Bounds on the neutrino oscillation parameters for reactor antineutrinos

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In these experiments we detected antineutrinos from three reactors located at distances 57.0, 57.6, and 231.4 m from the detector. Using these measurements, we determined that the cross section for the inverse beta-decay reaction of antineutrinos with protons is $\sigma_{\text{exp}} = [6.11 \pm 0.15$ (detector) ± 0.11 (reactor)$] \cdot 10^{-43}$ cm^2 per ^{235}U fission. From this we obtain the following bound on the neutrino oscillation parameter: $\Delta^2 \leqslant 8.3 \cdot 10^{-3}$ eV^2 for $\sin^2(2\theta) = 1$ (with a 90% confidence level). These neutrino experiments imply a value for $\lambda_{\tilde{\nu}p} = G_A/G_V$ of $1.24 \pm 3.4\%$ (with 90% confidence level).

The possibility of neutrino oscillations, which was advanced as a hypothesis more than 30 years ago,[1] remains a timely topic for discussion even in the present day. In practice, all the experiments of recent years have indicated that such oscillations are absent in the region of squared neutrino mass difference (Δ^2) greater than $\sim 10^{-2}$ eV^2. It is well-known that the sensitivity of an experiment to Δ^2 is proportional to $(\delta^{1/2}E)/R$, where δ is the relative experimental error, E is the neutrino energy, and R is the distance between the source and the detector. From this it is clear that maximum sensitivity to Δ^2 is attained in reactor experiments because reactor antineutrinos possess the smallest energy of all the artificial sources of neutrinos. However, here too, penetration into the region of Δ^2 below 10^{-2} eV^2 is extremely difficult, owing to the worsening signal-to-noise ratio, since it is necessary to carry out these measurements at considerable distances from the reactor.

In our experiments we measured and recorded the process of inverse beta decay of the proton ($\tilde{\nu}_e + p \to n + e^+$) because it possesses the largest cross section of all the reactor-neutrino interactions available for study. Our method of recording these events was integral, i.e., we detected only those neutrons that appear in the course of this reaction.

The integrated cross section for the process of inverse beta decay in the presence of oscillations depends on the distance between the reactor and the detector, (R), and can be written in the form

$$\sigma_{\text{exp}} = \sigma_0 [1 - I(R)\sin^2(2\theta)],$$

where

$$\sigma_0 = \int_E \sigma(E) n(E)\, dE$$

is the integrated cross section for the reaction in the absence of oscillations and

$$I(R) = \frac{1}{\sigma_0} \int_E \sigma(E) n(E) \sin^2\left(1{,}27 \frac{\Delta^2}{E} R\right) dE$$

is an oscillatory term; $\sigma(E)$ is the differential cross section for the interaction of an antineutrino with a proton, $n(E)$ is the spectrum of reactor antineutrinos, E is the energy of an antineutrino in MeV, and θ is the mixing angle of the various mass states of the neutrino.

In order to estimate the neutrino oscillation parameters we used the method of two distances, i.e., we compared the quantities

$$K_{\text{exp}} = \frac{N_2}{N_1} \left(\frac{R_2}{R_1}\right)^2$$

and

$$K_{\text{theor}} = \frac{1 - I(R_2)\sin^2(2\theta)}{1 - I(R_1)\sin^2(2\theta)},$$

where N_1 and N_2 are the numbers of events measured at distances R_1 and R_2 from the reactor. This ratio is quite insensitive to the form of the antineutrino spectrum;[7] by using it we practically exclude any error connected with insufficient knowledge of the spectrum of reactor antineutrinos.

The feature that distinguishes our experiment is the fact that our measurements were carried out using a single detector located at distances 57.0, 57.6, and 231.4 m from three practically-identical reactors. This allowed us to completely exclude systematic errors associated with the efficiency (i.e., aperture) of the detector and to greatly decrease errors arising from insufficient knowledge of the antineutrino flux (i.e., the degree of identity of the reactors and the method of measuring their power). An additional and considerable advantage of this method is that it ensures invariance of the background conditions of the experiment.

The general form of our integrating detector for reactor neutrinos is shown in Fig. 1. It consists of a hexagonal prism made of aluminum (the radius of the circle inscribed in the hexagon was 50 cm while the prism height was 110 cm). This prism was filled with granular polyethylene (with a bulk density 0.553 g/cm^3 and a weight 458.38 kg), and was axially threaded by 90 ^{3}He proportional neutrino counters with low intrinsic background.[3] In order to decrease the external background the detectors were surrounded on all sides by a passive shield made from borated polyethylene with a thickness of no less than 40 cm each side. They were covered on top by scintillation films made from PMMA (for active shielding from cosmic-ray mesons); the total area of these films was ~ 4 m^2. Additional passive shielding was provided by some tens of meters of water-equivalent material above the room in which the detector was located.

The antineutrino recording efficiency was determined from the recording efficiency of the detector for neutrons

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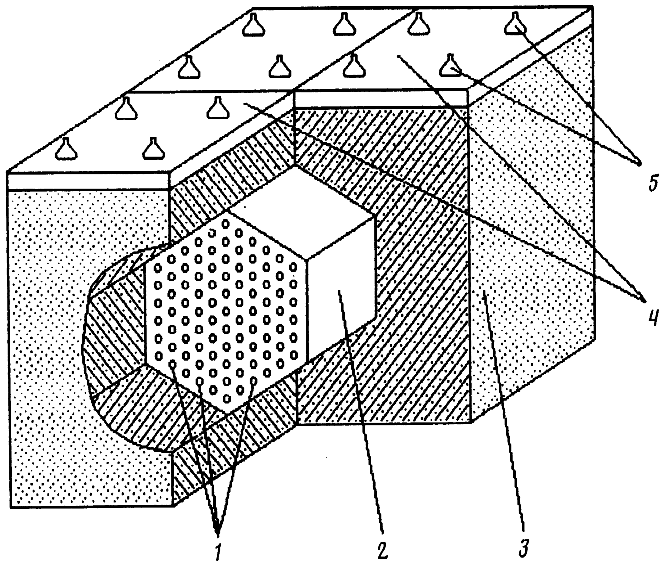

FIG. 1. Neutrino detector. *1*—^{3}He proportional neutrino counters; *2*—detector; *3*—shielding made of borated polyethylene; *4*—films for active shielding from cosmic-ray mesons; *5*—FEU-125 photomultiplier.

from the inverse beta decay reaction, which came to $(29.4 \pm 1.0)\%$; this corresponded to a detector aperture $\varepsilon N_p = 1.21 \cdot 10^{28}$. A more detailed description of the principles of operation of neutrino detectors analogous to this one is given in Ref. 2.

The total time period for these experiments was about ~ 490 hrs. Within this time all possible combinations of reactor operating regimes were implemented. The original information, referred to a single series of measurements, is given in the form of a system of linear equations

$$
\begin{aligned}
&(+++)\,1{,}058N_1+1{,}064N_2+1{,}085N_3+N_b=420{,}7\pm1{,}3,\\
&(++-)\,1{,}058N_1+0{,}964N_2+0{,}000N_3+N_b=404{,}4\pm2{,}6,\\
&(+-+)\,1{,}059N_1+0{,}000N_2+1{,}074N_3+N_b=307{,}2\pm3{,}1,\\
&(+--)\,1{,}057N_1+0{,}000N_2+0{,}000N_3+N_b=296{,}5\pm5{,}2,\\
&(-++)\,0{,}000N_1+1{,}061N_2+1{,}079N_3+N_b=304{,}4\pm2{,}7,\\
&(-+-)\,0{,}000N_1+1{,}009N_2+0{,}000N_3\pm N_b=286{,}5\pm2{,}8,\\
&(--+)\,0{,}000N_1+0{,}000N_2+1{,}100N_3+N_b=183{,}6\pm9{,}1,\\
&(---)\,0{,}000N+0{,}000N_2+0{,}000N_3+N_b=167{,}1\pm5{,}9.
\end{aligned}
$$

Here, the sign " + " implies that a reactor was included, while the sign " − " implies that it was excluded. The first column of these signs refers to the reactor located at a distance of 57.0 m from the detector, the second to the reactor at a distance 57.6 m, and the third to the most distant reactor (231.4 m). N_1, N_2, and N_3 are the numbers of events from the corresponding reactors after one series of measurements, reduced to the same power. N_b is the detector background, which consists of the intrinsic neutron background and that portion of the alpha background of the counters that lies within the amplitude window for detecting the neutron events.[3] The right-hand side of each equation shows the total number of useful events recorded for the corresponding regime of reactor operation and referred to a single series of measurements.

It is clear that the system of equations obtained here is overdetermined; solving it by the method of χ^2 minimization gives the following results:

$$N_1=113{,}1\pm2{,}1;\quad N_2=109{,}8\pm2{,}5;$$

$$N_3=7{,}9\pm2{,}0;\quad N_b=176{,}5\pm2{,}9.$$

Using the numbers of events from the nearest and farthest reactors (N_1 and N_3) we obtain

$$K_{\text{exp}}=\frac{N_1}{N_3}\left(\frac{57{,}0}{231{,}4}\right)^2=0{,}87\pm0{,}22.$$

The bounds on the neutrino oscillation parameters corresponding to this K_{exp} are shown in Fig. 2 (curve 1).

From the numbers of events for the first (N_1) and second (N_2) reactors the magnitudes of the integrated cross-sections for inverse beta decay for one fission of ^{235}U are found to equal respectively

$$\sigma(57{,}0)=[6{,}10\pm3{,}5\,\%\ (\text{detector})\ \pm2{,}5\,\%\ (\text{reactor})]\cdot10^{-43}\ \text{cm}^2/\text{div},$$

$$\sigma(57{,}6)=[6{,}05\pm3{,}8\,\%\ (\text{detector})\ \pm2{,}5\,\%\ (\text{reactor})]\cdot10^{-43}\ \text{cm}^2/\text{div}.$$

with a rather small (0.7%) correction for the composition of the fuel. In these expressions the first error includes the statistics and uncertainty associated with the detector efficiency, while the second reflects insufficient knowledge of the reactor power.

In our previous experiment,[2] in which we used another detector placed at a distance of 32.8 m from the first reactor, the analogous cross section had a magnitude

$$\sigma(32{,}8)=[6{,}19\pm4{,}3\,\%\ (\text{detector})\ \pm2{,}5\,\%\ (\text{reactor})]\cdot10^{-43}\ \text{cm}^2/\text{div}.$$

By comparing the results obtained from measurements on a particular reactor (the first) for these two experiments, we deduce the bounds on the neutrino oscillation parameter shown in Fig. 2 (curve *2*). On this figure we also show bounds from Ref. 4 (curve *3*). The level of confidence for all the curves was 90%.

The average integrated cross section for the process of inverse beta decay of the proton obtained from our two ex-

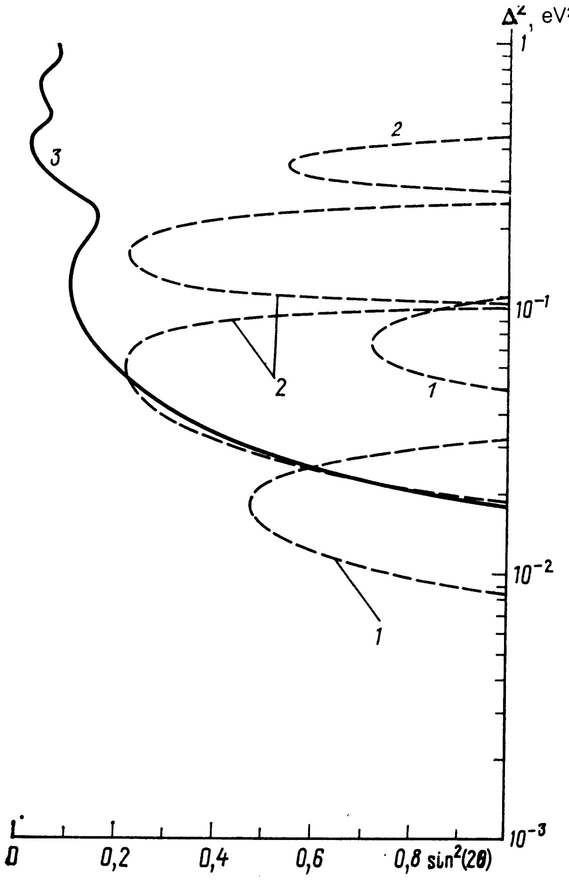

FIG. 2. Bounds on the neutrino oscillation parameters. *1*—from this work; *2*—from this work plus Ref. 2; *3*—from Ref. 4. The confidence level for all the curves was 90%.

periments (the three values given above) has the value

$$\sigma(^{235}\mathrm{U}) = [6{,}11 \pm 2{,}5\,\%\ (\text{detector}) \pm 1{,}8\,\%\ (\text{reactor})] \cdot 10^{-43}\ \mathrm{cm^2/div}.$$

The cross section obtained in the latest experiments[5] (see Ref. 5) equals

$$\sigma(^{235}\mathrm{U}) = [6{,}25 \pm 2{,}4\,\%\ (\text{detector}) \pm 2{,}5\,\%\ (\text{reactor})] \cdot 10^{-43}\ \mathrm{cm^2/div}.$$

The average of these results leads to the following value for the experimental cross section for inverse beta decay:

$$\sigma_{\text{exp}} = (6{,}17 \cdot 10^{-43} \pm 3{,}7\,\%)\ \mathrm{cm^2/div}.$$

The calculated value of the cross section can be evaluated using the formula

$$\sigma_{\text{calc}} = 0{,}98 \frac{G_V^2 + 3G_A^2}{\pi c^4 \hbar^4} \int_E n(E) \times (E - 1{,}293)\,[(E - 1{,}293)^2 + 0{,}511]^{1/2}\, dE,$$

where 0.98 is a coefficient that takes into account corrections for the effects of yield, weak magnetism, and radiative processes.[6] The confidence level for determining σ_{exp} and σ_{calc} is 90%.

The integral in this expression equals $6.85 \pm 4.2\%$, if we use the antineutrino spectrum from Ref. 7, which was obtained by conversion of the beta spectrum of fission fragments. Using the value $G_v = 1.4127 \cdot 10^{-43}$ erg·cm² (Ref. 8) the calculated cross section can be written in the form

$$\sigma_{\text{calc}} = (1{,}094 \cdot 10^{-43} \pm 4{,}2\,\%)\ (1 + 3\lambda^2_{\tilde{\nu}n})\ \mathrm{cm^2/div}.$$

where

$$\lambda_{\tilde{\nu}p} = G_A/G_V.$$

Comparing the calculated and experimental values of the cross section, we obtain for $\lambda_{\tilde{\nu}p}$ a value equal to $1.24 \pm 3.4\%$ (with a 90% confidence level).

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