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Neutrino oscillations: recent results and future prospects

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Contents

Abstract. A brief review of recent results on neutrino oscillations from accelerator and reactor experiments is presented. Emphasis is placed on the indication of *CP* violation in neutrino oscillations obtained in long-baseline accelerator experiments. The latest results of a search for a sterile neutrino are discussed and the nearest-term prospects for long and short-baseline oscillation experiments are outlined.

Keywords: neutrino oscillations, sterile neutrino, *CP* violation, neutrino mass hierarchy, short and long baseline experiments

1. Introduction. Present-day status of neutrino oscillations

The discovery of neutrino oscillations, the hypothesis that was put forward by Pontecorvo [1, 2], turned out to be one of the most interesting events in particles physics in the past two decades. This achievement merited a Nobel prize in 2015, and the actual result happened to be the first direct experimental proof of the existence of new physics beyond the Standard Model [3, 4]. As follows from oscillations, neutrinos have a small nonzero mass and mix, and the neutrino flavors (lepton numbers) are not conserved. This contradicts the basic principles of the Standard Model, according to which there are three flavors (types) 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, within which active neutrinos of three kinds, ν_e, ν_μ, ν_τ, exhibiting left-handed chirality, are related by a unitary matrix U [5] (the Pontecorvo–Maki–Nakagawa–Sakata mixing matrix, or the PMNS matrix) to mass states ν_1, ν_2, ν_3, to which masses m_1, m_2, m_3 correspond:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}. \quad (1)$$

The matrix U being unitary means that for each of the mass states ν_1, ν_2, ν_3, the total probability of the ν_e, ν_μ, ν_τ mix equals unity. In general, the elements of this matrix are complex quantities. A standard parameterization of 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 and on two mass squared differences, $\Delta m_{21}^2 = m_2^2 - m_1^2$, $\Delta m_{32}^2 = m_3^2 - m_2^2$, and also on the Dirac *CP*-odd phase δ_{CP}. The two Majorana phases present in the U matrix do not influence oscillations of the neutrino flavors. The relations between the elements of matrix (1) and the mixing angles are expressed as:

$$\frac{|U_{e2}|^2}{|U_{e1}|^2} = \tan^2\theta_{12}\,, \quad \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2} = \tan^2\theta_{23}\,,$$
$$U_{e3} = \sin\theta_{13}\exp(-\mathrm{i}\delta_{CP})\,. \quad (2)$$

The physics of neutrino oscillations, the experimental methods, and the obtained results are described in detail in reviews [6–10].

In less than 20 years since the discovery of oscillations, striking progress has been achieved in studies of the oscillation properties of neutrinos carried out in experiments with solar, atmospheric, reactor, and accelerator neutrinos. The mass squared differences characteristic of the oscillations of solar neutrinos, Δm_{21}^2, and of atmospheric neutrinos,

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$|\Delta m^2_{32}|$, and the respective mixing angles have been measured with an accuracy of several percent. These parameters were mainly measured in experiments in which the deficit (disappearance) of neutrinos of a certain flavor was studied. Subsequently, unambiguous confirmation of the phenomenon of oscillations was obtained in experiments dedicated to revealing the appearance of neutrinos of different flavors: the experiment T2K (Tokai-to-Kamioka) discovered $\nu_\mu \to \nu_e$ oscillations [11, 12], and the experiment OPERA (Oscillation Project with Emulsion-tRacking Apparatus) unambiguously confirmed the existence of the process $\nu_\mu \to \nu_\tau$ [13]. The result obtained in T2K was subsequently confirmed in the experiment NOνA (NuMI (Neutrino at the Main Injector) Off-axis ν_e Appearance), in which the appearance of electron neutrinos was also registered in the beam of muon neutrinos [14, 15].

We note that the sign of Δm^2_{32} is unknown, i.e., the mass hierarchy is not fixed. Both the normal neutrino mass hierarchy $m_3 \gg m_2 > m_1$ and the inverse one $m_2 > m_1 \gg m_3$ are possible. The problem of which order of masses is realized in Nature has fundamental significance for understanding the nature of the neutrino mass and the mixing mechanism, and it is also extremely important for the search of neutrinoless double beta-decay and the interpretation of oscillation data in long-baseline experiments.

Measurements of the θ_{13} angle merit particular attention. A real breakthrough took place when the first measurement result of $\nu_\mu \to \nu_e$ oscillations, performed in the T2K experiment and revealing a nonzero value of θ_{13}, was published in 2011 [11]. Accurate measurements of this angle were performed in 2012 in reactor experiments Double Chooz [16], Daya Bay [17], and RENO (Reactor Experiment for Neutrino Oscillation) [18]. Shortly after, this angle was measured with an error close to the standard deviations achieved for the two other mixing angles over 15 years.

Thus, experiments with solar, atmospheric, accelerator, and reactor neutrinos resulted in measurements of three mixing angles, which not only were nonzero but also turned out to be quite large: $\theta_{12} \simeq 34°$, $\theta_{23} \sim 45°$, $\theta_{13} \simeq 9°$, i.e., neutrinos of different flavors, unlike quarks, were revealed to undergo strong mixing. These results determined the main problems and research directions along which, at present, oscillation experiments that are under way or still being planned are focused: searching for *CP* violation in the lepton sector and measuring the *CP*-odd phase, determining the neutrino mass hierarchy, precision measurement of oscillation parameters, and searching for sterile neutrinos.

2. Search for *CP*-symmetry violation and measurements of oscillation parameters

2.1 Search for *CP* violation in neutrino oscillations

The following problem is fundamental: is *CP* invariance violated in neutrino oscillations? The Jarlskog parameter J_{CP} [19], which reveals the degree of *CP* violation in the case of neutrinos or, in other words, in the lepton sector, is expressed as

$$J_{CP}^{\mathrm{PMNS}} = \cos\theta_{12}\sin\theta_{12}\cos^2\theta_{13}\sin\theta_{13}\cos\theta_{23}\sin\theta_{23}\sin\delta_{CP}\,. \tag{3}$$

Because none of the three neutrino mixing angles, as in the case of quarks, is equal to zero, it follows that $J_{CP}^{\mathrm{PMNS}} \neq 0$ if $\delta_{CP} \neq 0$. In the quark sector, $J_{CP}^{\mathrm{CKM}} \sim 3\times10^{-5}$, while in the lepton sector, $J_{CP}^{\mathrm{PMNS}} \sim 0.035\sin\delta_{CP}$.

It must be stressed that hopes that *CP* violation in the quark sector could be the clue to the baryon asymmetry of the Universe are not justified. This is because quark masses are small compared to the characteristic scale of electroweak interactions, ~ 100 GeV. Taking *CP* violation in the quark sector into account yields a baryon asymmetry of the Universe that is approximately 10 orders of magnitude smaller than the observed value [20]. The large values of the mixing angles allow assuming the effect of *CP* violation in the lepton sector to be very significant (depending on the value of δ_{CP}) compared to such an effect in the quark sector.

Thus, the study of neutrino oscillations provides a unique possibility of searching for a new source of *CP* violation. The discovery of *CP* violation in neutrino oscillations, together with nonconservation of the lepton number, may serve as an important indirect argument in favor of the explanation of baryon asymmetry of the Universe on the basis of the leptogenesis mechanism [21]. Although the currently dominant idea implies no direct relation between *CP* violation in the lepton sector at low energies and *CP* asymmetry in the decays of heavy neutrinos in the early Universe, a number of proposed theoretical models establish such relations between these mechanisms [22–24].

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

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar\nu_\mu \to \bar\nu_e)}{P(\nu_\mu \to \nu_e) + P(\bar\nu_\mu \to \bar\nu_e)} \simeq -\frac{\cos\theta_{23}\sin(2\theta_{12})}{\sin\theta_{23}\sin\theta_{13}}\sin\frac{\Delta m^2_{21}L}{4E}\sin\delta_{CP}\,, \tag{4}$$

whence it follows that A_{CP} can be measured in experiments with neutrino and antineutrino beams. The value of A_{CP} is proportional to $1/\sin\theta_{13}$, while the probabilities $P(\nu_\mu \to \nu_e)$ and $P(\bar\nu_\mu \to \bar\nu_e)$, i.e., the number of registered electron neutrinos (antineutrinos) produced as a result of oscillations is proportional to $\sin^2(2\theta_{13})$. In the case of measurements of $\nu_\mu \to \nu_e$ and $\bar\nu_\mu \to \bar\nu_e$ transitions at the oscillation maximum, i.e., in the case of an optimal and constant ratio of the experimental baseline L and the neutrino (antineutrino) energy E, the value of *CP* asymmetry is independent of the neutrino (antineutrino) energy. With the use of the θ_{13} angle measured accurately in reactor experiments and with the probability $P(\nu_\mu \to \nu_e)$ that depends on θ_{13} and δ_{CP}, it is also possible to impose constraints on the region of values of the *CP*-odd phase. Analysis of data obtained by the T2K experiment using the muon neutrino and antineutrino oscillation data, together with constraints on the value of θ_{13} from reactor data, are presented below.

The first search for *CP*-symmetry violation was carried out in the T2K experiment using a pure off-axis quasimonoenergetic beam (shifted from the direction of the proton beam at 2.5°) of muon neutrinos (antineutrinos) created at the high-intensity proton accelerator J-PARC (Japan Proton Accelerator Research Complex). The neutrino (antineutrino) energy was tuned to the first oscillation maximum corresponding to oscillations of atmospheric neutrinos with $\Delta m^2 \sim 2.4\times10^{-3}$ eV^2. The neutrino beam parameters were

measured before the instant of possible oscillations by an array of the near neutrino detectors. The baseline in the experiment was 295 km; a water Cherenkov Super-Kamiokande (SK) detector was used as the far neutrino detector. A detailed description of the experiment, the experimental setup, the measurement technique, and the data analysis are presented in Refs [25–29].

The first signs of maximum *CP* violation in neutrino oscillations were revealed in the T2K experiment in 2013 [12]. For this purpose, a combination of the measured $\nu_\mu \to \nu_e$ transition probability and the value of θ_{13} obtained in reactor experiments was used. At the beginning of 2017, T2K published the results of the first direct search for CP-violation based on a comparison of $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$. Then, in 2017, the first result was published of searches for *CP* violation by the NOνA experiment (USA), which has a baseline 810 km long and an average energy of the off-beam neutrino beam of about 2.2 GeV. In this experiment, the $\nu_\mu \to \nu_e$ oscillation probability was measured, and the θ_{13} value from reactor experiments was used to obtain information on *CP* violation. The NOνA result [15] is in agreement with the T2K data, and it also points to maximum *CP*-violation.

Since the first publication, the T2K experiment significantly increased statistics of neutrino events. During the period between 2010 and 2017, the experiment collected statistics corresponding to an integral flux of 2.25×10^{21} protons on target. The ratio between the running times with the muon neutrino beam and the muon antineutrino beam was approximately 2:1. Substantial progress was also achieved in data analysis. The algorithms for the selection of neutrino events in Super-Kamiokande were improved, the contribution of the background of neutral pions produced in neutrino interactions via neutral currents to the number of electron events was reduced, the active volume of Super-Kamiokande was increased, and the oscillation analysis included events in which an electron was registered together with a pion in the Super-Kamiokande detector. This allowed improving the registration efficiency of useful events by 30%. The new result obtained in the summer of 2017 by the T2K experiment was presented at several conferences (see, e.g., Ref. [30]). The numbers of electron neutrinos and antineutrinos registered in Super-Kamiokande upon application of all selection criteria are presented in the Table. A total of 89 electron neutrinos were registered, while in the case of *CP*-symmetry conservation, about 67 events were expected. Seven electron antineutrinos were registered with the muon antineutrino beam, while in the case of *CP*-symmetry conservation, only nine events were expected.

Results of an oscillation analysis for the scheme with three active neutrinos and antineutrinos are shown in Fig. 1.

Table. Numbers of electron neutrinos and antineutrinos registered by the far Super-Kamiokande detector and the respective numbers predicted for different values of the *CP*-odd phase δ_{CP}.

Particle	Number of events				
	T2K data	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$
ν_e	74	73.5	61.5	49.9	62.0
$\nu_e + 1\pi$	15	6.92	6.01	4.87	5.78
$\bar{\nu}_e$	7	7.93	9.04	10.04	8.93

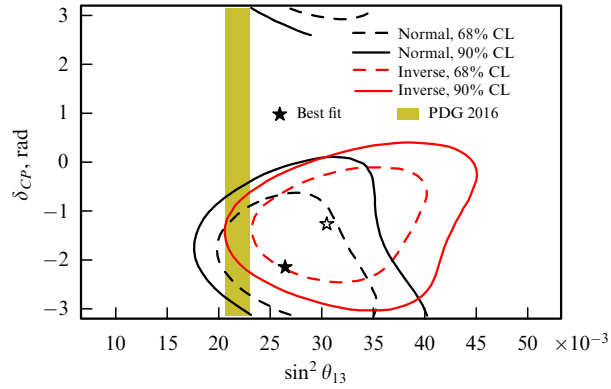

Figure 1. (Color online.) Preliminary T2K result showing the allowed region of δ_{CP} and $\sin^2\theta_{13}$ values in the case of normal and inverse mass hierarchies. The darkened band, indicated as PDG 2016, shows the interval of $\sin^2\theta_{13}$ values from reactor experiments. Asterisks show the best-fit values for the normal (black curves) and inverse (red curves) neutrino mass hierarchies.

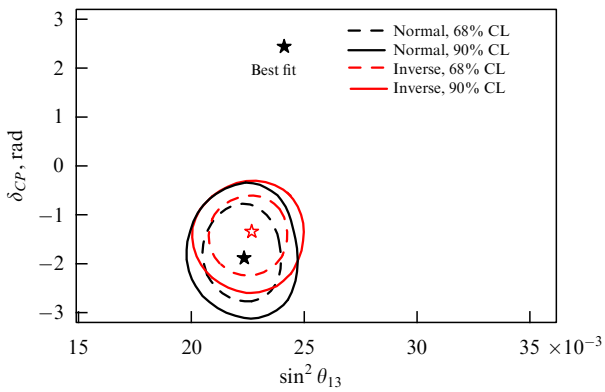

Figure 2. (Color online.) Region of allowed δ_{CP} and $\sin^2\theta_{13}$ values obtained in the T2K experiment (preliminary result) for normal and inverse mass hierarchies under the condition of restrictions from reactor experiments being imposed on the $\sin^2\theta_{13}$ values within the interval $\pm 1\sigma$. Asterisks indicate the best fit result for data in the cases of normal (black color) and inverse (red color) neutrino mass hierarchies.

With the value $\sin^2\theta_{13} = 0.0210 \pm 0.0011$ obtained from reactor experiments [31], the allowed region of possible values of the *CP*-odd phase can be additionally restricted. Figure 2 shows the confidence intervals in the $(\delta_{CP}, \sin^2\theta_{13})$ plane with account of the additional restriction on $\sin^2\theta_{13}$ from reactor data. The statistical significance with which δ_{CP} deviates from the value giving the best description of oscillation data for the normal and inverse mass hierarchies is shown in Fig. 3. The experimental data are best described for the value of the *CP*-odd phase $\delta_{CP} = -1.83^{+0.60}_{-0.66}$ rad for the normal mass hierarchy, which is close to the maximum *CP* violation. From Fig. 3, the values $\delta_{CP}=0, \pi$ are seen to be beyond the allowed confidence interval of 2σ. For example, the region of allowed δ_{CP} values for the confidence interval of 90% is limited to the interval $[-161°, -48°]$ for the normal mass hierarchy. Thus, the T2K result for the first time excludes conservation of *CP* symmetry in neutrino oscillations at the level of a 95% (2σ) confidence interval. This result makes previous indications of maximum *CP* violation in neutrino oscillations [12, 15, 32] even more significant.

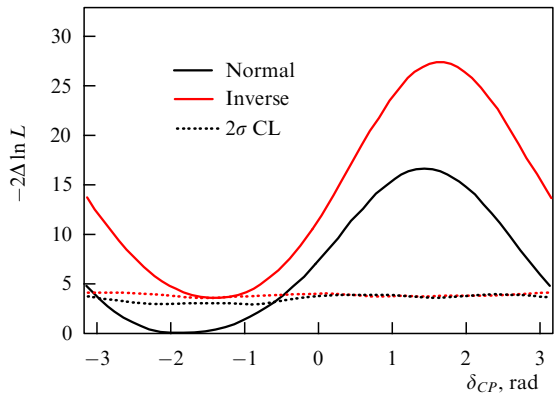

Figure 3. (Color online.) Dependence of the maximum likelihood function $-2\Delta\ln L$ on the δ_{CP} value for normal (black solid curve) and inverse (red solid curve) mass hierarchies. The dotted curves show the 95% confidence level (CL) of probability for normal and inverse mass hierarchies. The regions of δ_{CP} values corresponding to values of the likelihood function above the dotted curves are excluded at a level of 2σ (95% CL).

2.2 Measurements of oscillation parameters

The investigation of neutrino oscillations reveals the mixing of muon and tau neutrinos to be nearly maximal, i.e., the angle θ_{23} is close to $\pi/4$. However, it is not known whether it is precisely equal to $\pi/4$ or whether it differs a little from this value. The determination of the mass hierarchy and accurate measurement of the θ_{23} angle are extremely important both for the interpretation of oscillations of muon neutrinos (antineutrinos) into electron neutrinos (antineutrinos) and for sensitive searches for CP violation and measurements of the CP-odd phase δ_{CP}.

Recently, new results were published on measurements of the parameters $|\Delta m^2_{32}|$ and $\sin^2\theta_{23}$ in experiments with atmospheric neutrinos (IceCube [33] and Super-Kamiokande [35]) and accelerator neutrinos (T2K [32] and NOνA [15]). These results, as well as earlier data obtained in the MINOS (Muon Injector Neutrino Oscillation Search) experiment [34] are shown in Fig. 4. In a recent publication [37], the Super-Kamiokande collaboration somewhat reduced the allowed region of parameters $|\Delta m^2_{32}|$ and $\sin^2\theta_{23}$. We emphasize that a discrepancy exists between the results presented by T2K, IceCube, and Super-Kamiokande, pointing to maximal mixing, and data from the NOνA experiment that rule out maximal mixing at a level of 2.6σ. Because all the above experiments are collecting data, an explanation of the difference between the values of θ_{23} obtained in these experiments can be expected to appear quite soon, and may turn out to be a purely statistical fluctuation.

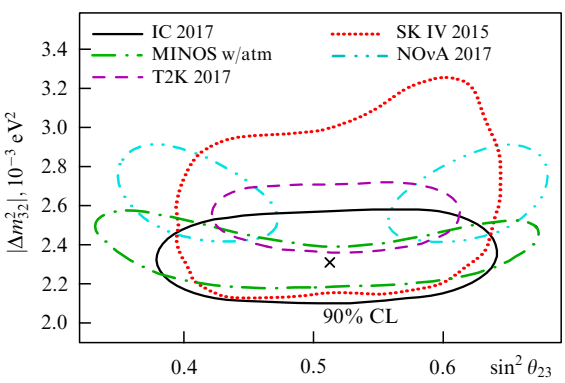

Figure 4. (Color online.) Regions of 90% confidence intervals in the plane of parameters $|\Delta m^2_{32}|-\sin^2\theta_{23}$, obtained under the assumption of the normal mass hierarchy in the experiments IceCube (IC 2017) [33], MINOS (MINOS w/atm) [36], T2K (T2K 2017) [32], NOνA (NOνA 2017) [34], and Super-Kamiokande (SK IV 2015) [35].

The most precise values for the θ_{13} angle were obtained in 2017 in the Daya Bay experiment [38]: $\sin^2(2\theta_{13}) = 0.0841\pm 0.0027(\text{stat.}) \pm 0.0019(\text{syst.})$. The result presented by the RENO experiment with a larger error, $\sin^2(2\theta_{13}) = 0.086\pm 0.006(\text{stat.}) \pm 0.005(\text{syst.})$ [39], is in good agreement with the Daya Bay result. However, it must be noted that a discrepancy at a level of $\sim 2\sigma$ exists between the most precise Daya Bay result and the latest measurements by the Double Chooz experiment, which recently presented a preliminary result [40]: $\sin^2(2\theta_{13}) = 0.119 \pm 0.016$. The level of significance of this discrepancy will be revealed in the nearest future, because these experiments are running, systematic errors are being analyzed, and data analysis is improving.

As was noted above, determination of the neutrino mass hierarchy is one of the key problems for oscillation experiments. The first results in resolving this problem have appeared recently. Owing to a long baseline (810 km), the NOνA experiment is quite sensitive to the neutrino mass hierarchy. The results of $\nu_\mu \to \nu_e$ measurements point to the existence of a normal mass hierarchy. For example, in the case of $\theta_{23} < \pi/4$, the inverse mass hierarchy is ruled out at a level of $> 93\%$ for all values of δ_{CP} [15]. Analysis of the data collected by the Super-Kamiokande detector in a 328 kt years exposition points to a preference for the normal mass hierarchy [37]. In the case of 90% confidence intervals for oscillation parameters, the Super-Kamiokande data reject the inverse hierarchy with a probability between 80.6% and 90.6%. Using the T2K data for imposing additional constraints allows Super-Kamiokande to reject the inverse mass hierarchy at a level of 91.4–94.4%. For fixed values of θ_{13} from reactor experiments and for $\delta_{CP} \sim -\pi/2$ from T2K, the statistical significance of the solution in favor of the normal mass hierarchy amounts to about 2.3σ [36].

3. Search for light sterile neutrinos

As noted in Section 1, oscillation results are described within a scheme involving three weakly interacting neutrinos, two independent quantities Δm^2, and three mixing angles. However, several so-called neutrino anomalies cannot be explained in the framework of such an approach, and they probably point to the existence of at least one more additional neutrino state (a sterile neutrino) of mass ~ 1 eV.

(1) In the short-baseline neutrino experiment LSND (Liquid Scintillator Neutrino Detector) [41], in which the mixing of muon antineutrinos and electron antineutrinos was studied and an excess of electron antineutrinos was found at a level of 3.8σ for the ratio $E/L \sim 1$ eV^2. A test of this effect was performed in the experiment MiniBooNE (Mini Booster Neutrino Experiment) [42], the results of which were on the whole in agreement with the LSND result; however, the sensitivity achieved in MiniBooNE did not provide unambiguous confirmation or refutation of the LSND result.

(2) In the case of measurements with artificial neutrino sources in the experiments SAGE (Soviet–American Gallium Experiment) and GALLEX (Gallium Experiment), the number of registered events was smaller than expected. The statistical significance of the effect (the 'gallium anomaly') amounted to about 2.9σ. This deficit can also be explained by

oscillations between electron neutrinos and sterile neutrinos with $\Delta m^2 \sim 1$ eV^2 [43, 44].

(3) A new estimate of the antineutrino flux from reactors in [45] showed that this flux was about 3% higher than the previous value used for a long time in reactor experiments. The neutrino fluxes measured in different experiments at distances $\leqslant 100$ m from the core of the reactor turned out to be less than the fluxes determined for these distances on the basis of Ref. [45]. Such a discrepancy between the predicted and measured antineutrino fluxes could be explained by the antineutrinos disappearing due to oscillations with $\Delta m^2 \sim 1$ eV^2. This effect, whose statistical significance amounted to 2.8σ, was termed the 'reactor anomaly'.

It must be noted, however, that the results obtained by LSND and MiniBooNE (the appearance of electron neutrinos and antineutrinos) contradict the results of the MINOS experiment (the disappearance of muon neutrinos), which did not see the deficit of muon neutrinos [46] expected in the case of oscillations with $\Delta m^2 \sim 1$ eV^2. Also unexpected was the observation in the Daya Bay, RENO, and Double Chooz reactor experiments of a bump in the antineutrino spectrum at an energy of about 5 MeV (see, e.g., a discussion of this effect in Ref. [47]), which was not predicted by theoretical models, raising the issue of the reliability of the prediction of an antineutrino flux or an overestimation of the statistical significance of the reactor anomaly. New results obtained recently concerning the search for sterile neutrinos are outlined in Sections 3.1, 3.2.

3.1 Test of the 'LSND anomaly'

3.1.1 IceCube. The IceCube installation was used to measure the spectrum of atmospheric neutrinos ($\nu_\mu + \bar{\nu}_\mu$) as a function of the zenith angle within the range of energies from 320 GeV up to 20 TeV [48]. For neutrino energies > 100 GeV, the period of oscillations for the 'atmospheric' mass squared difference becomes larger than the diameter of Earth, and this effect can be disregarded. The existence of a sterile neutrino with a characteristic range 0.1–10 eV^2 for the mass squared difference with respect to the active neutrino within the $3+1$ scheme (3 active neutrinos + 1 sterile neutrino) leads, owing to the Mikheyev–Smirnov–Wolfenstein effect, to a distortion of the spectrum, which can be measured by the IceCube detector. The result of the analysis of data accumulated for one year is presented in Fig. 5, which shows the restrictions on the region of parameters $\Delta m^2_{41} - \sin^2(2\theta_{24})$ within the $3+1$ scheme. The region of parameters corresponding to a 'positive' LSND/MiniBooNE signal, i.e., a signal pointing to the existence of a sterile neutrino, is ruled out at a confidence level (CL) of 99%.

3.1.2 Daya Bay/MINOS. A sensitive search for a sterile neutrino was also performed in the Daya Bay reactor experiment [51] and in the MINOS accelerator experiment [52]; the result of a joint analysis is presented in Ref. [53]. For this analysis, the data from the Bugey-3 reactor experiment were also used [54]. First of all, it must be noted that the search for sterile neutrinos in the experiments LSND and MiniBooNE was performed in the framework of the investigation of $\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$ oscillations. In the $3+1$ scheme for a unitary 4×4 mixing matrix that is actually an extension of the matrix U, the probability of oscillations is expressed as follows:

$$P(\nu_\mu \to \nu_e) \approx 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \quad (5)$$

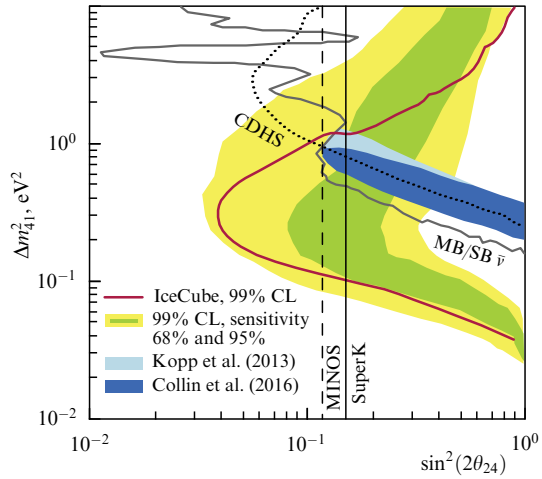

Figure 5. (Color online.) Result obtained by IceCube in the search for a sterile neutrino [48]. The region to the right of the solid dark-brown curve is excluded at a 99% CL. Constraints obtained in other experiments are also shown. The regions of allowed sterile neutrino parameters obtained on the basis of the global analysis of LSND/MiniBooNE data are shown in light blue [49] and blue [50]. The following notation is used: CDHS: CERN–Dortmund–Heidelberg–Saclay, MB: MiniBooNE, SB: SciBooNe.

for the region of parameters where $\Delta m^2_{41} \gg |\Delta m^2_{32}|$ and $\Delta m^2_{32} L/(4E) \sim 0$. The presence of the nonzero amplitude $4|U_{e4}|^2|U_{\mu 4}|^2$ is a possible explanation of the results obtained by LSND and MiniBooNE. The reactor experiment with a short baseline, in which the deficit of electron antineutrinos is measured, is sensitive to the matrix element $|U_{e4}|^2$ because

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - 4|U_{e4}|^2\left(1 - |U_{e4}|^2\right) \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right). \quad (6)$$

The accelerator experiment that measures the deficit of muon neutrinos is sensitive to $|U_{\mu 4}|^2$:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - 4|U_{\mu 4}|^2\left(1 - |U_{\mu 4}|^2\right) \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right). \quad (7)$$

Because the appearance of electron neutrinos in the beam of muon neutrinos requires the conditions $|U_{e4}| > 0$ and $|U_{\mu 4}| > 0$ to be satisfied, it follows that the sterile neutrino effect, if it was actually found in $\nu_\mu \to \nu_e$ oscillations, should also show up in measurements of the deficit of ν_μ and ν_e in experiments with energies and baselines tuned to the expected value $\Delta m^2_{41} \sim 1$ eV^2. The results of a joint analysis of the Daya Bay, MINOS, and Bugey-3 experiments are shown in Fig. 6, where the region of oscillation parameters excluded by the joint analysis is compared with the region preferred by the LSND and MiniBooNE experiments. A clear contradiction is seen to exist between these results.

3.2 Test of the 'reactor anomaly'

3.2.1 Reactor experiment NEOS. The NEOS (Neutrino Experiment for Oscillation at Short Baseline) reactor experiment [55] was performed in Korea at the Hanbit nuclear power plant, where the RENO experiment is underway. The detector was situated at a distance of about 24 m from the center of the core of the nearby reactor with a power of 2.8 GW, which permitted performing a sensitive search for sterile neutrinos with a mass of about 1 eV. The result of the

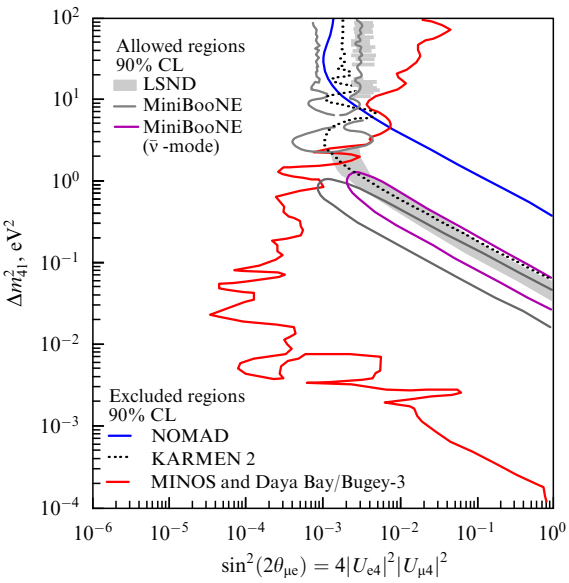

Figure 6. (Color online.) Results of a joint analysis of the data from MINOS, Daya Bay, and Bugey-3. Results from the experiments NOMAD (Neutrino Oscillation MAgnetic Detector) and KARMEN 2 (KArlsruhe–Rutherford interMediate Energy Neutrino 2) are also presented. The region of parameters to the right of the red curve is excluded at a 90% CL. Also shown are the regions preferred by the LSND and MiniBooNE experiments.

experiment is presented in Fig. 7. A new constraint on the mixing angle θ_{14} of active and sterile neutrinos for $\Delta m^2_{41} \sim 1$ eV^2 is obtained in the experiment, and the region of mixing parameters of active and sterile neutrinos, determined from the 'reactor anomaly', is limited but not totally excluded.

3.2.2 Reactor experiments DANSS and Neutrino-4. The DANSS (Detector of the reactor AntiNeutrino based on Solid Scintillator) short-baseline reactor experiments [56], which is underway at the Kalinin nuclear power plant, and 'Neutrino-4' [57] at the reactor CM-3 with a power 100 MW in Dimitrovgrad have also presented preliminary results of their data analysis. The results of the DANSS experiment based on measurements of the spectrum of antineutrinos at distances between 10.7 and 12.7 m from the core center are shown in Fig. 8. DANSS, like NEOS, significantly constrains the allowed region of mixing parameters and excludes the most probable values of the mass squared difference and the mixing angle between active and sterile neutrinos. The Neutrino-4 experiment measures the flux of antineutrinos at distances of 6–10 m from the center of the reactor core. A preliminary data analysis of this experiment shows no deviation of the antineutrino flux, characteristic of the existence of sterile neutrinos, from the function $\sim 1/R^2$, where R is the distance from the core center to the detector. DANSS and Neutrino-4 continue data taking, and their sensitivity to sterile neutrinos is to be improved in the nearest future.

4. Expected results and further prospects

What sensitivity to the mass hierarchy and to δ_{CP} can be expected from the current experiments T2K and NOνA? We assume the total integral luminosity of T2K to amount to 8×10^{21} protons on target (POT), which will permit a sensitivity at the level of $\sim 2\sigma$ to be achieved for the phase $\delta_{CP} = -\pi/2$. At present, a proposal concerning the second stage of this experiment, T2K-II, is under discussion. Here, the integral flux of 20×10^{21} POT is to be collected, and the sensitivity to the effect of CP violation to be achieved is about 3σ if $\delta_{CP} = -\pi/2$. The NOνA experiment will continue data taking for six years (three years with a neutrino beam and three years with an antineutrino beam) with the beam power of 700 kW. The sensitivity expected to be achieved for values of the phase $\delta_{CP} = \pi/2$ or $-\pi/2$ will be at a level $> 2\sigma$. The

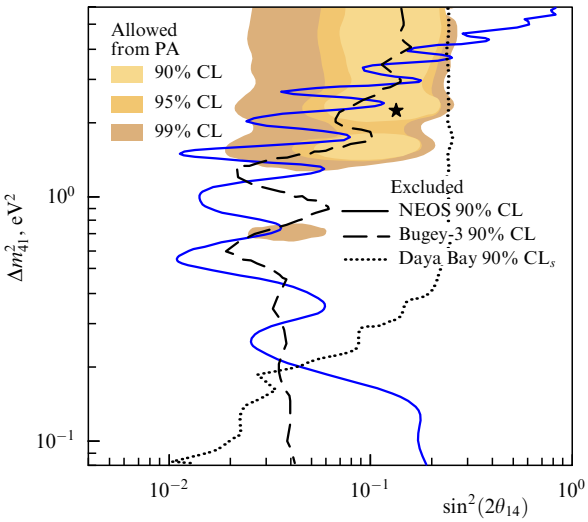

Figure 7. (Color online.) Constraints on the oscillation parameters in the 3 + 1 scheme for sterile neutrinos obtained in the NEOS experiment. The region to the right of the solid blue curve is excluded at a 90% CL. The allowed region of parameters for sterile neutrinos from the reactor anomaly (RA) [45] is shown in dark color. The asterisk indicates the optimal values of parameters Δm^2_{41} and $\sin^2(2\theta_{14})$ for the sterile neutrino, following from the RA. Constraints from the Daya Bay and Bugey-3 experiments are also shown.

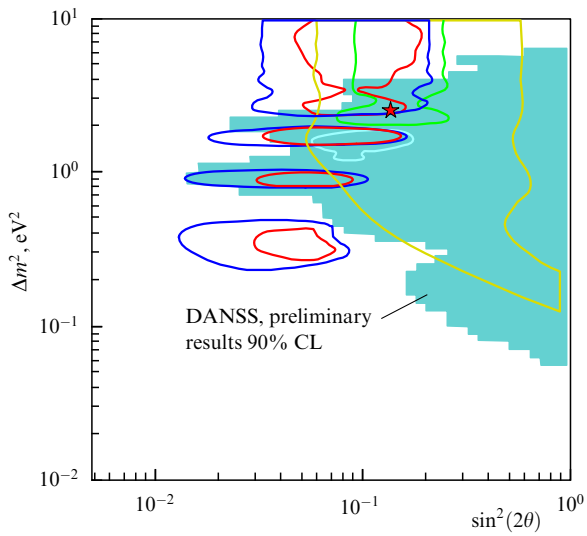

Figure 8. (Color online.) Preliminary constraints on the oscillation parameters in the 3 + 1 scheme for sterile neutrinos obtained in the DANSS experiment [56]. The blue region is excluded at a 90% CL. The asterisk shows the optimal values of parameters Δm^2 and $\sin^2(2\theta)$ for a sterile neutrino, which follow from the reactor anomaly. The curves of different colors identify allowed regions according to the results of different experiments. (The figure is adapted from Ref. [58].)

sensitivity to the mass hierarchy to be obtained in the NOνA experiment can reach a level $\sim 3\sigma$ for the above values of δ_{CP}. A plan is being discussed for continuing data taking in the NOνA experiment to 2024. Starting in 2019, the power of the proton beam to be used should amount to 800 kW, and in 2021 the power should amount to 900 kW. If this plan is realized, NOνA can achieve a statistical significance of about 4.5σ with respect to the mass hierarchy and exclude *CP* conservation at a level of 3σ [59].

At present, plans are being made for two long-baseline accelerator experiments, the main goals of which include a sensitive search for *CP* violation and determining the neutrino mass hierarchy, and one long-baseline reactor experiment aimed at determining the neutrino mass hierarchy.

DUNE (*Deep Underground Neutrino Experiment*). DUNE (USA) [60] will use the neutrino beam from the Fermi National Accelerator Laboratory (Fermilab), and the far neutrino detector will consist of four liquid-argon time-projection chambers. Two types of detectors are planned to be used in the experiment: a single-phase time projection chamber and a dual-phase chamber. Prototypes of both detector versions are at present under development in the framework of the Neutrino Platform (CERN) [61]. Four modules of a total active mass equal to 40 kt will be placed underground in the Homestake Neutrino Laboratory in South Dakota at a distance of 1300 km from Fermilab. Work on the construction of the underground laboratory for the DUNE detector complex was initiated in July 2017. The power of the proton beam will amount to 1.3 MW, and it may be increased to 2.4 MW. Data acquisition with a neutrino beam from Fermilab is to start in 2026. A sensitivity $> 5\sigma$ for a 50% interval of possible δ_{CP} values is expected to be achieved after 10 years of data taking. In this experiment, the difference between the normal and inverse mass hierarchies can be established at a 5σ level for the entire interval of possible δ_{CP} values from 0 to 2π.

T2HK (*Tokai-to-Hyper-Kamiokande*) *experiment*. The main purposes of the T2HK experiment (Japan) [62] are a sensitive search for *CP*-symmetry violation and the measurement of δ_{CP}. In this project, use will be made of high intensity off-axis muon neutrino and antineutrino beams, tuned to the first oscillation maximum, from the proton complex J-PARC and of two Hyper-Kamiokande giant water Cherenkov detectors with a total mass of 0.52 Mt, situated at a distance of 295 km from J-PARC. At the first stage of the experiment, only one Cherenkov detector of mass 0.26 Mt will function, while the power of the proton beam will amount to 1.3 MW. After 10 years of data taking, this configuration allows achieving a sensitivity to δ_{CP} better than 5σ within an interval of more than 57% of possible values of this parameter. If the mass hierarchy is established (for instance, in another experiment), then the sensitivity to *CP* violation for $\delta_{CP} \sim -\pi/2$ will amount to $\sim 8\sigma$. In August 2017, this project was included into the roadmap of large-scale Japanese projects of the highest priority. Financing of the project should be initiated in 2019, while construction of the detector should be completed and data taking should start in 2026. At the same time, work will continue on increasing the J-PARC proton beam intensity and on upgrading the near neutrino detector.

The sensitivity of the long-baseline experiments mentioned above is illustrated in Figs 9 and 10. The T2HK (first phase with a single Cherenkov detector) and DUNE have real chances to discover *CP* violation within a broad range of values of the *CP*-odd phase. Moreover, the measurement precision of the *CP*-odd phase is expected to be $\sigma \approx 22^\circ$ for $\delta_{CP} \approx \pm\pi/2$ and about 7° if δ_{CP} is 0 or π.

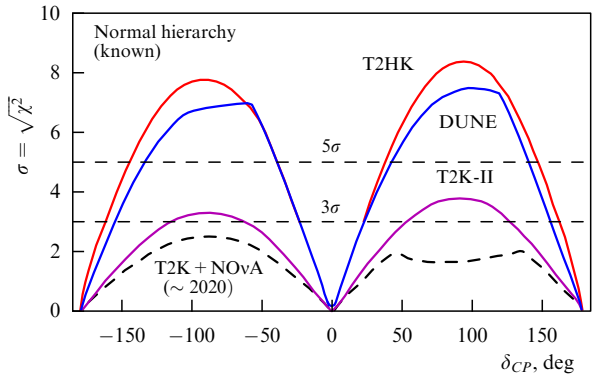

Figure 9. Statistical significance of *CP*-conservation elimination (discovery of *CP* violation) in neutrino oscillations [63]. The neutrino mass hierarchy is assumed to be known. In the T2HK experiment with a single Cherenkov detector, discovery of *CP* violation at a level $\geqslant 5\sigma$ is possible for $\geqslant 57\%$ of all admissible δ_{CP} values. DUNE has a similar sensitivity. The T2K-II experiment can achieve a sensitivity $\geqslant 3\sigma$ to *CP* violation for δ_{CP} values around $\pm\pi/2$. The sensitivity is also shown that can be achieved in T2K and NOνA in the case of a joint data analysis.

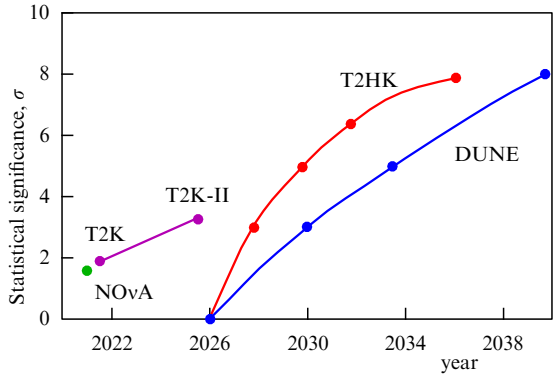

Figure 10. Statistical significance of the effect of *CP* violation in the case of the normal mass hierarchy and the value $\delta_{CP} = -\pi/2$ that can be achieved in long-baseline experiments [64]. The experiment T2HK (red curve) with a single Cherenkov detector and DUNE are expected to start data taking in 2026.

JUNO (*Jiangmen Underground Neutrino Observatory*) *reactor experiment*. The main tasks of the JUNO experiment (China) [65] are to determine the neutrino mass hierarchy and accurately measure the oscillation parameters. Construction work on the underground laboratory was started in January 2015. The detector of reactor antineutrinos to be used is a sphere 35 m in diameter filled with 20 kt of liquid scintillator. Essentially important for achieving the main goals of the experiment is the energy resolution of the neutrino detector. It is necessary to achieve a resolution of $3\%/\sqrt{E\,[\mathrm{MeV}]}$ and to perform calibration of the absolute energy scale of the detector and its control with a precision better than 1%, which is a difficult task and requires a new qualitative step in the technology of large neutrino detectors. It is planned that the experiment will determine the neutrino mass hierarchy

at a statistical significance level of $(3-4)\,\sigma$ and measure the mixing parameters $\sin^2\theta_{12}$ and Δm^2_{21} with an accuracy of better than 1% after six years of collecting statistics.

What results can be expected to be obtained in the nearest future in experiments aimed at searching for light sterile neutrinos? New data obtained in current experiments with atmospheric reactor and accelerator neutrinos will allow imposing further constraints on the region of allowed sterile neutrino parameters. For example, the NOνA collaboration published the first result of searches for sterile neutrinos, obtained by measuring the deficit (decrease) of neutral current events in the far detector [66]. The conclusive test of the LSND anomaly is to be performed at Fermilab in the framework of the neutrino program of short baseline experiments, the main purpose of which is a sensitive search for sterile neutrinos with a mass of about 1 eV [67]. For these measurements, three detectors based on liquid-argon time-projection chambers will be used: the near detector LAr1-ND, the far upgraded detector ICARUS-T600 (Imaging Cosmic And Rare Underground Signals), and the detector MicroBooNE. For an integral flux of 6.6×10^{20} POT during data taking with the LAr1-ND and ICARUS-T600 detectors, and also for the flux 13.2×10^{20} POT in measurements with the MicroBooNE detector, the sensitivity of these measurements to $\nu_\mu\to\nu_e$ oscillations in the region of the LSND signal, corresponding to a confidence interval of 99%, will amount to $\sim 5\sigma$. Data taking is expected to start in 2020.

The 'reactor anomaly' will be tested in several very-short-baseline reactor experiments that are underway and in the stage of preparation for collecting statistics. Besides the aforementioned NEOS, DANSS, and Neutrino-4, one must add the experiment SoLid (Short oscillation search with Lithium-6 detector) [68], to be installed at the BR-2 reactor of the Center of nuclear Research of Belgium (SCK (StudieCentrum voor Kernenergie)/CEN (Centre d'Étude de l'énergie Nucléaire)), PROSPECT (PRecision Oscillation and SPECTrum experiment) [69] at a reactor with a power of 85 MW at the Oak Ridge National Laboratory (USA), and the experiment STEREO [70] at the research reactor of the Institut Laue–Langevin (ILL) in Grenoble (France).

A test of the 'gallium anomaly' is to be performed in the SOX (Short distance neutrino Oscillations with BoreXino) experiment [71], where the BoreXino detector will be used for registration of electron antineutrinos from an artificial ^{144}Ce source of an activity of about 100–150 kCi, to be prepared at the Mayak Production Association, Russia. The source will be at a distance of about 8 m from the detector center. Measurements should start in 2018 and after 18 months of measurements the experiment is expected to achieve a sensitivity that allows excluding a larger part of the region of oscillation parameters corresponding to the 'gallium anomaly'. This anomaly can also be tested in the BEST (Baksan Experiment on Sterile Transitions) experiment [72], in which the flux of electron neutrinos from a ^{51}Cr source of activity 3 MCi is to be measured at two distances: about 0.4 and 0.8 m. A double-core reactor filled with liquid gallium will be used as the neutrino target/detector.

5. Conclusion

Searching for *CP*-symmetry violation in neutrino oscillations, determining the neutrino mass hierarchy, and searching for sterile neutrinos are among the most the fundamental tasks of neutrino physics. After the discovery of $\nu_\mu\to\nu_e$ oscillations and of the large value of θ_{13}, it actually became possible to find *CP* violation in neutrino oscillations. The first indications of maximal *CP* violation have already been obtained in the current long-baseline experiments T2K and NOνA. Next-generation experiments DUNE and T2HK have the real potential to discover *CP*-symmetry violation with a high statistical significance and to measure the value of δ_{CP}. Several experimental results, so-called neutrino anomalies, that do not fit in the mixing scheme of three active neutrinos have not been confirmed experimentally yet. On the contrary, the latest results have essentially reduced the region of allowed parameters for light sterile neutrinos, the existence of which could explain these anomalies. In turn, the unambiguous confirmation of at least one anomaly will certainly be a breakthrough result and will open a new page in neutrino physics. A broad experimental program involving accelerator, reactor, and artificial neutrino sources provides real chances for resolving the problem of light sterile neutrinos in the very nearest future.

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Added in proofreading. A series of important events occurred during the several months past since this article was written. Regretfully, the SOX experiment that used the Borexino detector was terminated owing to it being impossible to prepare a high-intensity cerium-144 source of neutrinos. Several new interesting results were presented at the XXVIII International Conference on Neutrino Physics and Astrophysics held in Heidelberg (Germany) from June 4 to 9, 2018 (https://www.mpi-hd.mpg.de/nu2018/). The experiment NOνA registered 18 electron antineutrinos, while the expected background was 5.3 events. The observation of oscillations with a statistical significance $>4\sigma$ was announced. This experiment also presented a new measurement of the θ_{23} mixing angle, whose allowed region changed compared to the data shown in Fig. 4. Now, it is in better agreement with the results of other experiments. The short-baseline experiments DANSS, PROSPECT, and STEREO that measure the flux and spectrum of reactor antineutrinos at short distances from the reactor core presented new results, in which no 'deficit' of the neutrino flux and/or distortions of the spectrum were observed. Thus, the 'reactor anomaly' has not been confirmed by several independent experiments, and one can assume that this effect will be finally 'closed' in the next one to two years.

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