Cross section for the inverse beta decay of the proton from nuclear-reactor measurements

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The cross section for the reaction $\tilde{\nu}_e + p \rightarrow n + e^+$ has been measured in the neutrino laboratory at the Rovenskiĭ nuclear power plant. Limits have been found on the parameters of the neutrino oscillations.

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Back in 1966, Nezrick and Reines[1] measured the cross section for the reaction

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

in a nuclear reactor. They reported the value[1)] $\sigma_{\tilde{\nu}} = (0.94 \pm 0.13) \times 10^{-43}$ cm^2 per $\tilde{\nu}_e$. Although reaction (1) has been studied in several more recent experiments,[4,5] no cross sections have been reported directly.

In this letter we report cross-section measurements based on 3196 neutrino events detected in the underground neutrino laboratory at the Rovenskiĭ nuclear power plant.[6] The measurements were taken with a scintillation spectrometer at a distance $R = 18.4$ m from the center of the core.

The target for the $\tilde{\nu}_e$'s and the neutron moderator was a liquid scintillator consisting of decahydronaphthalene (235.5 liters) with a gadolinium admixture. Events were detected on the basis of coincidences between the positron and the γ rays from the capture of neutrons from reaction (1) in gadolinium. The weight for the second event was from 4 to 150 μs after the first event. Positrons were detected over the kinetic-energy range 1.0–9.5 MeV (see Ref. 7 for more details).

TABLE I.

	Average power (MW)	Measurement time (s)	Number of events[2)]	Number of events in 10^5 s
Before shutdown	1389	6.6×10^5	2535	384 ± 10
During shutdown	0	20.9×10^5	2281	109 ± 4
After shutdown	1354	5.3×10^5	1960	370 ± 15

Table I shows the results of the measurements with the reactor in operation and shut down. It follows from these results that the count rate of neutrino events is $N_{\tilde{\nu}} = 269 \pm 13$ over 10^5 s with a background $N_b = 109 \pm 4$ over the same time interval. We might note that the data base was accumulated far more rapidly than in corresponding experiments over the past two decades.

The cross section for reaction (1), $\sigma_f^{(5)}$, was determined from

$$N_{\tilde{\nu}} = \frac{\overline{W}}{\overline{E}_f} \frac{1}{4\pi R^2} N_p \, \epsilon_{\beta n} \, (1+k)\, \sigma_f^{(5)} ,$$

where $\overline{W}$ is the average thermal power of the reactor (1373 MW), $\overline{E}_f$ is the average energy released in the reactor per fission event (202 ± 2 MeV), $R = 28.4 \pm 0.1$ m, $N_p = (1.59 \pm 0.03)\times 10^{28}$ is the number of protons in the installation, $\epsilon_{\beta n} = 0.285 \pm 0.021$ is the efficiency of the $\tilde{\nu}_e$ detection at the amplitude and time intervals used, and $k = -(0.04 \pm 0.02)$ is the correction for fission of ^{238}U, ^{239}Pu, and ^{241}Pu in the core.

We found the value $\sigma_f^{(5)} = 6.2\times 10^{-43}$ cm^2/fission $\pm 5\%$ statistical[3)] $\pm 9\%$ systematic. For comparison, here are some theoretical values of $\sigma_f^{(5)}$ which we have calculated from the $\tilde{\nu}_e$ spectra published in 1981–82 (in units of 10^{-43} cm^2/fission): 7.2 (Ref. 8), 6.5 (Ref. 3), 6.0 (Ref. 9), 6.1 (Ref. 10), and 6.8 (Ref. 11). In these calculations we used the cross section for reaction (1) for monoenergetic ν_e's:

$$\sigma_{\nu p} = \frac{2.63\cdot 10^{-41}}{f t_n} (\epsilon_\beta + 1) \sqrt{(\epsilon_\beta + 1)^2 - 1} \ \mathrm{cm}^2 ,$$

where ϵ_β is the kinetic energy of the positron in units of m_0c^2, $f = 1.715$, and t_n is the decay half-life of the neutron, expressed in seconds (630 ± 20).

Without giving preference to any of the theoretical values of $\sigma_f^{(5)}$, we can place a cautious limit on the Pontecorvo-oscillation effect[4)] (under the assumption that there are two oscillatory states with rest masses m_1 and m_2):

$$\Delta^2 = |m_1^2 - m_2^2| < 0,1\,(\mathrm{eV})^2 \ (\text{ for } \sin^2 2\theta = 1)$$

and $\sin^2 2\theta < 0,4$ (for $\Delta^2 > 4$ (eV)^2).

The oscillation effect will be discussed in more detail in a separate analysis of the positron energy spectrum found in this experiment.

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[1)]Here $\sigma_{\tilde{\nu}}$ is the cross section per antineutrino. This is a relative quantity, since many of the $\tilde{\nu}_e$'s emitted by fragments have energies below the reaction threshold (1.8 MeV). The actual number in this category depends on the composition of the zone, etc. Here we will use the value $\sigma_f^{(5)}$, which is the cross section per ^{235}U fission. It is generally assumed that [2,3] $\sigma_f^{(5)} = 6.14 \times \sigma_{\tilde{\nu}}$.

[2)]The random-coincidence background has been subtracted.

[3)]The statistical error was found from the actual scatter in the various series of measurements.

[4)]The estimate of the oscillations is of course somewhat arbitrary: If we adopt the theoretical value $\sigma_f^{(5)} = 6.5 \times 10^{-43}$ cm^2/fission (Ref. 3), we can obtain some much more stringent restrictions on Δ^2 and $\sin^2 2\theta$. We do not believe that this approach is justified.

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