Precise measurement of the cross section for the reaction $\tilde{\nu}_e + p \rightarrow n + e^+$ at a reactor of the Rovno nuclear power plant

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The cross section for the reaction $\tilde{\nu}_e + p \rightarrow n + e^+$ has been measured at a reactor of the Rovno nuclear power plant. An integral detector of a new generation has been used. From 120 000 reaction events detected, the value $\sigma = 6.29 \cdot 10^{-43}$ cm^2/(^{235}U fission) $\pm 2.9\%$ was found. Analysis of the results reveals a good agreement between the experimental data and the predictions of the standard model of the electroweak interaction. The following value was found for the axial β-decay constant: $G_A = (1.777 \pm 0.042) \cdot 10^{-49} \lambda = 1.256 \pm 0.030$.

The present study completes a series of measurements of the total cross section for the reaction

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

The study was begun at a VVÉR-440 reactor of the Rovno nuclear power plant in 1983.

The purposes of this study were to learn about the interaction of electron antineutrino with a free nucleon as accurately as possible, to measure the fundamental constants of β decay, and to test the minimal model of the electroweak interaction. The cross section for reaction (1) is also used in analyzing the experiments presently being carried out to learn about the interactions of $\tilde{\nu}_e$ with the deuteron,[1] for an absolute normalization of the $\tilde{\nu}_e$ energy spectra measured at the Rovno power plant,[2] in the search for $\tilde{\nu} \rightleftarrows \tilde{\nu}_x$[3] oscillations,[3] and in the laying of groundwork for remote control of reactors on the basis of their neutrino emission.[4]

In the measurements we used an integral detector of reaction (1), designed for the purpose. It was a refinement of the detector used in Ref. 5. The refinements improved the effect-to-background ratio and made it possible to determine more accurately the number of target protons and the efficiency at which events of reaction (1) are detected. We recall that in an integral detector reaction (1) is detected solely on the basis of the neutrons which are produced, by means of ^{3}He-filled proportional counters.

The target for the $\tilde{\nu}_e$ and the neutron moderator consisted of distilled water, in which the counters were arranged in a 16×16 square matrix at steps of 70 mm. Useful events were selected on the basis of an amplitude corresponding to the peak representing the total absorption of the products of the reaction $n + {}^3\text{He} \rightarrow T + p$ for counts in the central 14–14 counters.

As in the earlier work at the Rovno power plant, we used the principle of a cancellation of the neutron influx and leakage at the boundaries of the working volume in order to determine the working volume of the target. Some special experiments with low-energy neutron sources, of Pu–Li ($\overline{E}_n \sim 200$ keV) and Sb–Be ($E_n = 24$ keV), made it possible to test the degree of cancellation within 0.5% and to determine the working volume of the target, V_{eff}. The total number of target protons, N_p, was found from the expression $N_p = V_{\text{eff}} n$, where $n = 2\rho N_A/A = 6.66 \cdot 10^{22}$ cm^3. Here $\rho = 0.9964$ g·cm^3 is the density of water at the working temperature of 25 °C, $A = 18.016$ is the atomic weight of water, and N_A is Avogadro's number.

The absolute value of the neutron detection efficiency was determined from the multiplicity of prompt neutrons from the spontaneous fission of ^{252}Cf. We used a new value[6] for the average number of prompt neutrons per ^{252}Cf fission event: $\bar{\nu}_p = 3.757 \pm 0.010$ (earlier, we used the value[7] $\bar{\nu}_p = 3.735 \pm 0.014$). Methodological questions will be discussed in more detail in a publication presently being prepared.

During two working runs of the reactor, two series of measurements of the cross section of reaction (1) were carried out, under slightly different conditions (we will refer to these series of measurements as experiments 1 and 2). The experimental data and experimental conditions are outlined in Table I.

The detector background was measured while the reactor was shut down for a partial refueling. To find the neutrino effect, we selected series of measurements taken while the reactor was operating at a power close to the nominal power (120 000 neutrino events). After the background was subtracted, we obtained the count rate of neutrino events, N_ν, in each experiment (Table I) corresponding to a thermal power $W = 1375$ MW $\pm$ 2% and to an identical average composition of the reactor core:

Isotope	^{235}U	^{239}Pu	^{238}U	^{241}Pu
Contribution to total number of fission events	0.614	0.274	0.074	0.038

The experimental cross section was found from the expression

$$N_\nu = \frac{W}{E_f} \frac{1}{4\pi R^2} (N_p \epsilon) \sigma^{\dagger\,\text{expt}}, \tag{3}$$

where $E_f = 204.8$ MeV $\pm$ 0.4% (Ref. 8) is the average energy absorbed in the reactor core per fission event, and R is the on-center distance between the detector and the core. Table II shows the value of σ^{expt} in each experiment, along with the resultant value, found by averaging only the statistics of the measurements.

TABLE I.

	Experiment 1	Experiment 2
Number of protons, N_p	$5.034 \cdot 10^{28} \pm 0.5\%$	$4.953 \cdot 10^{28} \pm 0.5\%$
Efficiency, ϵ	$0.402 \pm 1\%$	$0.403 \pm 1\%$
Effect + background over 10^5 s	3502.6 ± 7.9	4092.9 ± 9.9
Neutrino effect over 10^5 s	1210 ± 17.1	1161.3 ± 15.7
Distance, R^2	325.66 m^2 $\pm$ 0.5%	336.38 m^2 $\pm$ 0.5%

TABLE II.

Experiment 1	$\sigma^{\text{expt}} = 5.83 \cdot 10^{-43}$ cm^2/fission $\pm 2.1\%$ (det) $\pm 2.1\%$ (react)
Experiment 2	$\sigma^{\text{expt}} = 5.87 \cdot 10^{-43}$ cm^2/fission $\pm 2.1\%$ (det) $\pm 2.1\%$ (react)
Result	$\sigma^{\text{expt}} = 5.85 \cdot 10^{-43}$ cm^2/fission $\pm 1.8\%$ (det) $\pm 2.1\%$ (react)

The first error in σ^{expt} is that associated with the characteristics of the detector and the statistics. The second error reflects the error in the measurement of the power W and the energy $\overline{E}_f$ and also the uncertainty regarding the geometry. Adding the errors quadratically, we find the final result for the composition of the nuclear fuel given above:

$$\sigma^{\text{expt}} = 5.85 \cdot 10^{-43} \text{cm}^2/\text{fission} \pm 2.8\%. \tag{4}$$

The expected (theoretical) cross section for reaction (1) was determined in the standard V–A model of the weak interaction, by summing the probabilities for the capture of monoenergetic $\tilde{\nu}_e$'s by a proton over the spectrum of reactor antineutrinos, $\rho(E_\nu)$:

$$\sigma^{\text{theo}} = \int \sigma^{V-A}(E_\nu)\rho(E_\nu)dE_\nu. \tag{5}$$

The quantity $\sigma^{V\text{-}A}$ can be expressed in terms of the vector β-decay constant G_V and the momentum p and energy E of the positron in reaction (1) as follows:

$$\sigma^{V-A} = \frac{1}{\pi c^3 \hbar^4} G_V^2 (1 + 3\lambda^2) pE(1 - \delta_c)(1 + \delta_R). \tag{6}$$

Here the correction δ_c reflects the nuclear structure and recoil effects, δ_R is an external radiation correction, and λ is the ratio of the axial and vector β-decay constants. The corrections δ_c and δ_R were found in Refs. 9 and 10. The value

$$G_V^2 (1 + 3\lambda^2) = [3{,}4135 \cdot 10^{-49} \ \text{erg} \cdot \text{cm}^3]^2 \pm 0{,}3\% \tag{7}$$

was adopted on the basis of results on the direct reaction: the decay of the free neutron. This value corresponds to a lifetime $\tau_n = 888.6 \pm 2.6$ s (Ref. 11).

The spectra of antineutrinos from the fragments of the fission of ^{235}U,^{239}Pu, and ^{241}Pu were taken from Refs. 12 and 13. The $\tilde{\nu}_e$ spectrum of the ^{238}U fragments was found on the basis of the calculations of Ref. 14.

The cross section which we would expect for mixture (2) on this basis is

$$\sigma^{\text{theo}} = 5{,}94 \cdot 10^{-44} \ \text{cm}^2/\text{fission} \pm 2{,}7\%, \tag{8}$$

where the error is determined by the uncertainty in the $\bar{\nu}_e$ spectrum.

We follow custom in also giving the experimental and theoretical cross sections as converted to the ^{235}U spectrum:

$$\sigma_{\text{expt}} = 6{,}29 \cdot 10^{-43} \ \text{cm}^2/\text{fission} \pm 2{,}9\%, \tag{9}$$

$$\sigma_{\text{theo}} = 6{,}38 \cdot 10^{-43} \ \text{cm}^2/\text{fission} \pm 2{,}5\%. \tag{10}$$

We can draw some conclusions from the experimental results.

1) From (4) and (8) we find

$$\sigma^{\text{expt}}/\sigma^{\text{theo}} = 0{,}985 \pm 0{,}038, \tag{11}$$

confirming the good agreement between the standard model and experimental data.

2) A comparison of (7) with the value

$$G_V^2(1+3\lambda^2) = [3.388 \cdot 10^{-49} \ \text{erg/cm}^3]^2 \pm 3.9\% \tag{12}$$

measured in the present experiment, reveals an agreement within the errors. This comparison appears to be the most accurate test of the equality of the probabilities for the forward and inverse processes under the influence of weak interactions. The lifetime of the free neutron corresponding to (12) is

$$\tau_n = 902 \pm 35 \ \text{s}; \tag{13}$$

3) Using the value $G_V/(hc)^3 = (1.14939 \pm 0.00065) \cdot 10^{-5}$ GeV^{-2} found in Ref. 15 from data on $0^+ \to 0^+$ transitions, along with the result in (12), we find

$$\lambda = 1{,}256 \pm 0{,}030,$$

$$G_A = (1{,}777 \pm 0{,}042) \cdot 10^{-49} \ \text{erg/cm}^3. \tag{14}$$

4) Following the data analysis method of Ref. 16, we find a limitation on the helicity of $\tilde{\nu}_e$:

$h \geqslant 0.95$ (the confidence level is 68%).

We note in conclusion that the result of this measurement of the cross section for reaction (1) agrees well with data found previously for ^{235}U at the Rovno power plant:[17]

$$\sigma_{\text{expt}} = 6{,}28 \cdot 10^{-43} \ \text{cm}^2/\text{fission} \pm 5\% .$$

It also agrees well with the average value over all experiments up to 1988 which was found in Ref. 18:

$$\sigma_{\text{expt}} = 6{,}32 \cdot 10^{-43} \ \text{cm}^2/\text{fission} \pm 3{,}3\%.$$

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[1] A. G. Vershinskiĭ, A. A. Meluzov, and L. A. Mikaélyan, Pis'ma Zh. Eksp. Teor. Fiz. **53**(10), 489 (1991) [JETP Lett. **53**, 513 (1991)].

[2] Yu. V. Klimov, V. I. Kopeĭkin, *et al.*, Yad. Fiz. **52**, 1574 (1990) [Sov. J. Nucl. Phys. **52**, 994 (1990)].

[3] L. A. Mikaélyan, S. V. Nikolaev, *et al.*, *Proceedings of International School on the Physics of Weak*

Interactions at Low Energies, Dubna, 1991.

[4] V. V. Arkhipov, S. N. Ketov, *et al.*, Izd. Akad. Nauk SSSR Ser. Energ. i Trans., No. **6**, 3 (1990).

[5] A. I. Afonin, S. N. Belen'kiĭ, *et al.*, Preprint IAÉ-4878/2 I. V. Kurchatov Institute of Atomic Energy, Moscow, 1989.

[6] N. E. Holden and M. S. Zucher, *Proceedings of Topical Meeting on Safeguards and Technology*, Hilton Head, South Carolina, 1983.

[7] Yu. A. Lazarev, At. Energ. Rev. **15**, 75 (1977).

[8] V. I. Kopeĭkin, Preprint IAÉ-4305/2, I. V. Kurchatov Institute of Atomic Energy, Moscow, 1988.

[9] S. A. Fayans, Yad. Fiz. **42**, 929 (1985) [Sov. J. Nucl. Phys. **42**, 590 (1985)].

[10] P. Vogel, Phys. Rev. D **29**, 1918 (1984).

[11] D. Dubbers *et al.*, Europhys. Lett. **11**, 195 (1990).

[12] F. Feilitzsch *et al.*, Phys. Lett. B **118**, 162 (1982).

[13] K. Sreckenbach *et al.*, Phys. Lett. B **160**, 325 (1985).

[14] P. Vogel *et al.*, Phys. Rev. C **24**, 1543 (1981).

[15] C. Hardy *et al.*, Nucl. Phys. A **509**, 429 (1990).

[16] E. Kh. Akhmedov, A. A. Borovoĭ, Yu. V. Gaponov, and A. N. Kheruvimov, Pis'ma Zh. Eksp. Teor. Fiz. **46**, 258 (1987) [JETP Lett. **46**, 325 (1987)].

[17] A. I. Afonin, S. N. Ketov, V. I. Kopeĭkin, *et al.*, Zh. Eksp. Teor. Fiz. **94**(2), 1 (1988) [Sov. Phys. JETP **67**, 213 (1988)].

[18] L. A. Mikaélyan, M. D. Skorokhvatov, and A. V. Étenko, Pis'ma Zh. Eksp. Teor. Fiz. **47**, 124 (1988) [JETP Lett. **47**, 149 (1988)].

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