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Reactor neutrino experiments: results and prospects

A G Olshevskiy

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Contents

Abstract. The role of reactor experiments in understanding the properties of neutrinos are discussed together with prospects for further development.

1. Introduction

The possibility of using nuclear reactors as intense and clean sources to detect antineutrinos was first discussed by Pontecorvo [1], who authored many essential ideas that determined the course of development in weak interaction and neutrino physics. For example, in [1], Pontecorvo proposed the first (radiochemical) method for detecting neutrinos; his articles presented the first discussions of the muon/electron universality hypothesis of weak interactions [2] and he proposed an experiment to clarify whether electron and muon neutrinos are different particles [3]; he also put forward the hypothesis of neutrino oscillations [4].

Practically all the main neutrino sources used in modern neutrino experiments were known quite long ago. Back in 1960, in review [5], Reines pointed out the possibility, in principle, of using reactors as sources of low-energy antineutrinos, in-flight decays of pions as sources of muon neutrinos, intense neutrino fluxes from thermonuclear reactions on the Sun, neutrino fluxes from meson decays in showers from cosmic rays interacting with the atmosphere, and high-energy neutrinos arriving from astrophysical objects. According to modern terminology, these are so-called reactor, accelerator, solar, atmospheric, and astrophysical neutrinos.

A G Olshevskiy Joint Institute for Nuclear Research,
ul. Joliot-Curie 6, 141980 Dubna, Moscow region, Russian Federation
E-mail: olshevsk@gmail.com

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As is known, the actual experimental discovery of the neutrino was made in 1956 by Reines and Cowan [6] in an experiment at the Savannah River Nuclear Plant (USA). To register antineutrinos from the reactor, Reines and Cowan used the inverse beta-decay reaction, which subsequently became a classic:

$$\bar{\nu}_e + p = e^+ + n\,. \tag{1}$$

It is interesting that this experiment was preceded in 1953 by an experiment performed by the same authors at the Hanford Site reactor, owing to which, in spite of its negative result, they became aware of the fundamental necessity of protection from the cosmic ray background.

Thus, the history of reactor neutrino experiments already spans 60 years, during which time numerous experiments [Institut Laue-Langevin (ILL)] [7], Bugey [8], Rivne Nuclear Power Plant [9], Goesgen [10], Krasnoyarsk [11], Palo Verde [12], and others] have contributed to the development of the antineutrino detection technique and to the implementation of detailed measurements of antineutrino fluxes at different distances from the reactor. In 2003–2008, the first observation was made by the reactor experiment KamLAND (Kamioka Liquid Scintillator Antineutrino Detector) [13] of the disappearance of the reactor antineutrino flux, consistent with the hypothesis of neutrino oscillations, which was previously confirmed in other kinds of experiments. Finally, in 2012, reactor experiments (together with indications from other types of experiments) provided one more result of fundamental importance: the mixing angle of the first and third neutrino mass states was shown not only to differ from zero but also to be relatively large, which opened up new possibilities for oscillation measurements.

2. Measurements of the mixing angle θ_{13} in reactor experiments

Neutrinos of three sorts (flavors) — the electron ν_e, the muon ν_μ, and the tau ν_τ — participating in weak interactions are related to the mass states ν_1, ν_2, and ν_3 by the Pontecorvo–

Maki–Nakagawa–Sakata (PMNS) mixing matrix:

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

The mixing matrix U has the following standard form:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\exp(-i\delta) \\ 0 & 1 & 0 \\ -\sin\theta_{13}\exp(-i\delta) & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{3}$$

The angle θ_{12} is introduced in order to describe solar and reactor oscillations, while the angle θ_{23} is for describing atmospheric and accelerator oscillations.

The relation between these oscillation modes is determined by the angle θ_{13}, while possible *CP* violation in the lepton sector is parameterized by δ. The respective oscillation frequencies are determined by the square mass differences for states m_1, m_2, and m_3. Measurements have been made of the small, $\Delta m^2_{21} \approx 7.6 \times 10^{-5}$ eV^2 (solar), and of the large, $\Delta m^2_{31} \approx \Delta m^2_{32} \approx 2.4 \times 10^{-3}$ eV^2 (atmospheric), square mass differences. Because oscillations are independent of the mass scale, the relation between the actual masses is unknown. The hypotheses $m_1, m_2 \ll m_3$ and $m_3 \ll m_1, m_2$ are respectively called normal and inverse hierarchies. An illustration of the normal and inverse hierarchies is presented in Fig. 1.

Oscillation measurements have revealed the mixing angles θ_{12} and θ_{23} to be large: $\theta_{12} \approx 35°$ and $\theta_{23} \approx 45°$; however, for a long time, only an upper bound for θ_{13}, determined in the Chooz experiment [14], existed: $\sin^2(2\theta_{13}) < 0.15$ at a 90% confidence level. In 2010–2011, the joint interpretation of neutrino oscillation data [15], of the accelerator experiments T2K (Tokai to Kamioka) [16] and MINOS (Main Injector Neutrino Oscillation Search) [17], and of Double Chooz [18] yielded the first indications that the angle θ_{13} might not be so small.

The conclusive contribution to measurement of the angle θ_{13} came from the reactor experiments Daya Bay [19] and RENO (Reactor Experiment for Neutrino Oscillation) [20]. The idea of these experiments was to observe a decrease in the reactor neutrino flux due to oscillations determined by θ_{13}. The optimal distance between the reactor and the detector depends on Δm^2_{31} and, in the case of the mean reactor antineutrino energy ~ 4 MeV, amounts to ~ 1.5 km.

Table 1. Parameters of reactor experiments measuring the θ_{13} angle.

Experiment	Thermal power of reactor complex, GW	Detector mass, t	Depth of position of (near) detectors, m.w.e.
Double Chooz	8.6	16 (2 × 8)	300 (120)
RENO	16.5	32 (2 × 16)	450 (120)
Daya Bay	17.4	160 (8 × 20)	860 (250)

However, the analysis of data from such experiments always involves an essential uncertainty due to the uncertainty in calculations of the initial antineutrino flux from the reactor. A solution of this problem was found by Russian physicists [21], who at the Neutrino-2000 conference first proposed carrying out an experiment at the Krasnoyarsk reactor with two detectors — a near detector (at which the total flux still equals the initial one) and a far detector (for measuring the decrease in the flux) (Fig. 2). Thus, with the aid of measurements by the far detector relative to the near one, it is possible to avoid many theoretical and experimental uncertainties in the flux prediction and possible general systematic uncertainties in the operation of both the near and far identical detectors.

The measurements proposed were not implemented at the Krasnoyarsk reactor, but the idea of using two detectors at different distances was successfully realized in other experiments. Table 1 presents the power values of reactor complexes and the masses and depths of underground detectors for three reactor experiments that searched for oscillations and measured the θ_{13} angle.

The Daya Bay experiment exceeds the others both in the value of the expected signal (a larger product of the power and mass) and in the reliability of the shielding against cosmic rays (a larger depth). In 2012, this experiment made the first measurement of θ_{13}, excluding its zero value at a level of five standard deviations [19]:

$$\sin^2(2\theta_{13}) = 0.092 \pm 0.016\,(\text{stat}) \pm 0.005\,(\text{syst}). \tag{4}$$

This measurement unambiguously confirmed earlier indications of a nonzero θ_{13}. The results obtained in this experiment are shown in Fig. 3.

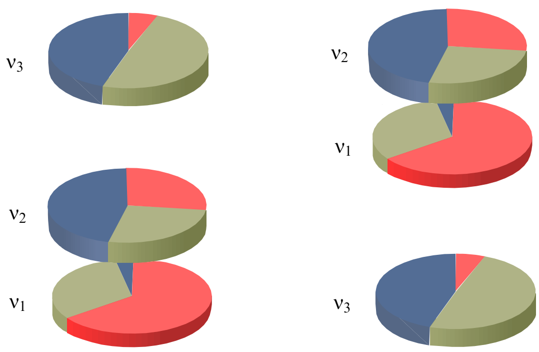

Figure 1. Illustration of the hypotheses of normal and inverse neutrino mass hierarchies.

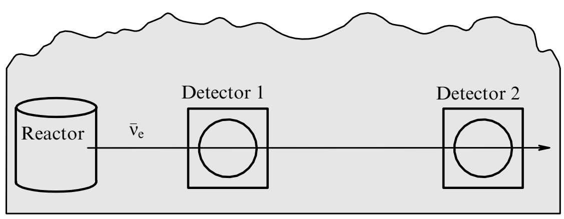

Figure 2. Plot of the proposed Krasnoyarsk reactor experiment at a depth of 600 meters water equivalent (m.w.e.). Detector 1 is at a distance of 45 m from the reactor, detector 2 is at a distance of 1000 m. The number of events is 4200 per day at the first detector, and 55 per day at the second; the signal-to-background ratio at the first detector is much greater than unity, and at the second it is of the order of 10:1.

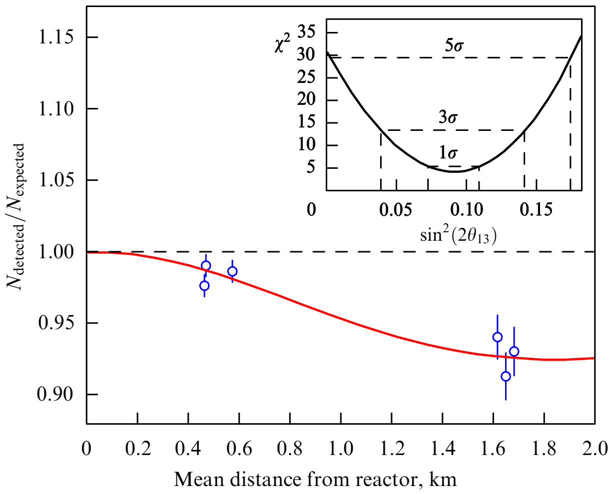

Figure 3. Measurements of reactor antineutrino fluxes at different distances from the reactor in the Daya Bay experiment. N_{detected} and N_{expected} are the number of registered antineutrinos and their expected number.

Measurements of the θ_{13} angle were also performed in the RENO experiment [20]. The modern value for this mixing angle is given by [22]

$$\sin^2(2\theta_{13}) = 0.095 \pm 0.010\,. \tag{5}$$

Here, the measurements of reactor experiments are dominant in accuracy.

The nonzero and relatively large value of θ_{13} permit the planning of further oscillation experiments sensitive to the mass hierarchy and to possible parity violation in the lepton sector. The sensitivity of oscillation measurements to different hierarchies is due to two effects: 1) oscillations in matter and 2) interference of the solar (Δm^2_{21}) and atmospheric (Δm^2_{31}, Δm^2_{32}) vacuum oscillation modes.

The first effect will be studied in accelerator experiments already under way or planned: T2K, NOvA (NuMi Off-axis ν_e Appearance), LBNE (Long-Baseline Neutrino Experiment), and others (see, e.g., Refs [23, 24]).

The second effect, like the value of θ_{13}, can be investigated by the decrease in the reactor antineutrino flux, but only at distances of several dozen kilometers. Such experiments are already being designed, but they are extremely complex from the standpoint of detector scales and parameters. In the JUNO (Jiangmen Underground Neutrino Observatory) project, for example, the use is contemplated of a liquid-scintillation detector (20 kt in mass and 3% resolution at an energy of 1 MeV), situated at a distance of ≈ 60 km from the reactor complexes with the total power of 34.8 GW. This detector will permit, by the evolution of oscillations, measuring which hierarchy is realized in Nature at a significance level exceeding three standard deviations (3σ). Besides its main task, a detector of such a scale will allow substantially improving the parameters of the PMNS matrix and performing measurements with neutrinos from supernovas and geoneutrinos, searches for sterile neutrinos, etc.

3. Experiments at the Kalinin nuclear power plant

Already more than 25 years ago, scientists from the Kurchatov Institute of Atomic Energy initiated experiments in the neutrino laboratory at the reactor of the Rivne Nuclear Power Plant. In the report by Mikaelyan [25] to the 1986 session of the Divisions of General and Nuclear Physics of the USSR Academy of Sciences, for example, results were presented of the measurements of positron spectra from the inverse beta-decay reaction as well as absolute cross section values for this reaction. Already at the time, measurements were performed at two distances, 18 m and 25 m, from the center of the reactor, and one of the goals of the measurements, formulated for the first time, was to investigate the possibility of controlling the reactor operation by its antineutrino radiation. Subsequently, this problem became more and more important, and currently several projects are already being carried out in the world with the aim to measure antineutrino fluxes and spectra with the aid of relatively small effective detectors with a volume of about 1 m^3. These devices, situated at distances of ~ 10 m from the reactor centers, are to measure antineutrino fluxes and spectra in order to perform independent control of the reactor power and to determine the fuel burnout regions and the existence of isotopes produced inside the fuel. Thus, neutrino experiments manifest their value not only from a fundamental standpoint but also from the standpoint of applications, providing information that is important for designing reactors and resolving safety problems and problems of nonproliferation of nuclear weapons.

From the standpoint of implementing neutrino studies, the Kalinin nuclear power plant (KNPP) is quite convenient, being situated in the north of the Tver region. It includes four water–water energy reactors (WWERs) of the WWER-1000 type with the thermal power up to 3 GW each. The technological rooms situated at a depth of 10–15 m under the reactor are used as scientific laboratories. The intensity of the neutrino flux provided at such a small distance from the center of the powerful reactor is very high ($\sim 3 \times 10^{13}$ cm^{-2} s^{-1}). Moreover, the reactor material, the technological equipment, and elements of the building construction above these rooms provide a shielding of up to 70 m.w.e. from cosmic rays.

3.1 Measurement of the neutrino magnetic moment

The first neutrino experiments carried out at the KNPP were those in search of the neutrino magnetic moment. In the framework of the Standard Model (SM), extended to massive neutrinos, their magnetic moment related to their nonzero mass should have a small value: $\mu_\nu \sim 10^{-19}\mu_{\text{B}}\,(m_\nu/1 \text{ eV})$, where μ_{B} is the Bohr magneton. However, in certain models, the magnetic moment can reach $\sim 10^{-14}\mu_{\text{B}}$ and even $\sim (10^{-10} - 10^{-11})\,\mu_{\text{B}}$, which is already within reach of modern experiments. Large values are predicted for the magnetic moment by models with Majorana neutrinos. Revealing neutrino electromagnetic properties at this level would point to new physics beyond the SM and would provide arguments in favor of the Majorana nature of the neutrino mass.

The Gemma (Germanium Experiment for Magnetic Moment Antineutrino) experiment searching for the neutrino magnetic moment was performed at the KNPP by a joint group of scientists from the Alikhanov Institute of Theoretical and Experimental Physics (ITEP) and from the Joint Institute for Nuclear Research (JINR). In the experiment, a germanium semiconductor detector 1.5 kg in mass cooled to ultra-low temperatures and situated at a distance of ≈ 14 m from the reactor center was used. A comparison of the spectra of signals from this detector during operation of the reactor and during interruptions permitted establishing the upper bound for the electron neutrino (antineutrino) magnetic moment:

$$\mu_\nu \leqslant 5.8 \times 10^{-11} \mu_B\,, \qquad (6)$$

at a confidence level of 90%. Additional data taking permitted improving this upper bound [26]:

$$\mu_\nu \leqslant 2.9 \times 10^{-11} \mu_B\,, \qquad (7)$$

at a 90% confidence level. The plans for the experiment GEMMA-2 include increasing the detector mass to 6 kg and installing it at a distance of 10 m from the reactor center. This upgraded experiment is to achieve the bound

$$\mu_\nu \leqslant 1.0 \times 10^{-11} \mu_B\,. \qquad (8)$$

3.2 Detecting reactor antineutrinos and controlling the reactor operation

One of the projects making part of the experiment for measuring the flux and spectrum of reactor antineutrinos is the DANSS (Detector of Anti-Neutrino based on Solid Scintillator) project, proposed by the ITEP–JINR group to be realized at the KNPP. The registering part of the detector consists of scintillation strips forming a plane and filling a volume of 1 m^3. This sensitive volume is surrounded by a shielding of heavy (copper, lead) and light (borated polyethylene) materials for protection from the neutron background and from gamma quanta. Moreover, for protection from the background due to cosmic muons, the device is covered by a scintillation veto-system.

The well-known inverse beta-decay reaction (1) is used to register antineutrinos. The positron produced in reaction (1) loses energy and annihilates. This signal, registered in the form of light in the scintillation strips, carries information on the antineutrino energy and serves as the first signature of the reaction. The neutron produced in reaction (1) loses energy (thermalizes) in collisions with nuclei and is captured in a time of the order of several tens of microseconds. To render this capture more effective, gadolinium, whose thermal neutron capture cross section is enormous, is added to the material. De-excitation of a gadolinium nucleus that has captured a neutron proceeds via a cascade of gamma quanta with a total energy of about 8 MeV. Thus, the second signature of the reaction is the registration of one more signal with an energy of ≈ 8 MeV, delayed with respect to the first signal by the thermalization time of the neutron. The construction of strips in the DANSS detector is depicted in Fig. 4.

This construction was jointly developed by a group from the JINR and the Institute of Scintillation Materials (ISMA) (Kharkov) for experiments in high-energy physics. The strips are produced at ISMA by extrusion of a polystyrene scintillation material together with a light-reflecting coating, to which, in the case of DANSS, gadolinium is also added. Light collection from the strip is performed by fibers glued into grooves, shifting the spectrum of reemitted light to green. Part of the fibers from different strips are collected at photomultiplier tubes (PMTs) for energy measurement, and the signals from other fibers are read out by semiconductor avalanche photo-diodes with a large number of cells.

Thus, unlike, e.g., liquid-scintillation detectors, the DANSS detector permits obtaining additional, more precise coordinate information, that permits examining events carefully and discriminating the background. The expected parameters of the DANSS detector are presented in Table 2.

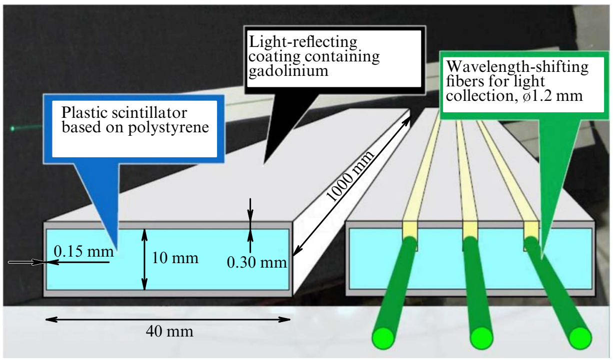

Figure 4. Construction of scintillation strips of the DANSS detector.

To test the operation mode of the DANSS detector, a small prototype, DANSSino [27], of this detector was made, which consists of 100 strips, read out only by two PMTs. Investigation of the prototype in laboratory conditions and at the KNPP with the reactor in operation and during interruptions permitted determining event selection and background suppression criteria. A comparison of measurements made during operation of the reactor and during interruptions permitted for the first time measuring the spectrum of reactor antineutrinos in such a detector [27]. The measured energy spectrum of positrons from the inverse beta-decay reaction compared with the predicted spectrum is presented in Fig. 5.

In spite of the small volume of DANSSino and the presence of significant boundary effects, the results of measurements and of simulation are quite consistent with each other, which confirms the expected parameters given in Table 2 for the DANSS detector of a larger volume. The DANSS detector is to be mounted and commissioned at the KNPP at the end of 2014 or the beginning of 2015.

3.3 Searching for sterile neutrinos in reactor experiments

At the beginning of 2011, a series of articles (see, e.g., Ref. [28] and the references therein) presented discussions of new theoretical calculations of reactor antineutrino fluxes. Analyses of the results of these calculations together with reactor data revealed a flux deficit in experiments compared to theoretical estimates.

Setting aside the ongoing discussion of the possible overestimation of the precision of these calculations, we

Table 2. Expected parameters of DANSS detector.

Sensitive (fiducial) volume and segmentation	1 m^3, *X*- and *Y*-planes, 2500 strips
Total mass (including shielding)	13 t
Registration efficiency for inverse beta-decay events	70 %
Expected number of inverse beta-decay events at the distance 11 m from the reactor center	10^4 day^{-1}
Expected number of background events	50 day^{-1}
Energy resolution	< 30 % at the energy 4 MeV

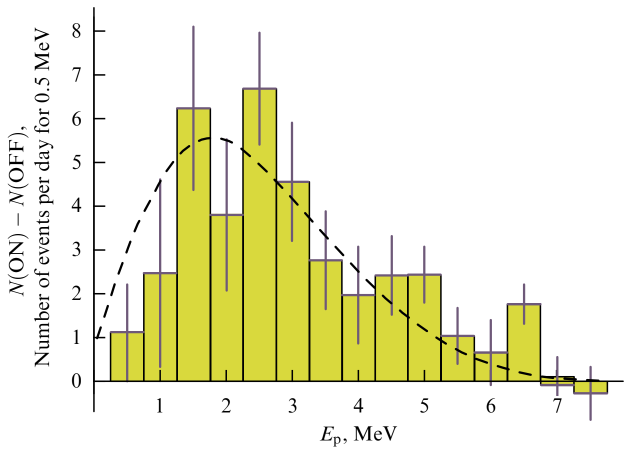

Figure 5. Energy spectrum of positrons from the inverse beta-decay reaction, due to reactor antineutrinos, measured by the DANSSino prototype. The dashed curve shows the predicted spectrum. N(ON) is the spectrum measured with the reactor in operation, N(OFF) is the spectrum during interruptions.

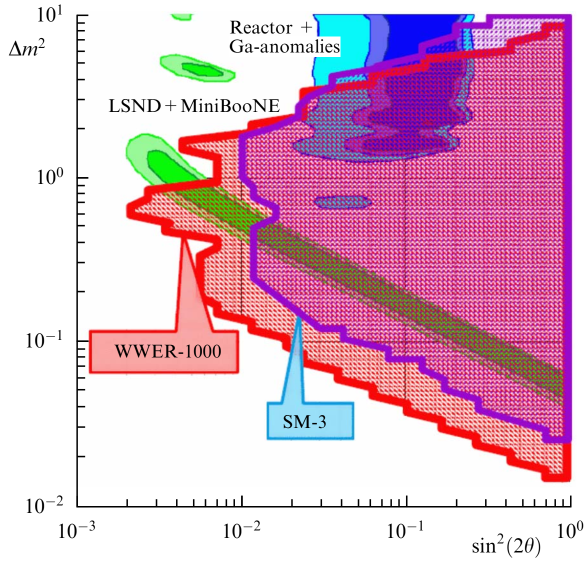

Figure 6. Sensitivity of the DANSS experiment to sterile neutrino parameters.

must note that an interesting hypothesis explaining this deficit is that there exists one more, sterile, neutrino state with a mass of $\sim$ 1 eV and a small mixing angle.

The existence of one more, heavy, neutrino could also explain the anomalous results obtained in the LSND and MiniBooNE (Mini Booster Neutrino Experiment) accelerator experiments, as well as the inconsistency between the calibrations of the gallium GALLEX (GALLium EXperiment) and SAGE (Soviet–American Gallium Experiment) solar detectors (see, e.g., Ref. [29] and also Refs [30, Section 2; 31, Section 7]).

Although the sterile neutrino parameters necessary for explaining the aforementioned anomalies are not quite consistent with each other, it seems interesting to check this hypothesis experimentally. If it is assumed to hold, oscillations due to the square mass difference ~ 1 eV^2 should be observed in reactor experiments at small distances (about 10 m). A detector like DANSS can be used in measuring and testing the hypothesis. The optimum would be to perform measurements at different distances from the reactor center and, with the aid of such relative measurements, to exclude the influence of theoretical uncertainties in the calculations of antineutrino fluxes from the reactor. This can be done inside the laboratory at the KNPP, because the same detector can be shifted for measurements at distances of 9.7 m and 12.2 m. The results of sensitivity simulation of such an experiment are presented in Fig. 6.

The curve labeled WWER-1000 corresponds to the DANSS experiment at the KNPP; it well outlines the main parameter regions of the square mass difference and the new mixing angle predicted for sterile neutrinos on the basis of the results of accelerator experiments (LSND + MiniBooNE), reactor experiments, and calibrations of solar detectors (Reactor + Ga-anomaly).

An essential peculiarity of experiments performed at the KNPP is the large size of the reactor core. In such reactors, it is of the order of 3–5 m, which significantly smears the oscillation curves and leads to reduction in the measurement sensitivity. The possibility of performing an experiment was also examined for the CM-3 high-flux research reactor (the Research Institute of Atomic Reactors, Dimitrovgrad city), which is a vessel-type water–water reactor with intermediate neutrons and a neutron trap. Measurements can be carried out in this reactor at distances of 5–15 m; the size of the core is $\approx$ 40 cm, but the thermal power amounts to 100 MW, which is one thirtieth of that at the industrial reactor of the KNPP.

The results of sensitivity simulation for the experiment at the SM-3 reactor are also shown in Fig. 6. It can be seen that the low power of the reactor is to a significant extent compensated by the core being 'pointlike'. In this comparison, account is not taken of the background conditions at SM-3 being worse than at the KNPP, owing to a lesser shielding from cosmic rays. A plan for the experiment at the SM-3 reactor, which was called Neutrino-4 [32], was proposed for implementation by a group from the Konstantinov Petersburg Institute of Nuclear Physics (PINP), which is a member of the National Research Center Kurchatov Institute (NRC KI). The device is a sectioned liquid-scintillation detector with a shielding and a veto-system, permitting the determination of the coordinate of a neutrino event and suppression of the background.

It must be noted that there are already several projects in the world of similar experiments at research reactors of relatively low power. The groups that developed detector techniques for these experiments have not yet been allowed to transfer them to industrial reactors for safety reasons.

Therefore, implementation of the DANSS experiment, based on the use of a safe plastic scintillator, is still a unique possibility.

However, we must not underestimate the role of research reactors for neutrino experiments. There are a number of measurements essentially important for neutrino physics and for the further development of neutrino detection methods. For example, at the PIK (PINP NRC KI) reactor [33], the following will be possible after the start of its stable operation: precision measurements of a reactor neutrino and beta spectra of irradiated targets necessary for comparison with theoretical results; the production of powerful calibration neutrino sources such as ^{51}Cr and ^{8}Li in extreme thermal neutron fluxes up to 4.5×10^{15} cm^{-2} s^{-1}; testing possible methods for detecting coherent neutrino scattering on nuclei; etc.

4. Conclusion

Experiments at reactors have played a significant role in studies of the properties of neutrinos. Recent measurements of the relatively large mixing angle θ_{13} open up new prospects for neutrino experiments at reactors, among which are accurate measurement of oscillation parameters and determination of the neutrino mass hierarchy. Russian institutes and the JINR have made an essential contribution to the preparation and implementation of fundamental reactor experiments. Continuing research based on the KNPP laboratory and other reactors of the Russian Federation will permit developing the neutrino detection technique and implementing experiments of interest for both fundamental and applied reasons.

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