Measurement of the cross sections for the interaction of fission antineutrinos with deuterons at the Rovno atomic power plant

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New experimental results have been obtained on the interaction of fission-reactor antineutrinos with deuterons in the neutral-current channel (NC) and the charged-current channel (CC). The measured cross sections are $\sigma_{NC} = (2.71 \pm 0.46 \pm 0.11) \times 10^{-44}$ cm^2/fission and $\sigma_{CC} = (1.17 \pm 0.14 \pm 0.07) \times 10^{-44}$cm^2/fission, where the errors specified are respectively statistical and systematic. These results agree with the predictions of the standard model of electroweak interactions.

We recently reported[1] observing interactions of electron antineutrinos with deuterons

$$\tilde{\nu}_e + d \rightarrow n + p + \tilde{\nu}_e{}' \quad (NC), \tag{1}$$

$$\tilde{\nu}_e + d \rightarrow n + p + e^+ \quad (CC) \tag{2}$$

at a reactor of the Rovno atomic power plant. Here NC and CC specify interactions between neutral currents and between charged currents.

The primary reason for the interest in this experiment is the opportunity which it opens up for studying weak neutral currents in the limit of a zero momentum transfer ($E_\nu < 10$ MeV), for testing the minimal model of the electroweak theory, and for searching for effects which go beyond the scope of that model, e.g., neutrino oscillations $\tilde{\nu}_e \rightleftharpoons \tilde{\nu}_x$.

In the present letter we are reporting the most recent results of ongoing measurements in the neutrino laboratory, in the $\tilde{\nu}_e$ flux from a VVÉR-440 reactor with a nominal thermal power $W = 1375$ MW ($\pm 2\%$). The experimental layout is shown in Fig. 1 (see Ref. 1 for more details). The target is highly enriched (99.9%) heavy water with a weight of 2985 ± 3 kg containing $N_d = 1.796 \times 10^{29}$ nuclei. The reactions are detected on the basis of neutrons alone, with the help of 196 ^{3}He counters penetrating the target. The cosmic-ray background is suppressed by an anticoincidence system consisting of scintillation plates around the detector and an "umbrella" of tanks filled with a liquid scintillator. The detector is at a distance $R = 18.06 \pm 0.05$ m from the center of the reactor core.

Events are selected on the basis of the height and multiplicity of the pulses in a waiting time window $T_{\text{wait}} = 1500\,\mu$s. To detect reaction (1), with one neutron in the final state, we use exclusively single events, which are not accompanied by repeated

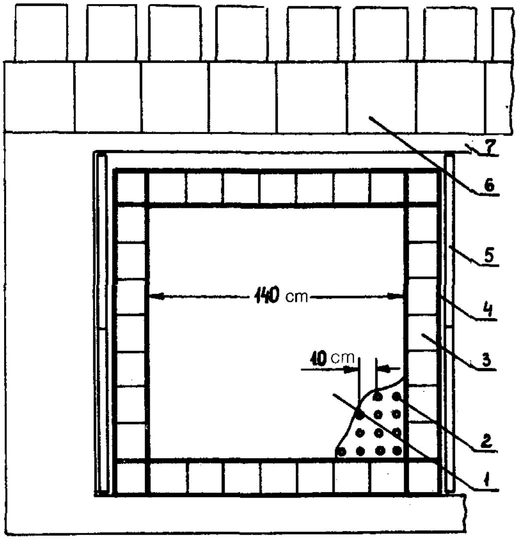

FIG. 1. Experimental layout. 1—D_2O detector; 2—^{3}He counter; 3—graphite; 4—cadmium; 5–7—anticoincidence system; 5—scintillation plates; 6—"umbrella"; 7—polyethylene.

pulses during $T_{\rm wait}$. Two neutrons are produced in reaction (2), so this reaction can be the source of both single events (if one of the neutrons is not detected) and double events, i.e., events with a repeated pulse during $T_{\rm wait}$. Events with multiplicities of three and more arise only in background processes and are detected as a control. The pulses from the anticoincidence system block the collection of useful events for a time $T_{\rm bl} = 1000\,\mu$s. The background events that arrive during $T_{\rm bl}$ are monitored separately in order to check for variations in the background.

So far, measurements have been carried out during two operating runs of a reactor: in 1989 (Ref. 1) and in 1990. In the 1989 experiment, neutrons from the reaction $\tilde{\nu}_e + p \rightarrow n + e^+$ penetrated to the polyethylene detector in the gap between the anticoincidence plates and the detector housing. These neutrons constituted a source of a background of single events which was correlated with a reactor power. For this reason, only the data from the central part of the detector, with 10×10 counters, were used in determining the cross section for reaction (1) in Ref. 1. In the 1990 experiment, the polyethylene around the detector was replaced by stacked graphite and a layer of cadmium (Fig. 1). The overall factor by which the correlated neutrons were attenuated was 0.10 ± 0.02. This change in the passive shielding made it possible to utilize the data from the entire detector in the analysis of the events corresponding to reaction (1). In other words, the luminosity of the experiment was increased by a factor ≈ 1.8.

The efficiency at which reactions (1) and (2) were detected was found experimentally with the help of neutron sources, SbBe ($E_n = 24$ keV) and PuLi (with an average neutron energy ≈ 200 keV). The activity of these sources was determined within about 2% in a separate experiment. The source was moved inside the detector at steps of 10 cm to simulate a uniform production of neutrons throughout the volume of the target. The detector efficiency was found by taking an average over all production points. After account was taken of the amplitude selection, the double events missed, and the finite window T_{wait}, the following values were found:

$$< \epsilon >= 0.330 \pm 0.010, \tag{3}$$

$$2 < \epsilon(1 - \epsilon >= 0.255 \pm 0.009, \tag{4}$$

$$< \epsilon^2 >= 0.236 \pm 0.012. \tag{5}$$

The results in (3)–(5) show the efficiencies with which the events of reaction (1) and the events of reaction (2) with one and two neutrons are detected. The errors in (3)–(5) are determined primarily by the difference between the energy spectra of the neutrons from reactions (1) and (2) and those of the sources that were used. The PuLi neutrons have a harder spectrum, so the slight differences (1.5–4%) in the results obtained with the SbBe and PuLi sources were used as upper limits on the errors in (3)–(5) associated with the energies of the neutrons.

The total number of interactions in the target of the detector in the neutral-current (charged-current) channel is related to the reactor power:

$$N_{NC(CC)} = \frac{W}{E_f}\frac{1}{4\pi R^2}N_d\sigma_{NC(CC)}, \tag{6}$$

where $E_f = \Sigma\alpha_i^i E_f$ is the average energy absorbed in the reactor core per fission event, and $\sigma = \Sigma\alpha_i^i\sigma$ is the mean value of the cross section for the given isotopic composition of the fuel. The quantities α_i $(i = 5,9,8,1)$ are the ^{235}U, ^{239}Pu, ^{238}U and ^{241}Pu components of the total number of fission events.

Measurements were carried out while the reactor was shut down ($W = 0$; these were measurements of the background) and during the reactor run, at two steady-state power levels (these were measurements of the effect and the background). The experimental data are summarized in Table I. This table also shows values of the effective power W_{eff} which incorporates the contributions from the other reactors at a Rovno atomic power plant to the total neutron flux.

The neutrino effect produced in 10^5 s which corresponds to a nominal power level of 1375 MW is, according to the experimental data in Table I,

$N_1 = 238 \pm 27$ and $N_2 = 51 \pm 6.$

From the number of single events detected we subtracted the correlated neutron background from the reaction $\tilde{\nu}_e + p \rightarrow n + e^+$:

TABLE I.

W MW	W_{eff} MW	$T_{\text{meas}} \times 10^5$ s	Count rate for multiplicity i (N_i over 10^5 s)		
			$i = 1$	$i = 2$	$i = 3$
0	49.5	18.3	8153 ± 21	419 ± 5	84 ± 2
855.3	904.8	10.0	8309 ± 29	445 ± 7	84 ± 3
1368.1	1409.4	28.3	8388 ± 17	470 ± 4	80 ± 2

a) 4 ± 1 events over 10^5 s associated with the hydrogen impurity in the heavy water,

b) 14 ± 4 events over 10^5 s associated with neutrons coming in from the hydrogenous material beyond the graphite stack.

The latter quantity was found by calculation and also by direct comparison of the 1989 data for the entire detector found under conditions corresponding to an unattenuated influx of the correlated neutrons.

The total numbers of interactions, $N_{NC} = 500 \pm 85$ and $N_{CC} = 216 \pm 25$, were calculated from the following relations with the help of (3)–(5):

$$< \epsilon^2 > N_{CC} = N_2,$$

$$< \epsilon > N_{NC} + 2 < \epsilon(1-\epsilon) > N_{CC} = (N_1 - 18).$$

From (6), the following cross sections were found:

$$\sigma_{\rm NC} = [2.71 \pm 0.46(\text{statistical}) \pm 0.11(\text{systematic})] \times 10^{-44}\ \text{cm}^2/\text{fission},$$
$$\sigma_{\rm CC} = [1.17 \pm 0.14(\text{statistical}) \pm 0.07(\text{systematic})] \times 10^{-44}\ \text{cm}^2/\text{fission}.$$

These figures correspond to the following isotopic composition of the reactor core:

$$\alpha_5 = 59{,}9\%;\quad \alpha_9 = 28.1\%;\quad \alpha_8 = 7.4\%;\quad \alpha_1 = 4{,}6\%.$$

The experimental cross sections agree with the expected values

$$\begin{aligned} \sigma_{NC} &= (2{,}96 \pm 0{,}12) \cdot 10^{-44}\text{cm}^2/\text{fission}, \\ \sigma_{CC} &= (1{,}08 \pm 0.07) \cdot 10^{-44}\text{cm}^2/\text{fission}, \end{aligned} \tag{7}$$

which were calculated in Ref. 2 for the standard energy spectrum of the $\tilde{\nu}_e$'s of the VVÉR-440 reactor. The errors in (7) reflects the uncertainties associated with the use of the spectrum. The contributions from exchange meson currents, weak magnetism, recoil effects, and radiation corrections were ignored in the calculations of the cross sections; these simplifications might introduce an additional error of about 5–6% in (7).

A paper presently being prepared for publication will report a more detailed analysis of the experimental results and also of some other experimental[3,4] and theoretical values of the cross sections for reactions (1) and (2).

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