Neutrino experiment in the reactor of the Rovno atomic power plant: cross section for inverse β decay

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Two experiments were carried out simultaneously to measure the cross section for the reaction $\tilde{\nu}_e + p \rightarrow n + e^+$ in the same $\tilde{\nu}_e$ flux by different methods in the neutrino laboratory at the Rovno atomic power plant. The results reveal 29×10^3 $\tilde{\nu}_e$. The cross section assigned to antineutrinos accompanying a single ^{235}U fission event is found to be $\sigma_f^5 = 6.08 \times 10^{-43}$ cm^2/fission $\pm 3.5\%$ (reactor) $\pm 5\%$ (detector). The results are compared with calculated cross sections. The problem of searching for Pontecorvo oscillations is discussed. Limitations on the characteristics of these oscillations are given.

1. Measurements of the cross section for the fundamental process

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

were begun in a neutrino laboratory at the Rovno atomic power plant in 1982 in order to determine the characteristics of this process as accurately as possible. Preliminary results which had been obtained by the summer of 1983 were published in Refs. 1 and 2. After several refinements of the procedure in 1984, a new series of measurements was undertaken, with a substantially greater statistical base. The measurements were taken at a point 18 m from the center of the reactor core of the VVÉR-440, 1375-MW reactor (thermal power).

In this letter we describe the most important aspects of this new approach, postponing a detailed description of the procedure to a future paper.

a) Measurements are taken in the same $\tilde{\nu}_e$ flux by two different detectors.

In one of the detectors, a scintillation spectrometer, a liquid organic scintillator containing gadolinium, doubles as a target for the $\tilde{\nu}_e$ and as a neutron moderator. The measurements are based on the delayed coincidences between the positron and the neutron. The energy threshold for the detection of positrons is lowered to 0.6 MeV, so that an extrapolation to a zero threshold can be carried out reliably.

In the other detector, reaction (1) is detected exclusively on the basis of neutrons. The target for the $\tilde{\nu}_e$ and the neutron moderator in this case is polyethylene, in which counters filled with helium-3 are embedded. The switch from the detection of positrons is extremely attractive for measurements of the total cross section. On the other hand, the absence of coincidences degrades the signal-to-background ratio.

b) The efficiency at which the events of inverse β decay are detected in these detectors is two or three times higher than in other detectors which have been used in

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reactor experiments in recent years. Because of this higher efficiency, the statistical base is increased, and—no less importantly—it becomes possible to more reliably determine the efficiency at which the reaction is detected and thus its cross section.

The basic characteristics of the apparatus are listed in Table I.

TABLE I.

	Scintillation spectrometer	Neutron detector
Target	Scintillator	Polyethylene
	$CH_{1,92}$ 190 kg	CH_2, 134 kg
Efficiency	32%	54%
Count rate	$310/10^5$ s	$370/10^5$ s
Number of detected events		
1984	15×10^3	14×10^3

The measurements were carried out until the reactor was shut down for preventive maintenance, during the shutdown, and after it. The average composition of the core (in terms of the number of fission events) over the measurement time interval was

isotope *(i)*	^{235}U	^{239}Pu	^{238}U	^{241}Pu
contribution α_i	0,606	0,277	0,074	0,043 .

(2)

2. The following values were found for the cross section for reaction (1), referred to isotope mixture (2):

scintillation: $\sigma_f = 5.97\times10^{-43}$ cm²/fission ± 3.0%(reactor)
spectrometer: ± 7% (detector)
neutron detector: $\sigma_f = 5.7\times10^{-43}$ cm²/fission ± 3.0%(reactor)
± 6% (detector) .

The average weighted value from the two experiments is

$$\sigma_f = 5.82\times10^{-43}\ \text{cm}^2/\text{fission} \pm 3\%(\text{reactor}) \pm 5\%\ (\text{detector}). \qquad (3)$$

The first of these errors, the "reactor" error, which is the same in the two experiments, reflects our estimate of the error in the knowledge of the reactor power and the experimental geometry. The second error, the "detector" error, includes the errors due to the statistics and other fluctuations. It also reflects the accuracy with which the characteristics of the detectors are determined.

From (3) we can also find the cross section (σ_f^5) for the most abundant isotope, ^{235}U; clearly,

$$\sigma_f = \sigma_f^5\left[1+\sum_{i=9,8,1}\alpha_i\left(\frac{\sigma_f^i}{\sigma_f^5}-1\right)\right] \equiv \sigma_f^5(1+K).$$

According to our estimates, for core composition (2) we have $K = -0.043 \pm 40\%$ and

$$\sigma_f^5 = 6.08\times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission} \pm 3.5\%\ (\mathrm{reactor}) \pm 5\%\ (\mathrm{detector}). \tag{4}$$

The error in the cross section for the inverse β decay is still three times the error in the lifetime of a free neutron.

3. The cross section for reaction (1) can be calculated from the equilibrium $\tilde{\nu}_e$ spectra from the products of the fission of uranium and plutonium.[3-6] In these calculations we used an analysis of neutron decay[7] and a decay half-life $T_{1/2} = 623$; we took into account recoil, the weak magnetism, and the radiation corrections in reaction (1). As a result, we found the following values (in cm^2/fission) for isotope mixture (2):

$7{,}05\times10^{-43}$ [3]; $6{,}03\times10^{-43}$ [4]; $5{,}73\times10^{-44\ 1)}$ [5] and $5{,}66\times10^{-43}$ [6].

We see that the experimental results confirm Ref. 5 well; furthermore, Refs. 4 and 6 are consistent with the experimental results, while the spectrum of Ref. 3 leads to a significantly larger cross section.

4. Reaction (1) has recently been studied at various distances from a reactor in a search for Pontecorvo oscillations: 8.76 m at Grenoble,[8] 13.6 and 18.3 m at Bouger,[9] 37.9 and 45.9 m at Gezgen,[10] and 18 m at Rovno (the present study).

The total statistical base of events detected throughout the world exceeded 100 000 in 1984. This statistical base might be used for a comparison and refinement of the results, but this comparison is hampered by the circumstance that the results reported in Refs. 8–10 are not the cross section itself but the count rate with respect to its "expected" value. The cross section reported in Ref. 10, found at distances of 37.9 and 45.9 m, is apparently several percent higher than that of the present study, but the difference lies within the errors. It is even more difficult to make a comparison with the results of Refs. 8 and 9.

5. The impression that we get is that the reactor experiments being carried out on a global scale are not yielding any definite indications of Pontecorvo oscillations. On the other hand, the data available still leave us some latitude and room for speculation. For example, Fig. 1 shows the relative change in the cross section with distance (R) from the reactor which we would expect on the basis of a model of two mixed states (m_1 and m_2 are the masses, and θ is the Pontecorvo mixing angle). The corresponding cross section has the structure

$$\sigma(R) = \sigma(0)\,[1 - \sin^2 2\theta\, f(R\cdot\Delta^2)],$$

where $\Delta^2 = |m_1^2 - m_2^2|$, and f, a function of the product $R\Delta^2$, is essentially insensitive to the particular choice of spectrum of reactor ν_e's. Calculations have been carried out for $\sin^2 2\theta = 0.2$ and $\Delta^2 = 0.25$ eV^2. The resulting picture, within the errors, again

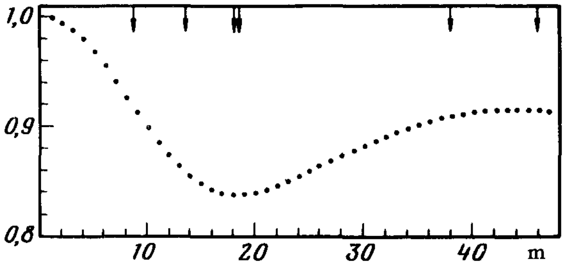

FIG. 1. Cross section for reaction (1) versus the distance in the model of oscillations with the parameter values $\sin^2 2\theta = 0.2$ and $\Delta^2 = 0.25$ eV^2. The arrows show the distances at which experiments have been carried out.

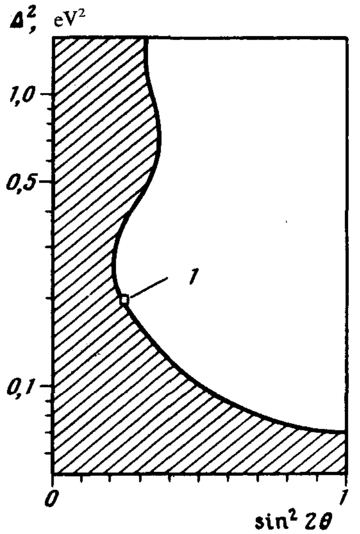

FIG. 2. Restrictions on the characteristics of Pontecorvo oscillations. The hatching shows the region in which oscillations may occur. 1—Best fit according to Ref. 11.

seems consistent with the data available. For these parameter values the first minimum occurs at 18 m, where the cross section is 16% lower than $\sigma(0)$, while the first maximum, at 40–50 m, has a 9% increase. At 9, 38, and 46 m, on the other hand, the cross sections are very accurately equal to each other (for identical compositions of the reactor core).

While we were writing this paper, a French group reported an observation of oscillations at the Bouger reactor.[11] The experimental data given above are not extremely strong arguments against oscillations, and they do not contradict the parameters of Ref. 11 (Fig. 2).

At this stage of the study we suggest, conservatively, that the oscillation effect at distances $R \geqslant 18$ m from the reactor does not reduce the cross section by more than 16%, if it does so at all. From this assertion we find the limitations shown in Fig. 2, where the hatched region shows the values of the parameters Δ^2 and $\sin^2 2\theta$ in which oscillations may occur.

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(1) In Ref. 5. the $\tilde{\nu}_e$ spectra were given only for the most abundant isotopes, ^{235}U and ^{239}Pu. We found spectra for ^{238}U and ^{241} Pu by combining the data of Refs. 4 and 6.

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