$\tilde{\nu}_e$ spectra at two distances from the reactor of the Rovno nuclear power plant: search for oscillations

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(Submitted 16 January 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **45**, No. 5, 201–204 (10 March 1987)

The spectra of positrons from the reaction $\tilde{\nu}_e + p \rightarrow e^+ + n$ were measured at distances of 18.3 and 25.3 m from the reactor. The spectra are found to be identical within the statistical error ($\sim$32 000 $\tilde{\nu}_e$'s detected). Limitations are found on the parameters of neutrino oscillations. The reported observation of oscillations at the Bourges reactor, in an experiment at distances of 13.6 and 18.3 m, is not confirmed.

1. A study of the reaction

$$\tilde{\nu}_e + p \rightarrow e^+ + n \tag{1}$$

is continuing at the neutrino laboratory of the Rovno nuclear power plant. Two different detectors in the same $\tilde{\nu}_e$ flux at a point 18 m from the center of the reactor core have revealed the total cross section for this reaction per ^{235}U fission event[1]:

$$^5\sigma_f = 6.08 \times 10^{-43}\ \text{cm}^2/\text{fission} \pm 5.4\%\ (68\%\ \text{confidence level}). \tag{2}$$

The same measurements yielded the positron spectra in absolute normalization.[2]

A knowledge of the absolute characteristics of reaction (1) is important from many points of view. In particular, these characteristics are the metrological base for a study of other processes involving the interaction of reactor $\tilde{\nu}_e$'s. In a study of the Pontecorvo oscillations, however, some well-known difficulties stem from (on the one hand) the uncertainty about the actual spectrum of reactor antineutrinos and (on the other) the errors in the determination of the characteristics of the detector.

2. In this letter we report measurements of the energy spectra of positrons from reaction (1) carried out at two distances from the reactor: $^1R = 18.3$ m and $^2R = 25.3$ m. By comparing these spectra measured at the different distances, we can find estimates of the parameters of the oscillations which are free of several of the errors inherent in an absolute method.

In the model of oscillations with two states of masses m_1 and m_2 with a mixing angle θ, the spectrum of positrons from reaction (1), $S(E_e)$, varies in the following way with the distance (R) from the point of the $\tilde{\nu}_e$ production:

$$S_{\theta,\Delta^2}(E_e, R) = S_0(E_e)\left[1 - \sin^2 2\theta \sin^2 \frac{1.27\,\Delta^2 R}{E_e + 1.29}\right], \tag{3}$$

where $S_0(E)$ is the spectrum in the absence of oscillations, $\Delta^2 = |m_1^2 - m_2^2|$ eV^2, and

0021-3640/87/050247-05$01.00

E_e is the total energy of the positron, whch is related to the energy of the $\tilde{\nu}_e$ by the relation $E_e + 1.29 = E_{\tilde{\nu}}$ (MeV).

It follows from (3) that for each positron energy there is a corresponding spatial period in the variation of the intensity over distance. This period is inversely proportional to $E_3 + 1.29$ MeV, so that a spectral experiment is equivalent to a search for oscillations for many energies simultaneously.

3. In the present measurements we use a spectrometer containing 238 liters of a liquid organic scintillator with gadolinium additives.[3] Neutrino events are distinguished by the method of delayed coincidences between the positron and the γ rays resulting from the capture of neutrons by the gadolinium. The detection efficiency (32%) is independent of the direction of the $\tilde{\nu}_e$ flux. The response function in the detection of positrons depends on the actual energy resolution of the spectrometer and the spectrum of energies left in the working volume by the annihilation γ rays. For monoenergetic positrons, the width of this function at half-maximum ranges from 0.75 MeV (at $E_3 = 1.5$ MeV) to 1.0 MeV (at $E_e = 6.5$ MeV). In the experiment we detected a total of about 32000 events, of which 16000 were detected at 25 m.

The energy scale of the spectrometer is checked within an error of 0.7% up to 4 MeV on the basis of the ^{60}Co and ^{24}Na total-absorption peaks; at higher energies, the scale is checked on the basis of the spectrum of γ rays resulting from the capture of neutrons by gadolinium.

To minimize the uncertainties which result from variations in the $\tilde{\nu}_e$ spectrum of the reactor in the course of the project, we carried out the measurements in an identical way at each distance: before the reactor was shut down for refueling, during a shutdown (this was a background measurement), and again after the reactor was brought back up to power. The composition of the fuel was therefore nearly identical at the two distances.

Figure 1 shows the spectra found experimentally for the working reactor (effect + background) and for the reactor during shutdown (background). After subtraction of the background, we made some small corrections to the spectra to allow for the other reactor at the Rovno plant.

The spectrum measured at 25 m can be converted into that measured at 18 m by multiplying by a geometric factor of 1.908 and by a factor of 0.995, which reflects the slight differences in the measurement conditions at the two distances. The spectra found in this manner are shown along with their ratio, $(^{25}S/^{18}S)^{\rm expt}$, in Fig. 2. The ratio of the integrals over these spectra is $(^{25}I/^{18}I) = 0.977 \pm 4.7\%$.

4. It can be seen from the data shown in Fig. 2 that the spectra measured at the two distances are the same, within the errors. The best agreement of the spectra was found by making a fine adjustment of the spectra toward each other: changing the relative normalizations by 0.8% and carrying out a 1.34% relative extension of the scales. This fine adjustment resulted in a minimum value of χ^2. A search was made for restrictions on the parameters of the oscillations, Δ^2 and $\sin^2 2\theta$, by comparing the experimental ratios $(^{25}S/^{18}S)^{\rm expt}$ with the theoretical ratios $(^{25}S/^{18}S)^{theo}$ by the maximum-likelihood method. For a comparison, the theoretical ratios were averaged over the dimensions of the reactor core and the response function of the detector.

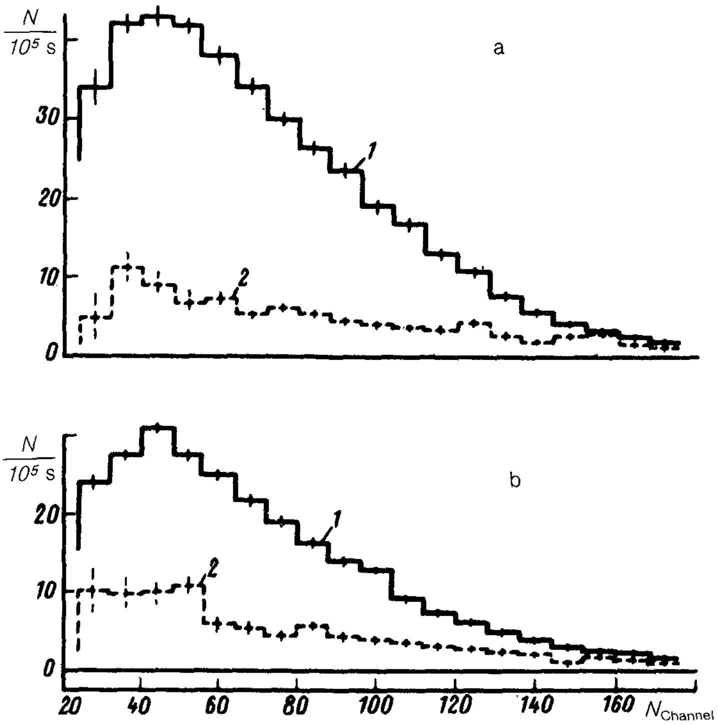

FIG. 1. Experimental spectra measured (1) with the reactor working and (2) with the reactor shutdown. a—$^1R = 18.3$ m; b—$^2R = 25.3$ m.

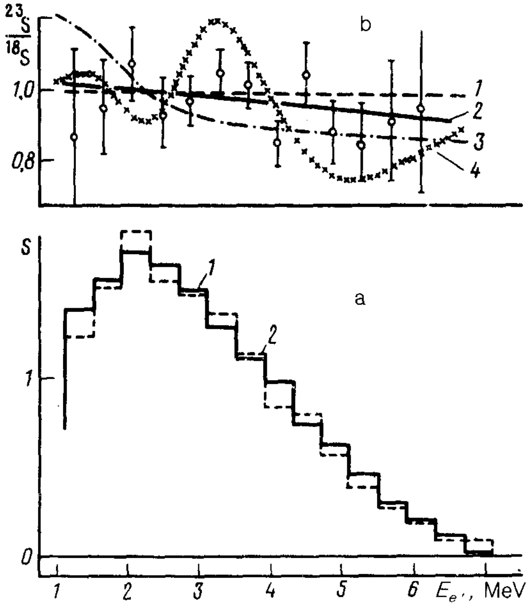

FIG. 2. a: Experimental e^+ spectra measured at distances of (1) 18.3 m and (2) 25.3 m. b: Ratios of spectra. Points with error bars—experimental; curves—theoretical. 1—With allowance for the actual compositions of the reactor core; 2—best fit of experiment (without oscillations); 3—with oscillations, with the parameter values $\sin^2 2\theta = 0.25$, $\Delta^2 = 0.2$ (eV)^2; 4—the same, with $\sin^2 2\theta = 0.25$ and $\Delta^2 = 0.9$ (eV)^2.

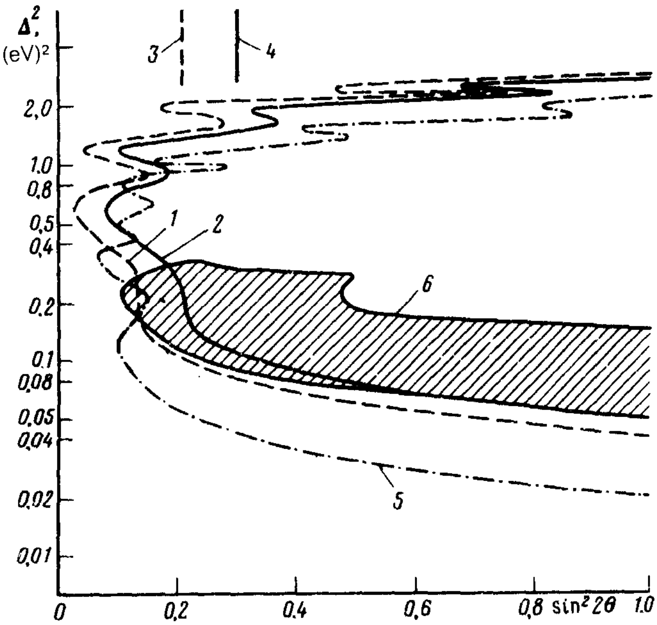

FIG. 3. Limitations on the parameters of the oscillations in the ($\sin^2 2\theta$, Δ^2) plane. Rovno (present study): 1—Confidence level of 68%; 2—90%. Rovno[1]: 3—Confidence level of 68%; 4— 90%; 5—Gesgen,[7] confidence level of 90%; 6 (the hatched region)—the region in which oscillations were observed in accordance with Ref. 6.

5. The restrictions found are shown in Fig. 3. At small values of Δ^2, the experiment loses sensitivity. At large values of Δ^2, the quantity $\sin^2(1.27\Delta^2 R)/(E_e + 1.29)$ begins to oscillate rapidly, so that when an average is taken over the geometry and the response function, the Δ^2 dependence drops out of spectrum (3), and we have $S \to S_0(1 - \frac{1}{2}\sin^2 2\theta)$.

It can now use an absolute method to find limitations on $\sin^2 2\theta$ at large Δ^2. At large Δ^2, the cross section tends toward the limiting value

$$\sigma_{\rm osc} = \sigma_0(1 - \tfrac{1}{2}\sin^2 2\theta), \tag{4}$$

where σ_0 is the cross section in the absence of oscillations.

To calcuate σ_0, we used the most recent $\tilde{\nu}_e$ spectrum for ^{235}U from Ref. 4. Correcting for recoil, the slight magnetism, and radiation corrections in accordance with Ref. 5, we find $\sigma_0 = 6.31 \times 10^{-43}$ cm^2/fission. Comparing (4) with (2), we find

$$\frac{{}^5\sigma_f^{\rm expt}}{\sigma_0} = \frac{6.08 \pm 5.4\%\ (68\%\ \text{confidence level})}{6.31 \pm 4.2\%\ (68\%\ \text{confidence level})}$$

$$= 0.964 \pm 0.068\ (68\%\ \text{confidence level}). \tag{5}$$

We thus find the limitation

$$\sin^2 2\theta \leqslant 0.21 \text{ (68\% confidence level; large values of } \Delta^2\text{)}. \quad (6)$$

We thus see (Fig. 3) that the report[6] of an observation of an oscillation effect at the Bourges reactor is not confirmed by our own experiments. On the other hand, the sensitivity of reactor experiments is still low. It follows from Fig. 3 that if oscillations were actually occurring, but with a mixing angle amounting to 0.7 to 1.0 times θ_C, the quark mixing angle ($\theta_C \simeq 13°$; the Cabibbo angle), this circumstance would have gone unnoticed in the reactor experiments which have been carried out to date.

We wish to thank N. A. Markov and S. T. Belyaev for their time and interest; S. L. Gavrilov, L. A. Levin, and A. N. Kheruvimov for assistance in the measurements; A. A. Borovyĭ and S. A. Fayans for useful discussions; V. T. Danilov, Yu. G. Kuvatov, and Yu. I. Murinov for assistance with the scintillator; and the directors and staff of the Rovno nuclear power plant for their constant assistance.

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Translated by Dave Parsons