Limitations on the magnetic moment and charge radius of the electron antineutrino

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(Submitted 24 December 1991)
Pis'ma Zh. Eksp. Teor. Fiz. **55**, No. 4, 212–215 (25 February 1992)

An elastic scattering of an antineutrino by an electron has been observed in the flux of antineutrinos from a power reactor. A 103-kg detector of a fluoroorganic scintillator was used. The cross section for $(\tilde{\nu}_e e)$ scattering was measured for energies of the recoil electron in the interval 3150-5175 keV. The result is $\sigma = (4.5 \pm 2.4) \times 10^{-46}\,\mathrm{cm}^2/\mathrm{fission}$. Limitations are found on the magnetic moment ($\mu_\nu \leqslant 2.4 \times 10^{-10} \mu_\mathrm{B}$) and the charge radius ($|r| \leqslant 2.7 \times 10^{-16}$ cm) of the electron neutrino at a 90% confidence level.

The scattering of electron neutrinos by electrons is an interesting process because it involves only leptons, one of which is neutral. It thus becomes possible to see weak-interaction effects in their pure form and to study properties of neutrinos that go beyond the standard theory of electroweak interactions. Analysis of the results of the measurements by the Davis group,[1-3] the results of the KAMIOKANDE experiments, and other results suggest an anticorrelation between the flux of solar neutrinos and solar activity. If this is the case, then an anticorrelation might be linked with the electromagnetic properties of neutrinos and might be explained on the basis that the electron neutrino has a magnetic moment[4-7] $\mu_\nu \simeq (1\text{–}10) \times 10^{-11}\, \mu_B$.

When the weak interaction, the magnetic moment, and the charge radius are taken into account, the cross section for $(\tilde{\nu}_e e)$ scattering is written[8]

$$\frac{d\sigma}{dT} \left(\frac{G_F^2 m_e}{2\pi}\right) \left\{ (g_V' + \delta - g_A')^2 + (g_V' + \delta + g_A')^2 (1 - T/E)^2 \right. \\ \left. + \left[g_A'^2 - (g_V' + \delta)^2 \right] \frac{m_e T}{E^2} \right\} \\ + \frac{\pi \alpha^2 \mu_\nu^2}{m_e^2} \times \frac{1 - T/E}{T},$$

where $g_V' = 2 \sin^2\theta_W + 1/2$, $g_A' = 1/2$, E is the energy of the incident antineutrinos, T is the energy of the recoil electrons, m is the mass of an electron, α is the constant of the electromagnetic interaction, μ_ν is the magnetic moment of the neutrino, expressed in electron Bohr magnetons $\mu_B = e/2m_e$, and the contribution δ comes from the charge radius of the neutrino.

From the standpoint of the possibility of observing the magnetic moment of a neutrino (or an antineutrino), we would prefer to carry out experiments with low-

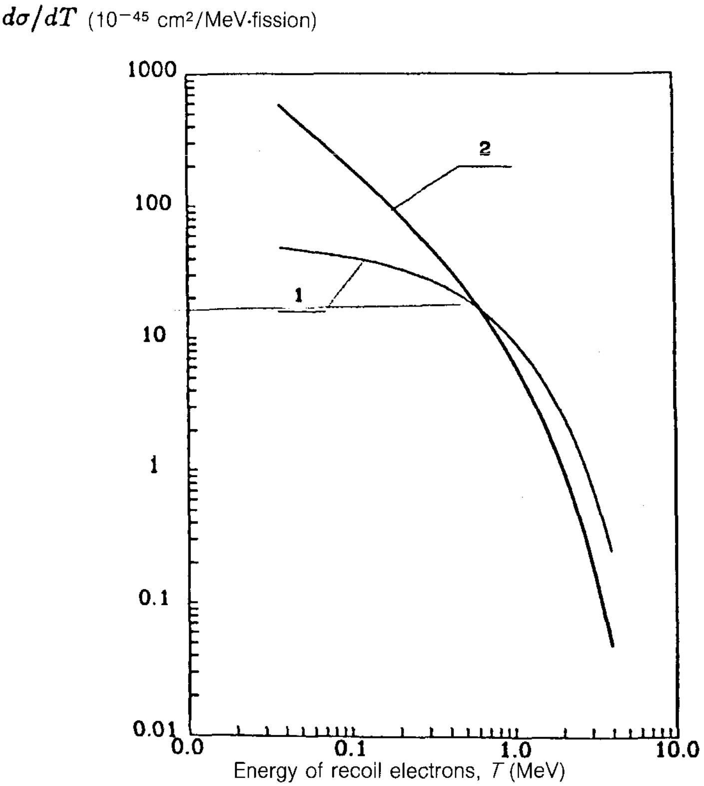

FIG. 1. Calculated differential spectrum of recoil electrons from the scattering of reactor antineutrinos by electrons. 1—As a result of the weak interaction with $\sin^2\theta_W = 0.23$; 2—as a result of the magnetic moment of the antineutrino, $\mu_{\bar{\nu}} = 10^{-10}\mu_B$.

energy neutrinos (or antineutrinos), since the relative contribution of the magnetic moment to the cross section increases with decreasing energy. A nuclear reactor is an intense source of low-energy antineutrinos here on the earth. Figure 1 shows the behavior of the cross section for $(\tilde{\nu}_e e)$ scattering as a result of the weak interaction with $\sin^2\theta_W = 0.23$ (line 1) and as a result of the magnetic moment of the antineutrino, $\mu_\nu = 10^{-10}\mu_B$ (line 2), for the reactor spectrum of antineutrinos.[9,10]

So far, the scattering of reactor antineutrinos by electrons has been studied by only three groups.[11-13] In Ref. 12, it had not yet been found possible to improve the signal-to-background ratio, which was less than 1/50. In Ref. 11, the target was a hydrogenous scintillator, which introduced serious difficulties in efforts to combat a correlated background from inverse β decay at the proton. The present study was a continuation of Ref. 13, in which $(\tilde{\nu}_e e)$ scattering was detected by means of a low-background fluoroorganic detector. The total amount of working material (scintillation hexafluorobenzene) was 103 kg; the number of electrons was 3.0×10^{28}; and the admixture of hydrogen atoms in the scintillation additives was 1.6×10^{25}.

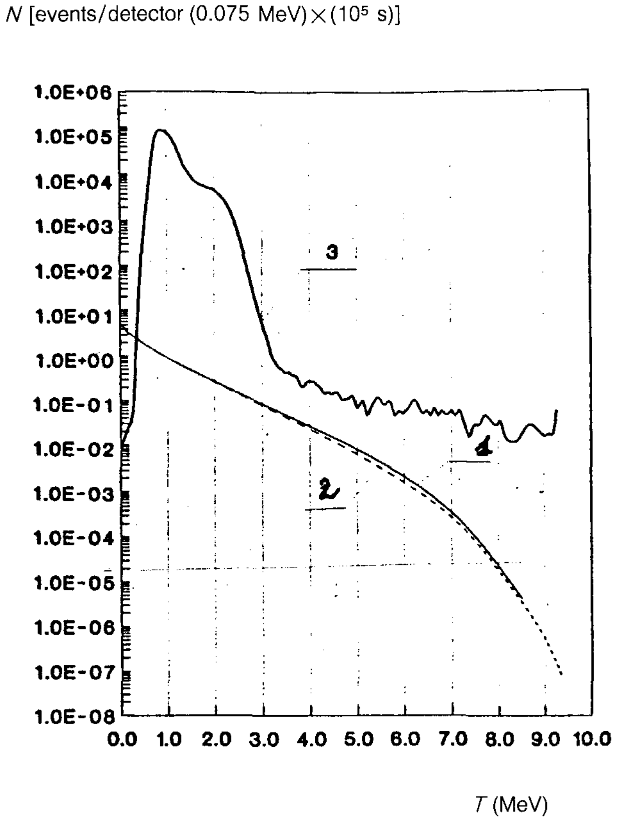

FIG. 2. Expected spectrum of recoil electrons from weak $\tilde{\nu}e$ scattering with $\sin^2\theta_W = 0.23$, with allowance for the instrumental distortion; 2—with allowance for the contribution of positrons from inverse β decay at hydrogen atoms of the scintillation additives; 3—experimental differential spectrum of the background of the $\tilde{\nu}e$-scattering detector at the experimental position.

The detector was installed at a reactor in an antineutrino flux $\sim 2.7 \times 10^{12}$ $\tilde{\nu}(\mathrm{cm}^2\cdot\mathrm{s})$. Measurements were carried out for 254 days with the reactor operating and for 78 days with the reactor shut down. Curve 3 in Fig. 2 shows the background spectrum, recorded while the reactor was shut down. Shown for comparison, by curves 1 and 2, are calculated spectra of recoil electrons from weak $(\tilde{\nu}_e e)$ scattering with $\sin^2\theta_W = 0.23$. Curve 1 reflects the energy resolution and the wall effect; curve 2 also reflects positrons from the competing reaction $\tilde{\nu}_e + p \rightarrow n + e^+$ at hydrogen atoms in the scintillation additives. In these calculations we used the spectra of reactor antineutrinos from Refs. 9 and 10, since the spectrum of antineutrinos from the particular reactor which was selected was determined almost exclusively by the fission products of ^{235}U. It can be seen from Fig. 2 that the optimum measurement range is 3150–5175 keV. In this energy range, the effect-to-background ratio was 1/10, and the calculated value of the correlated background from inverse β decay amounted to 14% of the expected effect.

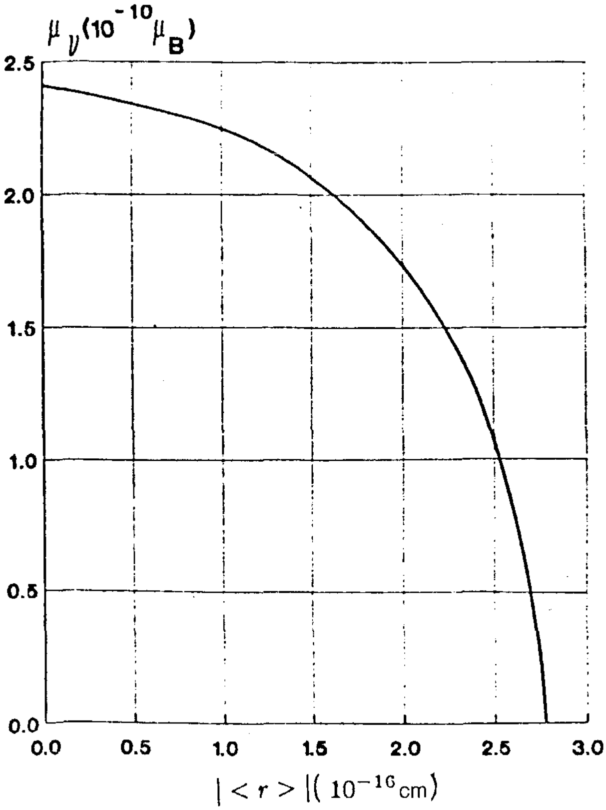

FIG. 3. Limitations on the values of the magnetic moment and the charge radius of the electron antineutrino.

As a result of these measurements, we found the cross section for $(\tilde{\nu}_e e)$ scattering over the energy range 3150-5175 keV: $\sigma_{\nu e} = (4.5 \pm 2.4) \times 10^{-46}$ cm^2/fission.

If we assume that the $(\tilde{\nu}_e)$ scattering occurs only through the weak interaction, then we draw the conclusion $\sin^2\theta_W = 0.22^{+0.7}_{-0.8}$ from this cross section.

If we instead assume $\sin^2\theta_W = 0.23$ (Refs. 14 and 15), we find the following limitations on the magnetic moment and charge radius of the electron antineutrino, at a 90% confidence level:

$$\mu_{\tilde{\nu}} \leq 2.4 \cdot 10^{-10}\mu_B \quad \text{and} \quad |r| \leq 2.7 \cdot 10^{-16}\text{cm}.$$

Figure 3 shows the region of limitations on the charge radius and magnetic moment of the electron antineutrino.

At the moment, these limitations are among the stiffest which have been established as the result of experiments in the laboratory.[8,16,17]

In order to raise the sensitivity of the experiment with respect to the magnetic moment of the antineutrino, it would be necessary to measure the cross section for $(\tilde{\nu}_e e)$ scattering at recoil-electron energies ~1.5–3.0 MeV. Such measurements, however, would require reducing the detector background in this energy region by at least two orders of magnitude. We see the following ways out of this situation:

1) Upgrade the passive shielding of the detector, using "pure" materials ("pure" in the radiation sense).

2) Increase the volume of the detector and divide it into sections. These approaches would make it possible to improve the active shielding, by virtue of an increase in the efficiency with which rescattered γ rays are detected.

3) Reduce the relative amount of structural material in the detector.

Work is presently being carried out in these directions.

We wish to thank S. T. Belyaev for constant interest in this study and for useful discussions, S. E. Averochkin, S. L. Zimin, Yu. F. Tarasov, A. I. Kireev, V. I. Nikitkin, and I. V. Panov for assistance in the preparation for these experiments and in the experiments themselves. We also thank the reactor staff for maintaining good working conditions.

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Translated by D. Parsons