Physics – Uspekhi **56** (11) 1120 – 1125 (2013)

PHYSICS OF OUR DAYS

PACS numbers: 14.60.Pq, 25.30.Pt

T2K observation of muon-to-electron neutrino oscillations

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DOI: 10.3367/UFNe.0183.201311d.1225

Contents

Abstract. **A major result of the long-baseline T2K experiment, the observation of muon neutrinos oscillating into electron neutrinos, is presented. Prospects for detecting *CP* violation in neutrino oscillations are discussed.**

1. Introduction

At the HEP 2013 conference of the European Physical Society, held in Stockholm in July 2013, the discovery of muon-to-electron neutrino oscillations in the long-baseline accelerator experiment T2K (Tokai-to-Kamioka) was announced. An interesting result was presented revealing remarkable possibilities for searches for new *CP* violation sources in studies of neutrino oscillations.

Neutrino physics has been one of the most rapidly developing parts of elementary particle physics in the past 20 years. Many fundamental results have been obtained, the most important of which is the discovery of neutrino oscillations, which happens to be the first direct experimental proof of the existence of novel physics beyond the Standard Model. It follows from oscillations that neutrinos have a small nonzero mass, they mix, and neutrino flavors (quantum numbers) are not conserved. This contradicts the Standard Model, according to which there are three sorts (flavors) of active neutrinos that are massless particles and cannot change flavor in the course of propagation at the speed of light, i.e., cannot mix. The hypothesis of $\nu \to \bar{\nu}$ neutrino oscillations was put forward, by analogy with $K^0 \to \bar{K}^0$ oscillations, by Pontecorvo [1, 2]. The first experimental indication of neutrino oscillations was obtained in the experiment performed by Davis [3], when a deficit of solar ν_e was observed: the experimentally measured neutrino flux amounted to about 1/3 of the predicted value. Subsequently, the existence of neutrino oscillations between three sorts of neutrinos was demonstrated unambiguously in experiments with solar [4–10], atmospheric [11], reactor [12], and accelerator [13, 14] neutrinos, and the oscillation parameters were measured.

Neutrino oscillations are described by the so-called Standard Neutrino Model, in which the three sorts of active neutrinos, ν_e, ν_μ, ν_τ, with left-handed helicity, are related by a unitary matrix U [15] (the Pontecorvo–Maki–Nakagawa–Sakata or PMNS matrix) with mass states ν_1, ν_2, ν_3, to which correspond masses m_1, m_2, m_3. In general, the elements of this matrix are complex quantities. A standard parameterization of the 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, on 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 on the Dirac *CP*-odd phase δ. The two Majorana phases present in the matrix U do not affect oscillations between the neutrino flavors. The physics of neutrino oscillations is discussed in detail in reviews [16–20].

2. Present-day status of neutrino oscillations

Since the discovery of oscillations, astonishing progress has been achieved in the measurement of oscillation parameters: $\sin^2\theta_{12} = 0.857 \pm 0.024$, $\sin^2 2\theta_{23} > 0.95$ at a 90% confidence level (90% C.L.), $\Delta m_{21}^2 = (7.50 \pm 0.20) \times 10^{-5}$ eV^2, $|\Delta m_{32}^2| = (2.32^{+0.132}_{-0.08}) \times 10^{-3}$ eV^2. From the above data, the errors of these parameters are seen to amount to only a few percent. It must be noted that the sign of Δm_{32}^2 is unknown, i.e., the hierarchy of the neutrino masses has not been determined. Both the normal hierarchy $m_3 \gg m_2 > m_1$ and the inverted one $m_2 > m_1 \gg m_3$ are possible.

Special attention is to be paid to the measurement of the angle θ_{13}. Until recently, θ_{13} had remained an unknown parameter: only its upper bound, $\sin^2 2\theta_{13} < 0.15$ (90% C.L.), had been experimentally determined by the CHOOZ collaboration [21]. Many theoretical models predicted a very small or zero value for this angle. A real breakthrough here

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Received 4 October 2013, revised 14 October 2013
Uspekhi Fizicheskikh Nauk **183** (11) 1225 – 1230 (2013)
DOI: 10.3367/UFNr.0183.201311d.1225
Translated by G Pontecorvo; edited by A M Semikhatov

Table. Neutrino and quark mixing angles and *CP*-odd phases.

Angle	Neutrinos	Quarks
θ_{12}	34°	13°
θ_{23}	45°	2°
θ_{13}	9°	0.2°
δ	$-\pi - +\pi$	68°

occurred in 2011, when the T2K collaboration published its first result on the measurement of $\nu_\mu \to \nu_e$ oscillations and obtained an indication of a nonzero value of θ_{13} [22]. This result was subsequently confirmed by another accelerator experiment, MINOS (Main Injector Neutrino Oscillation Search) [23]. The most precise measurements of θ_{13} were performed in 2012 in the reactor experiments Double CHOOZ [24], Daya Bay [25], and RENO (Reactor Experiment for Neutrino Oscillation) [26]. The value averaged over the three reactor experiments amounted to $\theta_{13} = 9.1^\circ \pm 0.6^\circ$ [27]. In a short period of about two years, θ_{13} was measured with an uncertainty close to the uncertainties achieved for the other two mixing angles over 15 years. Thus, all the three mixing angles, $\theta_{12}, \theta_{23}, \theta_{13}$, turned out to differ from zero. The neutrino mixing parameters (the PMNS matrix), the quark mixing angles, and the *CP*-odd phases, which are parameters of the Cabibbo–Kobayashi–Maskawa (CKM) matrix, are given in the Table.

3. T2K experiment

The probability of muon-to-electron neutrino oscillations with the effect of matter taken into account is expressed as

$$\begin{aligned} P(\nu_\mu \to \nu_e) &\simeq 4 \sin^2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[\Delta(1-A)]}{(1-A)^2} \\ &+ \alpha^2 \sin^2(2\theta_{12}) \cos^2\theta_{23} \frac{\sin^2(A\Delta)}{A^2} + 2\alpha \sin\theta_{13} \sin(2\theta_{12}) \\ &\times \sin(2\theta_{23}) \cos(\Delta \pm \delta) \frac{\sin(A\Delta)}{A} \frac{\sin[\Delta(1-A)]}{1-A}\,, \end{aligned} \tag{1}$$

with $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$, $\Delta = \Delta m^2_{31} L/(4E)$, and $A = 2EV/\Delta m^2_{31}$, where L is the baseline of the experiment, E is the neutrino energy, and V is the effective potential of matter. It must be noted that α, Δ, and A are sensitive to the neutrino mass hierarchy, i.e., to the sign of Δm^2_{31}. In expression (1), the plus sign is applied in the case of neutrinos, and the minus sign in the case of antineutrinos. Passing from the neutrino to the antineutrino involves $V \to -V$, which corresponds to $A \to -A$. A numerical expression convenient for explaining oscillation effects in a medium (assuming the average density of the ground traversed by the neutrinos to be approximately 3 g cm^{-3}) has the form

$$|A| = 0.09 \left(\frac{E}{\text{GeV}}\right) \left(\frac{2.5 \times 10^{-3}\ \text{eV}^2}{|\Delta m^2_{31}|}\right). \tag{2}$$

As can be seen from (1), $P(\nu_\mu \to \nu_e)$ depends strongly on the mass hierarchy when the effect of matter is large ($|A| \geqslant 1$). If $|A| = 1$, resonance amplification of the effect of oscillations occurs in neutrinos and the normal mass hierarchy or in antineutrinos and the inverted mass hierarchy.

The search for $\nu_\mu \to \nu_e$ oscillations and measurement of the angle θ_{13}, the precision measurement of oscillation parameters, and the search for *CP* violation in neutrino oscillations are the main goals of the T2K experiment [28] being carried out in Japan. About 500 scientists from 11 countries are members of the T2K collaboration. Russia is represented by the RAS Institute for Nuclear Research, which takes part in the experiment. The experiment itself, the experimental device, and the measurement technique are described in detail in Refs [28–31].

The general layout of the experiment is shown in Fig. 1. The main elements of the setup are the neutrino beamline, based on the J-PARC (Japan Proton Accelerator Research Complex) high-current proton accelerator, a near detector complex (ND280), situated in a mine 280 m from the target, and a far detector (Super-Kamiokande), located at a distance of 295 km from the target. The ND280 complex [32, 33], consisting of two neutrino detectors is used for measuring parameters of the neutrino beam close to the target (before oscillations occur), for permanently monitoring its properties, and for measuring the cross sections of neutrino interactions with nuclei. One of the detectors (INGRID, Interactive Neutrino GRID, monitoring the neutrino beam) is situated on the beam axis, i.e., at a zero angle to the direction of the proton beam, while the other, a near neutrino detector, is placed at an angle of 2.5° on the axis connecting the decay volume and the far Super-Kamiokande detector. T2K is the first experiment to use a quasi-monoenergetic off-axis neutrino beam. As follows from the $\pi \to \mu + \nu$ decay kinematics, in the case of small angles between the pion and neutrino momenta, the neutrino energy E_ν is practically independent of the pion energy E_π. The off-axis deflection was chosen to be 2.5° for the intensity peak of the neutrino energy spectrum to be tuned to the first oscillation maximum at $L = 295$ km and $|\Delta m^2_{32}| = 2.4 \times 10^{-3}\ \text{eV}^2$, as shown in Fig. 2. The above conditions determine the characteristic energy of the neutrino beam, $E_\nu = \Delta m^2_{32} L/2\pi \approx 0.6$ GeV, in the T2K experiment.

At present, the J-PARC 30 GeV proton beam power amounts to 230 kW, corresponding to an intensity of about 1.1×10^{14} protons per spill for a spill duration of about 3.0 μs and fast extraction of the beam impinging on the target once every 2.5 s. At energies corresponding to the intensity maximum of the neutrino spectrum, the electron neutrino contamination from the decay chain $\pi \to \mu \to e$ and from kaon decays amounts to about 0.5% for the angle 2.5°.

The far detector is the Super-Kamiokande water Cherenkov detector [34], 50,000 m^3 in volume viewed by 11,000 photomultiplier tubes. The size, shape, and orientation of the Cherenkov cone are used for event identification: an event may be single-ring muonlike, single-ring electronlike, or multiring. Time synchronization of the J-PARC proton accelerator pulse and Super-Kamiokande is realized using GPS (Global Positioning System) with a precision of about 150 ns. Such a precision permits observing the beam microstructure in the neutrino events registered by Super-Kamiokande and suppressing the background for atmospheric neutrinos to a negligible level.

3.1 Result obtained in 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). In this period, the operation efficiencies of Super-Kamiokande and ND-280 in collecting statistics respectively amounted to 99% and 96%.

To measure $\nu_\mu \to \nu_e$ oscillations and to determine the mixing angle θ_{13}, it is necessary to effectively detect electrons produced in Super-Kamiokande by electron neutrinos inter-

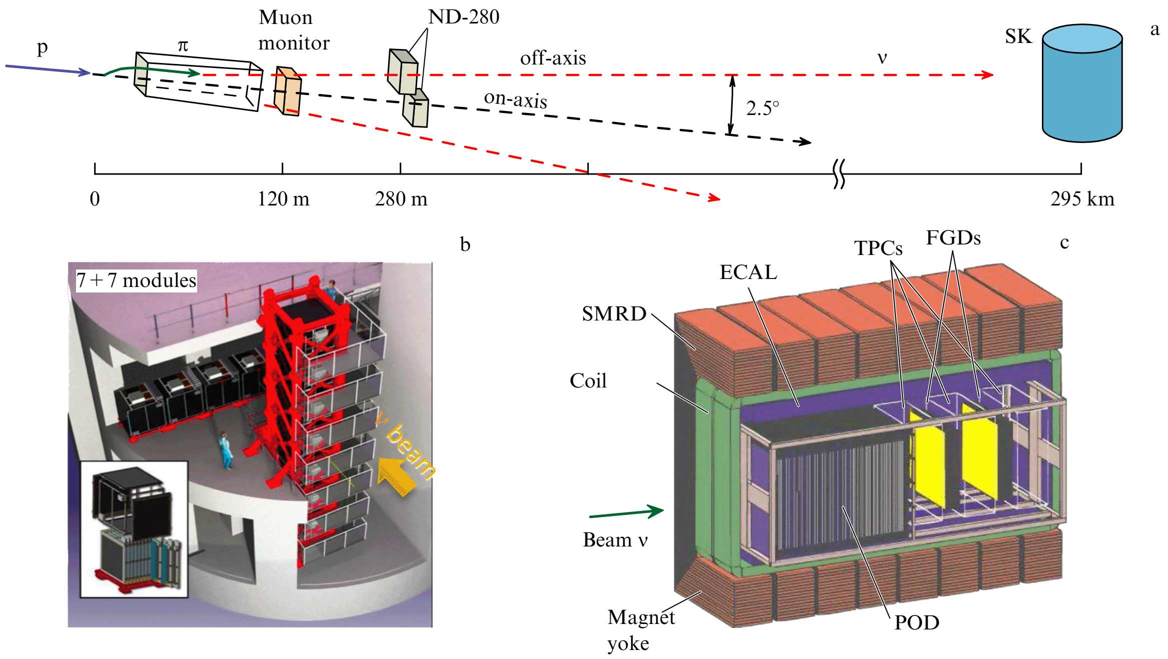

Figure 1. Layout of the T2K experiment. (a) Main elements of the setup: neutrino beam; neutrino beam monitor; ND-280 near neutrino detector, situated at a distance of 280 m from the target, and Super-Kamiokande (SK) far neutrino detector. (b) General view of on-axis neutrino beam monitor INGRID. (c)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

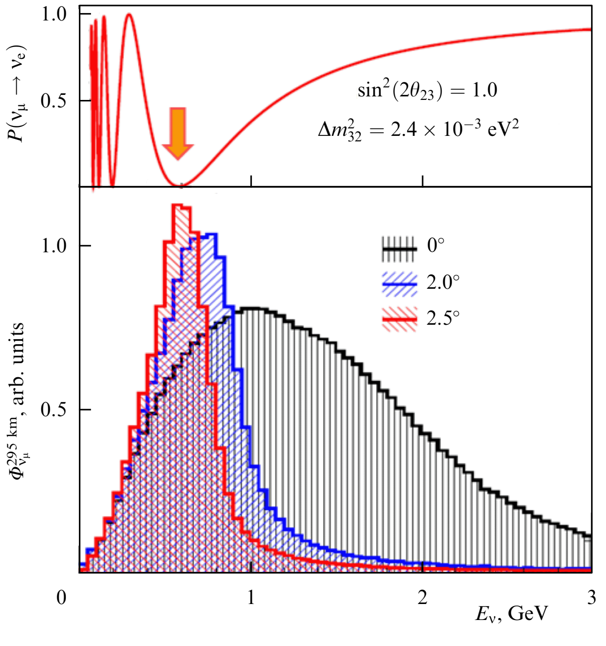

Figure 2. Spectra of muon neutrinos for angles 0°, 2.0°, and 2.5° near the target, i.e., before possible oscillations. The upper part of the picture shows the oscillation curve (the probability of ν_μ disappearance) for a distance of 295 km and oscillation parameters $\Delta m_{23} = 2.4 \times 10^{-3}$ eV^2, $\sin^2(2\theta_{23}) = 1$. The maximum in oscillations (indicated by the arrow) corresponds to a neutrino energy of about 600 MeV.

acting with nucleons owing to charged currents and also to achieve significant suppression of the backgrounds, among which those due to neutral pions produced by all sorts of neutrinos via neutral currents are dominant. The problem consists in identification of π^0 in the asymmetric decay $\pi^0 \to \gamma\gamma$, when one of the photons has a small energy, which only leads to a small number of the Super-Kamiokande photomultipliers being fired and to the detection of the Cherenkov ring of this particular photon being rendered difficult. Particulars of the analysis of experimental data are described in detail in Ref. [29]. The following selection criteria are used in detecting an electron produced by an electron neutrino undergoing quasielastic scattering $\nu_e + n \to e^- + p$ via a charged current: (1) the event in Super-Kamiokande is correlated in time with the J-PARC beam with a precision of ≈ 150 ns; (2) the energy of the neutrino event is fully detected by the internal detector (no activity occurs in the external detector); (3) the neutrino interaction vertex is at a distance longer than 2 m from the walls of the internal detector; (4) the number of rings equals unity; (5) the registered energy of the event exceeds 30 MeV; (6) the ring is electronlike, i.e., it has the fuzzy profile peculiar to electrons and photons, and there is no delayed electron signal. The last condition is required in order to exclude events in which a muonlike ring with a profile exhibiting sharp boundaries would satisfy the selection criteria for an electron ring and thus be identified erroneously. This permits significantly improving the separation of muon and electron rings, because a Michel electron from the decay of a stopped muon is an additional factor leading to identification of the Cherenkov ring as a muon ring.

To reduce the background from π^0, a second electronlike ring related to the event is sought. If it is found, the invariant mass is reconstructed and the condition is imposed that it be less than 105 MeV. The assumption is also made that the registered event is due to quasielastic scattering via a charged current and that the reconstructed neutrino energy is smaller than 1250 MeV. This permits eliminating the high-energy tail, containing a large admixture of ν_e, in the neutrino spectrum.

Monte Carlo simulation reveals that under the above conditions, a significant reduction is to be expected in the level of background events. For example, it turns out to be possible to suppress the $\pi^0 \to 2\gamma$ decays by a factor of

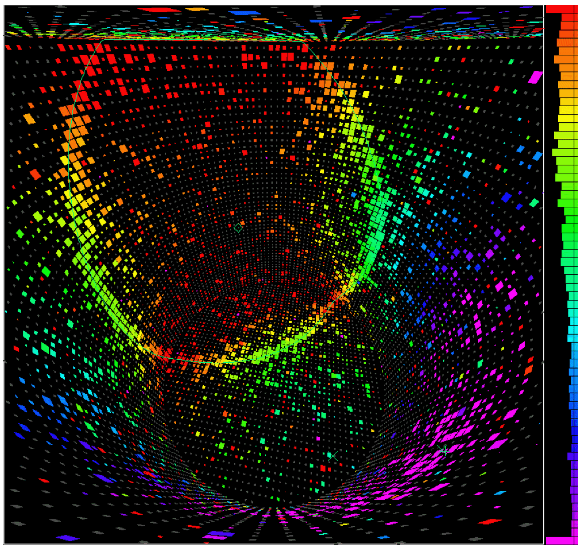

Figure 3. (In color online.) Typical electronlike event in Super-Kamiokande. The parallelograms, squares, and rectangles show the locations of the fired photomultipliers. Their size is proportional to the signal, while the color reflects the registration times of the signals: violet indicates early firing, red later, and grey the absence of any signal.

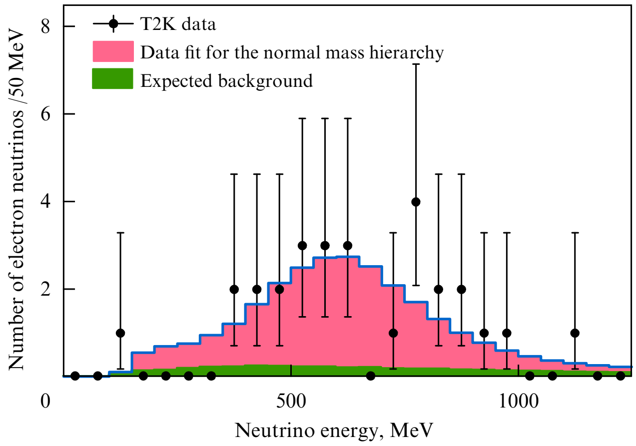

Figure 4. (In color online.) Energy distribution of the 28 electron neutrinos registered by Super-Kamiokande. The histograms show the fitting of the signal for a normal neutrino mass hierarchy (in red) and the expected background (in green).

approximately 300 and at the same time to preserve the high registration efficiency of the expected signal (~ 40%). In total, Super-Kamiokande registered 532 events due to neutrinos that covered the distance of 295 km from J-PARC. The energy of each of these events was fully measured by the internal detector in the absence of any signal from the external detector. The background expected from atmospheric neutrinos amounted to 0.07 events.

Upon application of all the aforementioned selection criteria, 28 electronlike events that were candidates for electron neutrinos were found [35]. One such event is shown in Fig. 3. The number of electronlike events expected in the absence of $\nu_\mu \to \nu_e$ oscillations ($\theta_{13} = 0$) would have only amounted to (4.64 ± 0.52) during the measurement time. The energy distribution of the 28 events and the expected background are shown in Fig. 4. Statistical analysis reveals the measured effect of the appearance of ν_e, i.e., of the $\nu_\mu \to \nu_e$ oscillation, to be 7.5σ. The probability of a random statistical fluctuation resulting in the observed excess of ν_e in the ν_μ beam is extremely small ($< 10^{-12}$). This result is the first direct observation of muon neutrinos transforming into electron neutrinos, i.e., neutrino oscillations have been observed for the first time as the appearance of ν_e in a pure ν_μ beam, while in previous oscillation experiments, the disappearance of different sorts of neutrinos was measured.

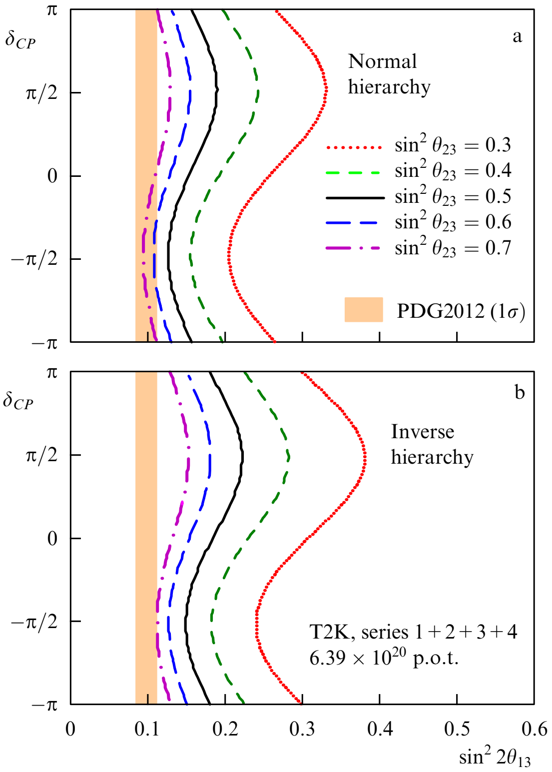

Figure 5. The preliminary T2K result showing the dependence of δ on $\sin^2(2\theta_{13})$ for several possible values of the mixing angle $\sin^2(\theta_{23})$: (a) normal and (b) inverted neutrino mass hierarchy. The solid black curve corresponds to the maximum mixing $\theta_{23} = \pi/4$. Also presented is the value of $\sin^2(2\theta_{13})$ obtained in reactor experiments (denoted as PDG2012).

The dependence of the *CP*-odd phase δ on the value of $\sin^2(2\theta_{13})$ for the normal and inverted mass hierarchies is shown in Fig. 5, where also shown is the value of $\sin^2(2\theta_{13})$ obtained in reactor experiments [27]. 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 $\delta \approx -\pi/2$.

We also note that in two more experiments, evidence was found of the appearance of ν_τ, i.e., of the direct observation of $\nu_\mu \to \nu_\tau$ oscillations. In the Super-Kamiokande experiment with atmospheric neutrinos, an excess of ν_τ registered in the detector was observed at the level of 3.8σ, as compared with the flux expected in the absence of oscillations [36]. In the long-base experiment OPERA (Oscillation Project with Emulsion-tRacking Apparatus), in which searches for $\nu_\mu \to \nu_\tau$ oscillations are under way, three ν_τ have been found at present against an expected background of 0.23 events, and the effect due to the appearance of ν_τ in the ν_μ beam amounts to 3.5σ [37].

4. How to search for *CP* violation in the lepton sector

A fundamental issue to be resolved by neutrino physics is whether *CP* invariance is violated in neutrino oscillations. The Jarlskog (C Jarlskog) parameter J_{CP} [38], characterizing the degree of *CP* violation, has the following form for neutrinos, or, in other words, in the lepton sector:

$$J_{CP}^{\mathrm{PMNS}} = \cos\theta_{12}\sin\theta_{12}\cos^2\theta_{13}\sin\theta_{13}\cos\theta_{23}\sin\theta_{23}\sin\delta\,. \quad (3)$$

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 $\delta \neq 0$. *CP* violation in the quark sector is $J_{CP}^{\mathrm{CKM}} \sim 3 \times 10^{-5}$, while for the lepton sector, $J_{CP}^{\mathrm{PMNS}} \sim 0.035 \sin\delta$. We emphasize that hopes for *CP* violation in the quark sector, being the key to understanding the baryon asymmetry of the Universe, were not justified owing to the smallness of J_{CP}^{CKM}. Taking into account that 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), as 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 turn out to represent important indirect arguments in favor of the explanation of the 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. This is due to the second *CP*-even term in expression (1) being strongly suppressed owing to the smallness of α^2. At the same time, as is seen from expression (2), the effect of matter simulating *CP* violation is proportional to the neutrino energy, and therefore this false effect must be separated from the *CP* violation effect. It must be noted that, in the case of small neutrino energies (500–700 MeV) and, accordingly, relatively small experimental baselines (200–300 km), the effect of matter is not dominant. If, for simplicity, we consider oscillations in the vacuum, then the *CP* asymmetry can be expressed as

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

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 between the experimental baseline L and the neutrino energy E is optimal and constant, the *CP* asymmetry does not depend on the neutrino energy. Thus, the asymmetry A_{CP} can be measured in experiments with neutrino and antineutrino beams. Another method consists of 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 sole neutrino beam, if the mass hierarchy is known.

The rapid progress in measuring the angle θ_{13} and its unexpectedly large value not only led to a revision of theoretical models describing neutrino mixing and to the formulation of new crucial questions for the theory, but also significantly altered the entire landscape of the accelerator neutrino physics. The value of θ_{13} being 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 neutrino beams and detectors that are currently available. At the same time, the long-term strategy has changed for planned experiments of the next generation, whose main goal has now become a high-sensitivity search for *CP* violation using the $\nu_\mu \to \nu_e$ oscillation mode.

5. Short-term prospects

Before briefly discussing short-term plans and expected results of long-baseline experiments, we touch upon certain important aspects related to the measurement of the mass hierarchy and to the revelation of *CP* violation in neutrino oscillations. Information on the mass hierarchy plays a particularly important role for experiments in search of neutrinoless double beta-decay. In the inverted mass hierarchy, the sensitivity of planned experiments permits observing this process, which would be an unambiguous proof of the Majorana nature of the neutrino. This would also mean that two of the three masses should be practically identical, which is not observed in the mass spectrum of charged leptons and quarks. Moreover, determination of the mass hierarchy will serve as an important key is determining the absolute neutrino mass scale, formation mechanism represents one of the greatest mysteries of elementary particle physics. The nonzero *CP* phase δ measured in neutrino oscillations, i.e., at low energies, is a fundamental parameter. Although no model-independent indications of any relation between the *CP* symmetry in neutrino oscillations and the asymmetry in heavy neutrino decays in the early Universe exist, the elegant explanation of neutrino mass via the see-saw mechanism, which relates heavy neutrinos of masses $10^{10} - 10^{15}$ GeV and light active neutrinos, may turn out to be a bridge between these two asymmetries.

What sensitivity to the mass hierarchy and to δ can be expected of the current T2K and NOνA experiments? NOνA (NuMI (Neutrinos at the Main Injector) Off-Axis ν_e Appearance Experiment) has a baseline 810 km long, has the average energy of the off-axis neutrino beam about 2.2 GeV, and started data accumulation in September 2013. Assuming the total integral T2K luminosity to be 8×10^{21} p.o.t. and data taking in the NOνA experiment to continue for six years (three years with the neutrino beam and three years with the antineutrino beam) at a beam power of 700 kW, the combined analysis of data on the appearance of ν_e in both experiments will permit achieving a sensitivity at a level of 2σ for the phase $\delta = \pi/2$ or $-\pi/2$. A sensitivity to the mass hierarchy at a level of $\sim 3\sigma$ can also be achieved for δ values of around $\pi/2$ and $-\pi/2$ [39].

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

(1) LBNE (Long-Baseline Neutrino Experiment) (USA) [40]. This experiment is to use a broad neutrino beam from the Fermi National Accelerator Laboratory directed toward a far detector located at a distance of 1300 km in the vicinity of the

Homestake mine (South Dakota, USA). Several versions of the detector and its location (on the surface or underground) are being considered. The most probable one will be a liquid-argon detector with a mass of 34 kt, situated in the mine underground. Utilization of a 700 kW proton beam for 10 years of data taking (5 years with the neutrino beam and 5 years with the antineutrino beam) should permit achieving a sensitivity to the phase δ at a level $\geqslant 3\sigma$ for 60% of the entire available range of phases from $-\pi$ to π. The experiment can also determine the mass hierarchy with a significance of about 3σ about a year after data taking with the neutrino beam is completed.

(2) LAGUNA-LBNO (Large Apparatus studying Grand Unification and Neutrino Astrophysics–Long Baseline Neutrino Oscillation Experiment) project [41]. In Europe, the possibility of an experiment using the neutrino beam from CERN directed toward the Pyhäsalmi mine (Finland), which is to house a neutrino detector representing a liquid-argon time-projection chamber of mass 70 kt, is under consideration. A wide neutrino beam with energies in the 1–9 GeV range and an experimental beamline 2300 km long will permit measuring $\nu_\mu \to \nu_e$ oscillations at the first and second oscillation maxima, which determines the unique sensitivity of the experiment to the mass hierarchy ($> 5\sigma$) for the entire aforementioned range of values of the *CP*-odd phase and permits revealing the effect of *CP* violation for 60% of the values of δ.

(3) Hyper-Kamiokande project (Japan) [42]. The purpose of the experiment is a high-sensitivity search and measurement of δ using intense off-axis neutrino and antineutrino beams from J-PARC, tuned to the first oscillation maximum, and of a gigantic megaton water Cherenkov detector situated at a distance of 295 km from J-PARC. The proton beam power planned to be achieved is 1.66 MW, which, in five years of data taking, will permit obtaining a sensitivity to δ better than 3σ in the range of over 70% of the possible values of this parameter. However, such a sensitivity may be obtained 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.

6. Conclusion

The discovery of $\nu_\mu \to \nu_e$ oscillations in the T2K experiment and the nonzero and unexpectedly large value of the angle θ_{13} measured in reactor and accelerator experiments has dramatically altered the situation in accelerator neutrino physics and opened up a unique possibility of searching for *CP* violation in the lepton sector and determining the neutrino mass hierarchy in long-baseline accelerator experiments. The large value $\theta_{13} \sim 9°$ has significantly increased the chance of measuring the mass hierarchy and of revealing *CP* violation in experiments that are either under way or being planned. The T2K and NOvA experiments under way may provide the first indication of *CP* violation in neutrino oscillations, but global progress in this area can only be expected from next-generation experiments. If *CP* violation is discovered, i.e., if $\delta \neq 0$ and $\delta \neq 180°$, then a broad physics program will open up for long-baseline experiments, the cornerstone of which is a precision measurement of the phase δ, which remains the only parameter of the PMNS matrix still to be measured.

This work has been supported by the program of the RAS Presidium "Fundamental Properties of Matter and Astrophysics" and by the joint RFBR/JSPS (Japan) grant 13-02-92101-NP-a.

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