04π to π are excluded at a 90% CL.

It must also be noted that indications of the 'appearance' effect in neutrino oscillations were recently obtained in two more experiments. This was a direct observation of $\nu_\mu \to \nu_\tau$ oscillations. In the Super-Kamoikande experiment with atmospheric neutrinos, a deficit of tau neutrinos registered in the detector was observed at a level of 3.8σ compared with the flux expected in the absence of oscillations [26]. At present, three tau neutrinos have been observed in the long-baseline experiment OPERA (Oscillation Project with Emulsion-tRacking Apparatus) searching for $\nu_\mu \to \nu_\tau$ oscillations, while the expected background is 0.23 events and the appearance effect of tau neutrinos in the muon neutrino beam is 3.5σ [27].

4. Near future

The following are fundamental issues of neutrino physics to be resolved: is CP invariance violated in neutrino oscillations and which order (mass hierarchy) is realized in nature?

The Jarlskog parameter J_{CP} [28] characterizing the degree of CP violation has the following form for neutrinos, or, in other words, in the lepton sector:

$$J_{CP}^{\mathrm{PMNS}} = \cos\theta_{12} \sin\theta_{12} \cos^2\theta_{13} \sin\theta_{13} \cos\theta_{23} \sin\theta_{23} \sin\delta. \tag{1}$$

Because all three neutrino mixing angles, as in the case of quarks, differ from zero, it follows that $J_{CP}^{\mathrm{PMNS}} \neq 0$ if $\delta \neq 0$. In the case of CP violation in the quark sector, $J_{CP}^{\mathrm{CKM}} \sim 3\times10^{-5}$, while for the lepton sector, $J_{CP}^{\mathrm{PMNS}} \sim 0.035\sin\delta$. We emphasize that hopes that CP violation in the quark sector would be the key to understanding the baryon asymmetry of the Universe were not justified owing to the smallness of J_{CP}^{CKM}.

Because the mixing angles are quite large, the effect of CP violation in the lepton sector can in principle be very significant (depending on the value of δ) compared to such an effect in the quark sector. Thus, the investigation of neutrino oscillations opens up a unique possibility for searches for a new source of CP violation. The discovery of CP violation in neutrino oscillations, together with nonconservation of the lepton number, may provide important indirect arguments in favor of the explanation of baryon asymmetry of the Universe based on the leptogenesis mechanism.

How can CP violation be revealed and measured in neutrino oscillations? The discovery of $\nu_\mu \to \nu_e$ oscillations provides an excellent chance to search for CP violation. If, for simplicity, we consider oscillations in the vacuum, then the CP asymmetry can be expressed as

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \simeq \frac{\Delta m_{21}^2 L}{4E} \frac{\sin(2\theta_{12})}{\sin\theta_{13}} \sin\delta. \tag{2}$$

The value of A_{CP} is proportional to $1/\sin\theta_{13}$, while $P(\nu_\mu \to \nu_e) \sim \sin^2(2\theta_{13})$. In measurements at the oscillation maximum, i.e., when the ratio of the experimental baseline L to the neutrino energy E is optimal and constant, the CP asymmetry does not depend on the neutrino energy, and A_{CP} can be measured in experiments with neutrino and antineutrino beams. Another method consists in measuring $\nu_\mu \to \nu_e$ oscillations with wide neutrino and antineutrino beams at the first and second oscillation maxima. A comparison of the shapes of the electron neutrino spectra and of the intensities and positions of the first and second oscillation maxima permits measuring the phase δ even with a single neutrino beam, if the mass hierarchy is known. The presence of matter when oscillation measurements are performed simulates a false CP violation effect, which must be separated from the 'true' CP violation.

The nonzero CP phase δ measured in neutrino oscillations, i.e., at low energies, is a fundamental parameter. Although no model-independent indications exist of a relation between the CP asymmetry in neutrino oscillations and the asymmetry in heavy neutrino decays in the early Universe, the elegant explanation of the neutrino mass via the 'see-saw' mechanism, which relates heavy neutrinos with masses of $10^{10}-10^{15}$ GeV and light active neutrinos, may turn out to be a bridge between these two asymmetries.

Information on the mass hierarchy plays an extremely important role for experiments devoted to the search for neutrinoless double beta decay. In the case of an inverse mass hierarchy, the sensitivity of planned experiments will allow observing this process, which will be unambiguous proof of the Majorana nature of neutrinos. This will also mean that two of the three masses should practically coincide, which is not observed in the mass spectrum of charged leptons and quarks. Moreover, determining the mass hierarchy is an important key for establishing the absolute neutrino mass scale, whose formation mechanism is one of the greatest mysteries of elementary particle physics.

The θ_{13} angle value close to $9°$ opened up a unique possibility for measuring the neutrino mass hierarchy and searching for CP violation in long-baseline accelerator experiments using the existing neutrino beams and detectors. First of all, this concerns the experiments T2K and
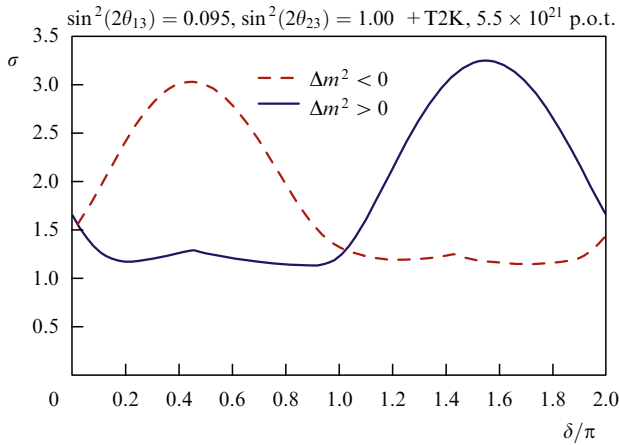
Figure 6. Combined sensitivity σ of experiments NOvA and T2K to the mass hierarchy. Data taking in NOvA: three years with a neutrino beam + three years with an antineutrino beam at a power of 700 kW. The statistics of the experiment T2K correspond to the integral luminosity equal to 5.5×10^{21} p.o.t.
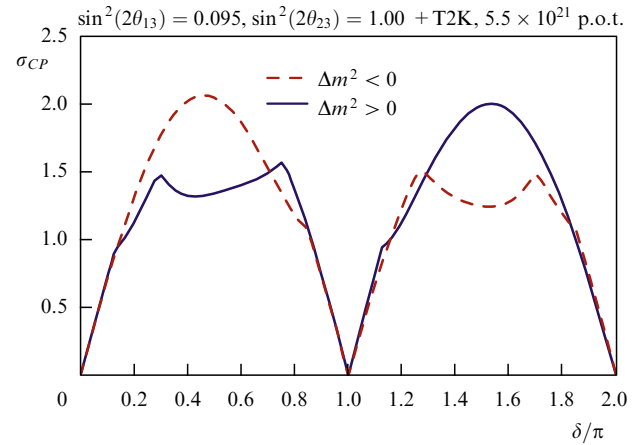
Figure 7. Combined sensitivity σ_{CP} of experiments NOvA and T2K to the CP-odd phase δ. Data taking in NOvA: three years with a neutrino beam + three years with an antineutrino beam at a power of 700 kW. The statistics of the T2K experiment corresponds to the integral luminosity equal to 5.5×10^{21} p.o.t.

NOvA (NuMI (Neutrinos at the Main Injector) Off-Axis ν_e Appearance Experiment).

The NOvA experiment [29] uses an off-axis neutrino beam with a mean energy of about 2.2 GeV directed from the Fermi National Accelerator Laboratory (Fermilab) toward a far detector with a mass of 14 kt located at a distance of 810 km. The parameters of the neutrino beam before oscillations are measured by the near detector with a mass of 0.3 kt, installed at a distance of 1 km from the target. Both detectors represent segmented track calorimeters, whose active part (a liquid scintillator) amounts to about 70% of the total mass of the detectors. The experiment started collecting data in September 2013, with part of the installed blocks of the far detector and the power of the 120 GeV proton beam equal to about 280 kW. The near detector is to be completely assembled and commissioned at the beginning of 2014. Under the assumption that data taking in the NOvA experiment will continue over a period of six years (three years with a neutrino beam and three years with an antineutrino beam) with the beam power equal to 700 kW, while the total integral luminosity of T2K will amount to 8×10^{21} p.o.t., the combined analysis of data on the appearance of electron neutrinos in both experiments will permit achieving a sensitivity to the mass hierarchy at a level of 3σ for a small range of δ in the favorable case of maximum CP violation, which can be seen from Fig. 6. The expected sensitivity to δ shown in Fig. 7 reaches the level of $(1.5-2)\,\sigma$ in the most favorable cases [30]. Thus, it can be asserted that the capacities of current experiments permit obtaining an indication of CP violation and determining the mass hierarchy with a sensitivity of 3σ for a small range of δ values, but they are certainly insufficient to achieve a complete and unambiguous solution to the problem of CP violation and mass hierarchy.

5. Far future

Currently, there are three projects of long-baseline accelerator experiments, whose main purposes consist in determining the neutrino mass hierarchy and in a high-sensitivity search of CP violation. These projects are based on the two mutually complementary methods discussed in Section 4.

5.1 LBNE experiment
LBNE (Long-Baseline Neutrino Experiment) [31] is to use a broad neutrino beam from Fermilab directed toward a far detector located at a distance of 1300 km in the Homestake mine (South Dakota, USA). The far detector is a single-phase liquid-argon time-projection chamber with a mass of 35 kt (the sensitive volume). The power of the 60–120 GeV proton beam is 700 kW (after an upgrade, a power of 2.3 MW is to be achieved). The dependence of the sensitivity to the mass hierarchy on the exposure time is shown in Fig. 8 for an 80 GeV proton beam. From the figure, the influence of systematic errors on the sensitivity to the mass hierarchy is seen to be insignificant.

The sensitivity to the CP-odd phase is shown in Fig. 9. Unlike the sensitivity to the mass hierarchy, the sensitivity to δ depends strongly on systematic uncertainties. In the case of
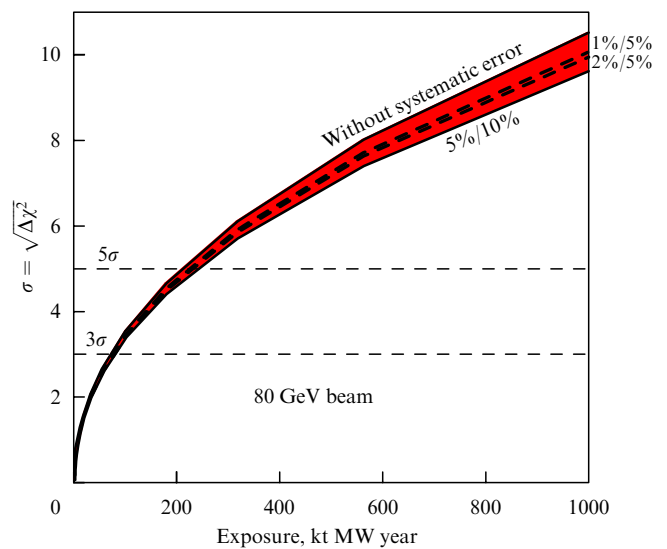
Figure 8. LBNE sensitivity to the mass hierarchy versus the exposure time (kt MW year) on the neutrino beam [31]. The curves are presented for the case where the error is only statistical, and for the following ratios between the systematic errors in the signal and background: 1%/5%, 2%/5%, and 5/10%.
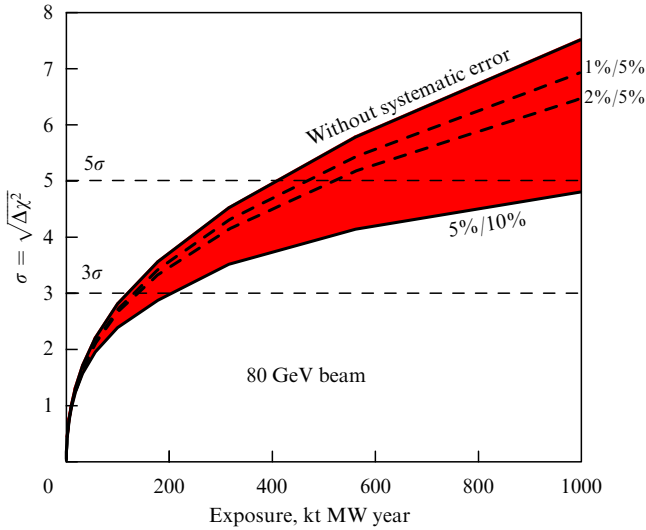
Figure 9. LBNE sensitivity to the CP-odd δ versus the exposure time (kt MW year) on the neutrino beam [31]. The curves are presented for a 50% range of possible δ values in the case where the error is only statistical and for the following ratios between the systematic errors in the signal and background: 1%/5%, 2%/5%, and 5/10%.

Figure 10. Sensitivity of the T2HK experiment to the phase δ in the case of the normal mass hierarchy and systematic errors of 10%, 5%, and 2%. The integral luminosity is 7.5 MW year.
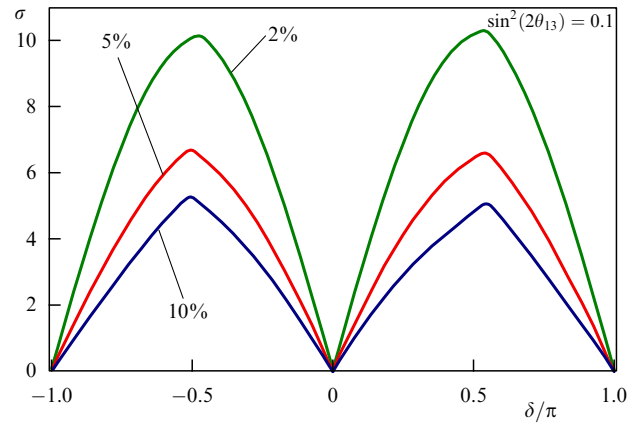
a detector mass equal to 35 kt and data taking over three years, the systematic uncertainties significantly reduce the sensitivity of the experiment to δ. After 10 years of data taking (five years with a neutrino beam and five years with an antineutrino beam), the sensitivity to δ is expected to reach a level of $\geqslant 3\sigma$ for only 60% of the entire possible range of phases from $-\pi$ to π. The experiment can also determine the mass hierarchy with a nearly 3σ confidence in approximately two years of data taking with the neutrino beam.

5.2 LAGUNA-LBNO experiment

In Europe, the feasibility is being considered of the LAGUNA–LBNO (Large Apparatus studying Grand Unification Neutrino Astrophysics–Long Baseline Neutrino Oscillation) experiment with a neutrino beam from CERN [32] directed toward the Pyhäsalmi mine (Finland), where plans are being made to install a neutrino detector in the form of a two-phase liquid-argon time-projection chamber with a mass of 70 kt (20 kt at the first stage) and a magnetic 35 kiloton neutrino detector (MIND, Magnetized Iron Neutrino Detector). A wide neutrino beam with energies in the 1–9 GeV range and an experimental baseline 2300 km long permits measuring $\nu_\mu \to \nu_e$ oscillations at the first and second oscillation maxima, which determines the uniquely high sensitivity of the experiment to the mass hierarchy ($> 5\sigma$) for the entire aforementioned range of values of the C-odd phase and also permits revealing the effect of CP violation for 60% of the values of δ. Such a sensitivity is expected for the integral number of 400 GeV protons on the target, amounting to 1.25×10^{21}. The first step in preparing this experiment will be to create and test a two-phase liquid-argon time-projection chamber of dimensions $6 \times 6 \times 6$ m^3, which is a prototype of the 70 kiloton neutrino detector. This task will be implemented at CERN.

5.3 T2HK experiment

The purpose of the T2HK (Tokai-to-Hyper-Kamiokande) experiment [33] consists in a sensitive search and measurement of the phase δ using the intense off-axis neutrino and antineutrino beams from JPARC, tuned to the first oscillation maximum, with the gigantic 1-megaton water Cherenkov detector (its effective mass 0.56 Mt is equivalent to the mass of 25 Super-Kamiokande detectors), situated at a distance of 295 km from JPARC. The registration of Cherenkov light will be performed by 100,000 photomultiplier tubes 20 inches in diameter. After an upgrade of the JPARC proton accelerator, the power of the proton beam is to be increased to 1.66 MW. The muon neutrino (antineutrino) energy at the maximum of the spectrum is about 600 MeV.

The large value of θ_{13} favors rapid accumulation of data statistics for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, but the CP asymmetry at the first oscillation maximum lies within the 10–30% interval for all possible values of δ, as follows from expression (2). In the experiment, it is therefore necessary to obtain a level of systematic uncertainties lower than 5% in order to achieve a good sensitivity to δ, as can be seen from Fig. 10. The T2K experiment reduced the level of systematic errors in measuring the probability of $\nu_\mu \to \nu_e$ transitions significantly — to 8.8%, which renders the goal of ensuring the systematic errors in T2HK to be $\leqslant 5\%$ quite achievable.

Plans for 10 years of data taking are to achieve the sensitivity to δ at a level of $\geqslant 3\sigma$ for a 70% interval of possible values of this parameter. The δ measurement precision is expected to be $20°$ if the phase is close to $\pi/2$ or $-\pi/2$, and $10°$ if the phase is close to 0 or π. It must be especially noted that such a sensitivity can be achieved only if the mass hierarchy is determined in other experiments, because this experiment is not sensitive to the mass hierarchy owing to its relatively short baseline.

5.4 Neutrino experiment on the basis of ESS

The purpose of the European project ESS (European Spallation Source) is to create a powerful pulsed neutron source based on the high-intensity proton accelerator in Lund, Sweden. A superconducting linear accelerator with a power of 5 MW is to be constructed, which will permit obtaining a proton beam with the on-target intensity 1.6×10^{16} p.o.t. s^{-1}. The mean energy of the neutrino beam will be 0.2–0.4 GeV. The first beam is expected to be ready in 2017, while the total intensity will be achieved by 2022. Given the parameters of this complex, the possibility is being considered of performing an oscillation experiment with a baseline 360 or 560 km long and a water Cherenkov detector

500 kt in mass [34] installed in a Swedish mine. Such an experiment will reach a high sensitivity to *CP* violation and will have real chances, after 10 years of data taking, to measure δ with an accuracy of $10° - 15°$.

5.5 Nonaccelerator experiments

5.5.1 JUNO and RENO-50. The large value of the θ_{13} angle gives rise to the interesting possibility of determining the neutrino mass hierarchy in reactor experiments with baselines about 50 km long. At present, two such experiments are proposed: one in Korea, RENO-50 [35], and the other, JUNO (Jiangmen Underground Neutrino Observatory) [36], in China. In the JUNO experiment, the intention is to use a scintillation detector with a mass of 20 kt situated at a distance of 50 km from reactors with the total power of 36 GW, while in the RENO-50 experiment, a scintillation detector with mass of 10 (or 18) kt installed at a distance of 47 km from reactors with the total power 16.5 GW is to be used. The reactor antineutrinos in these experiments are detected using the inverse beta-decay:

$$\bar{\nu} + p \rightarrow e^+ + n \,. \tag{3}$$

Here, sensitivity to the mass hierarchy arises owing to the interference effect of two oscillation modes: the 'atmospheric' mode with Δm^2_{32} and the solar mode with Δm^2_{21}, and also due to the mixing angle θ_{12} differing from $\pi/4$. To resolve the mass hierarchy problem successfully in these experiments, it is necessary to obtain the energy resolution of the detector $\leqslant 3\%/\sqrt{E\,[\mathrm{MeV}]}$ in measuring the oscillation spectrum, which is a very difficult task due to the relatively small masses of the detectors. For example, the energy resolution of the KamLAND (Kamioka Liquid-scintillator Anti-Neutrino Detector) with a mass of 1 kt amounts to $6\%/\sqrt{E\,[\mathrm{MeV}]}$. If a resolution of $3\%/\sqrt{E\,[\mathrm{MeV}]}$ is successfully achieved, then the mass hierarchy can be determined at a level of 3σ assuming six years of data taking.

5.5.2 PINGU (Precision IceCube Next Generation Upgrade). The main goal of the PINGU experiment (a project of upgrading the IceCube/DeepCore detector for the detection of atmospheric neutrinos with a lower threshold of several GeV) consists in measuring of the neutrino mass hierarchy using the dependence of the Mikheev–Smirnov–Wolfenstein effect on the mass hierarchy when atmospheric neutrinos travel through Earth. For this, 40 additional strings are to be installed in the central part of IceCube/DeepCore at distances of 20 m from each other with 60 optical modules in each string [37]. After one year of data taking, the sensitivity to the mass hierarchy is expected to be about 2σ.

5.5.3 INO (India-based Neutrino Observatory). The main detector in INO will be a 50 kiloton calorimeter consisting of passive layers of magnetized iron and of active detectors — resistive plane chambers (RPCs) [38]. The layers of magnetized iron produce a magnetic field equal to 1.3 T, which permits determining the charges of particles and measuring oscillations of atmospheric neutrinos and antineutrinos separately. The detector is expected to start functioning in 2018, and after 10 years of data taking an answer to the question concerning the mass hierarchy may be obtained with an approximately 2.5σ confidence. A combination with other experiments may enhance the sensitivity to $\sim 3.5\sigma$.

6. Conclusion

For many decades, Pontecorvo's idea about the possibility of neutrino oscillations determined the most interesting and fruitful direction of particle physics in which fundamental results have been obtained.

The discovery of $\nu_\mu \rightarrow \nu_e$ oscillations in the T2K experiment and the nonzero value of the θ_{13} angle measured in reactor and accelerator experiments altered the situation in accelerator neutrino physics drastically and opened up a unique possibility for searches of *CP* violation in the lepton sector and for determining the neutrino mass hierarchy in long-baseline accelerator experiments. The T2K and NOvA experiments in operation, together with reactor experiments, may provide a first indication of *CP* violation in neutrino oscillations, but global progress in this area can be expected in next-generation experiments. The mass hierarchy can be established in accelerator experiments and in reactor experiments and in experiments with atmospheric neutrinos. The discovery and further investigation of *CP* violation in the lepton sector is only possible in long-baseline accelerator experiments. If *CP* violation is revealed in neutrino oscillations, i.e., if $\delta \neq 0$ and $\delta \neq 180°$, then a broad research program in physics will open up for long-baseline accelerator experiments, and the cornerstone of this program will be precision measurements of the phase δ, which is the only parameter of the PMNS matrix that has not been measured yet.

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