Limitations on the characteristics of neutrino oscillations

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New results are reported on the observation of inverse beta decay of the proton. The data were obtained in an underground laboratory near the nuclear reactors of a Krasnoyarsk group of enterprises. The new results add substantially to the results available previously, because of the particular experimental conditions, which involved a stepped shutdown of two of the three reactors. The cross section for inverse beta decay of the proton has been determined: $\sigma_{\text{expt}}(\tilde{\nu}\text{p}) = (6.26 \pm 0.26) \times 10^{-43}$ cm^2/div. Limitations are found on characteristics of the neutrino oscillations: $\Delta m^2_{1,2} \leqslant 7.5 \times 10^{-3}$ eV^2 for $\sin^2 2\theta = 1$ and $\sin^2 2\theta \leqslant 0.15$ for $\Delta m^2_{1,2} \geqslant 5.0 \times 10^{-2}$ eV^2.

The cross section for inverse beta decay was measured by an integral method with the help of the detector described in Ref. 1. This detector was a hexagonal prism filled with 458.4 kg of granulated polyethylene, with a density of 0.553 g/cm^3. The prism was transfixed by 90 ^{3}He proportional counters, with a reduced intrinsic alpha background.[2] The efficiency of the detector with respect to neutrons from the inverse beta decay of the proton was $\epsilon = 29.4 \pm 1.0\%$.The luminosity of the detector (the product of its efficiency and the total number of hydrogen atoms) was 1.21×10^{28}.

If oscillations occur, the cross section for the inverse beta decay depends on the distance between the reactor and the detector (R) and can be written

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

where

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

is the cross section for the reaction in the absence of oscillations,

$$I(R) = \frac{1}{\sigma_0} \int_E \sigma(E) n(E) \sin^2 \left(1.27 \frac{\Delta m^2}{E} R \right) dE$$

is the oscillatory term, $\sigma(E)$ is the differential cross section for an antineutrino–proton interaction, $n(E)$ is the spectrum of reactor antineutrinos, E is the energy of the antineutrinos in MeV, and θ is the mixing angle of the two neutrino states. The measurements were carried out in the flux of reactor antineutrinos from three reactors, at distances of 57.0, 57.6, and 231.4 m from the detector. The "live" time of the entire experiment was 800×10^5 s. The results of these measurements can be presented as a system of seven equations:

$$(+++)\ 1.058N_1+1.041N_2+1.058N_3+N_b=404.9\pm1.1,$$

$$(++-)\ 1.058N_1+0.882N_2+0.000N_3+N_b=380.6\pm1.9,$$

$$(+-+)\ 1.059N_1+0.000N_2+1.059N_3+N_b=292.6\pm2.7,$$

$$(+--)\ 1.026N_1+0.000N_2+0.000N_3+N_b=276.8\pm1.5,$$

$$(-++)\ 0.000N_1+1.027N_2+1.047N_3+N_b=284.8\pm2.2,$$

$$(--+)\ 0.000N_1+0.000N_2+1.051N_3+N_b=166.6\pm5.6,$$

$$(---)\ 0.000N_1+0.000N_2+0.000N_3+N_b=157.1\pm2.1,$$

where the + means that the reactor is operating; the − means that the reactor is shut down; N_1 is the count of neutrino events over 10^5 s associated with the operation of the reactor at the distance of 57.0 m; N_2 is the corresponding count for the reactor at 57.6 m; N_3 is the corresponding count for the reactor at 231.4 m; and N_b is the count of background events, which is the sum of the neutrino background and the background of alpha particles due to natural radioactivity of the counter walls. The effects due to all reactors are reduced to a common power level, and correction factors are introduced in the equations to deal with the actual power levels of the reactors.

The three reactors were identical and operated at essentially the same power level. Furthermore, since the distances from the detector to the first and second reactors differed by only ~1%, the effects due to the first and second reactors were reduced to the effect from a single reactor at a distance of 57.0 m.

As a result, we found the redefined system of equations

$$2.077N_1+1.058N_3+N_b=404.9\pm1.0,$$

$$1.921N_1+0.000N_3+N_b=380.6\pm1.9,$$

$$1.059N_1+1.059N_3+N_b=292.6\pm2.7,$$

$$1.026N_1+0.000N_3+N_b=276.8\pm1.5,$$

$$1.005N_1+1.047N_3+N_b=284.8\pm2.2,$$

$$0.921N_1+0.000N_3+N_b=266.0\pm2.4,$$

$$0.000N_1+1.051N_3+N_b=166.6\pm5.6,$$

$$0.000N_1+0.000N_3+N_b=157.1\pm2.1,$$

Solving this system of equations, we find

$$N_1=114.54\pm1.09,\quad N_3=8.07\pm1.43,\quad N_b=159.4\pm1.46,$$

where $\chi^2=0.97$ and $P(\chi^2)=0.43$.

There are two generally accepted methods for evaluating oscillation characteristics. The first is to compare the experimental cross section with σ_0. The second is to carry out measurements at two distances and to compare the values of

$$K_{\mathrm{expt}}=\frac{N_1}{N_3}\left(\frac{R_1}{R_3}\right)^2 \quad \text{and} \quad K_{\mathrm{theor}}\frac{1-l(R_1)\sin^2 2\theta}{1-l(R_3)\sin^2 2\theta},$$

where N_1 and N_3 are the effects in the cases of the measurements at the distances R_1 and R_3 from the reactor. This ratio is relatively insensitive to the spectrum of antineutrinos and also to the reactor power.

From the measurements at two reactors (at 57.0 and 57.6 m) we find the following cross section for the inverse beta decay at the proton, per ^{235}U fission, with a small correction (0.7%) for the composition of the fuel: $\sigma_{\mathrm{expt}}(\tilde{\nu}p)=(6.26\pm 0.26)\times 10^{-43}$ cm^2/div. [The error here incorporates the uncertainties in the values of the detector efficiency (3.4%) and of the reactor power (2.5%).] The theoretical cross section σ_0 is calculated from

$$\sigma_0(\tilde{\nu}p)=0.98\frac{G_V^2+3G_A^2}{\pi c^2\hbar^4}\int_E n(E)(E-1.293)[(E-1.293)^2+0.511^2]^{1/2}dE,$$

where 0.98 is a coefficient which reflects corrections for recoil effects, a slight magnetism, and corrections for one-photon exchange.[3] For the calculations we used the $n(E)$ spectrum of Schreckenbach reactor antineutrinos from Ref. 4, $G_V=1.412\ 71\times 10^{-43}$ erg · cm^3 (Ref. 5), and $G_A/G_V=1.2628\pm 0.0019$, which is the best estimate according to Ref. 6.

A comparison of the experimental reaction cross section with the cross section calculated without allowance for oscillations [$\sigma_0=(6.33\pm 0.17)\times 10^{-43}$ cm^2/div] yields the ratio

$$\frac{\sigma_{\mathrm{expt}}(\tilde{\nu}p)}{\sigma_0(\tilde{\nu}p)}=0.99\pm 0.05.$$

Comparison of the effects from the near and far reactors yields the ratio

$$K_{\mathrm{expt}}=\frac{N_1}{N_3}\left(\frac{R_1}{R_3}\right)^2=0.86\pm 0.15.$$

Analysis of the experimental results by the two methods leads to the following restrictions on the characteristics of the neutrino oscillations, at a 90% confidence level:

$$\Delta m_{1,2}^2\leqslant 7.5\times 10^{-3}\,\mathrm{eV}^2 \quad \text{for} \quad \sin^2 2\theta=1,$$

$$\sin^2 2\theta\leqslant 0.15 \quad \text{for} \quad \Delta m_{1,2}^2\geqslant 5.0\times 10^{-2}\ \mathrm{eV}^2.$$

Figure 1 shows the constraints imposed on the characteristics of the neutrino oscillations.

It was asserted in a paper[7] by the KAMIOKA-II group that oscillations of the $\nu_\mu\leftrightarrow\nu_\tau$ type had been observed. In Fig. 1, the region of allowed values of the characteristics lies to the right of the corresponding curve. Restrictions on the character-

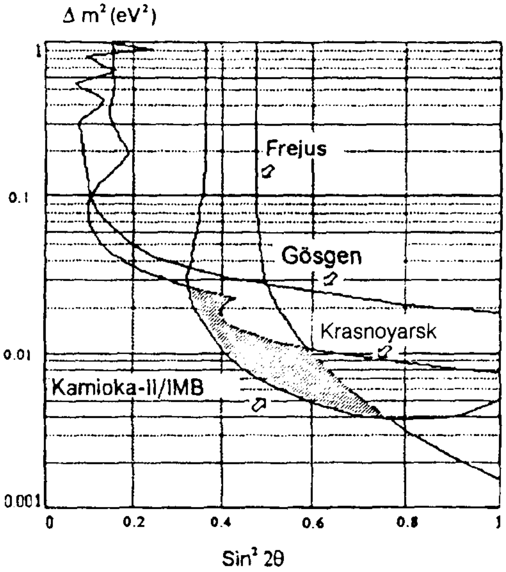

FIG. 1. Constraints imposed on characteristics of the neutrino oscillations.

istics of neutrino oscillations were reported in Refs. 8 and 9; the forbidden regions lie to the right of the curves in Fig. 1. The hatched region satisfies the results of all these experiments. In order to confirm or reject the possibility that oscillations with characteristics corresponding to the hatched region actually exist, it will be necessary to measure the cross section for inverse beta decay at hydrogen nuclei with a larger distance between the detector and the source of neutrinos (or antineutrinos): 1 km or more.

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