Observation of the interaction of reactor antineutrinos with deuterons in neutral and charged current channels at the Rovno nuclear power station

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At the Rovno nuclear power station the first results have been obtained in a study of reactions of the interaction of $\tilde{\nu}_e$ with a deuteron, $\tilde{\nu}_e + d \rightarrow n + p + \tilde{\nu}'_e$ and $\tilde{\nu}_e + d \rightarrow 2n + e^+$, which occur through the weak, neutral, and charged current channels. From the 2900 single neutrons and 400 neutron pairs that were detected an estimate is made of the cross sections of the reactions and the axial constant of the weak nucleon current $g_A^{NC};g_A^{NC} = 1.25\cdot(1.06 \pm 0.16)\cdot g_F$, where g_F is the Fermi constant.

1. At the Rovno nuclear power station studies have begun on the interaction of reactor $\tilde{\nu}_e$ with deuterons

$$\tilde{\nu}_e + d \rightarrow n + p + \tilde{\nu}'_e \tag{1}$$

$$\tilde{\nu}_e + d \rightarrow 2n + e^+. \tag{2}$$

These processes were first observed by F. Reines and his coworkers[1] in 1979. Soviet workers have also recently reported the observation of reaction (2).[2]

From a fundamental point of view, reaction (1) is the best one for studying the structure of the neutral current (*NC*) in the limit of zero momentum transfer, involving electron antineutrinos and nucleons.

The simultaneous study of reaction (1) (*NC*), along with reactions (2), and

$$\tilde{\nu}_e + p \rightarrow n + e^+, \tag{3}$$

which occur via the channel of charged currents (*CC*), can, if the measurements are precise enough, be used to search for oscillations of the type $\tilde{\nu}_e \rightleftarrows \tilde{\nu}_{\mu,\tau}$. Interaction (1) (*NC*) is not sensitive to these oscillations and is governed by the total neutrino flux. Reactions (2) and (3) (*CC*), on the other hand, are not sensitive to the component $\tilde{\nu}_{\mu,\tau}$.

2. For reactor $\tilde{\nu}_e$ of low energy (to 8–9 MeV), the transitions $d \rightarrow n + p$ and $d \rightarrow 2n$ take place between the ground state of the deuteron, 1 +, and the states of two nucleons in the continuum, O +, and are of the Gamov-Teller type. The cross sections of reactions (1) and (2) are determined by the squares of the axial constants of the neutral g_A^{NC} and the charged $g_A^{CC} = \lambda g_F \cos\theta_c$ currents, respectively, where g_F is the Fermi constant, θ_c is the Cabbibo angle ($\cos^2\theta_c = 0.98$) and $\lambda = 1.25$. Reaction (3)

is governed by the combination $g_F^2 \cos^2 \theta_c (1 + 3\lambda^2)$. According to the minimal model, $g_a^{NC} = \lambda g_F$ (4).

A calculation of the cross section of reaction (1) for monoenergetic $\tilde{\nu}_e$ was first carried out by Gaponov and Tyutin.[3] The quantity involved in the reactor experiment is the cross section convoluted with the energy spectrum of the $\tilde{\nu}_e$. We use the "standard" spectrum of the $\tilde{\nu}_e$ of the VVER reactor,[4] measured in 78 000 detected neutrinos. The "recommended" cross sections for reactions (1) and (2) were calculated in Ref. 4 in accordance with the minimal model (in units of cm^2/fission):

$$\sigma_d^{NC} = (2.89 \pm 4.9\%) \cdot 10^{-44}, \; \sigma_d^{CC} = (1.05 \pm 7.3\%) \cdot 10^{-44} \tag{5}$$

and the ratio

$$\sigma_d^{CC} / \sigma_d^{NC} = 0.364 \pm 3.6\%, \quad \frac{\sigma(\tilde{\nu}_e + p \rightarrow n + e^+)}{\sigma_d^{NC}} = 20 \pm 2.5\% \; . \tag{6}$$

The errors in (5) and (6) take into account only the indeterminacies associated with using the spectrum. In the calculations of the cross sections (5) the nuclear part of the matrix element is found in the effective-radius approximation, and the contributions of the exchange meson currents, weak magnetism, and radiation corrections, which were ignored, introduce into (5) an additional error on the order of 5–6%.

3. Following the authors of Refs. 1 and 2, we use the method of separating the events of reactions (1) and (2) by detecting the neutrinos with the use of gas-filled proportional counters, as proposed first in Ref. 5. The detector (Fig. 1) is set up in the chamber of the neutron laboratory (for more detail, see Ref. 6) at a distance of 18.06 m from the center of the VVER-440 reactor along with a neutrino spectrometer and an inverse beta decay (3) detector of the integrating type.

The target for the $\tilde{\nu}_e$ was highly enriched (99.9%)heavy water of mass 2980 ± 3 kg, poured into the stainless-steel case, which has inside dimensions of $1400 \times 1400 \times 1600$ mm. In the through horizontal channels were placed 196 He-3 neutron detectors, forming a square matrix of 14×14 with a spacing of 100 mm. The useful counter length was 960 mm; the inside diameter was 31 mm and the He-3 pressure was 4 atm. The quantities that were measured were the amplitude of the counter signal, the identification number of the counter and the multiplicity of the event; i.e., the number of neutron events during the time $T_{\mathrm{op}} = 1500$ μs the window was open (the average lifetime of the neutrons created uniformly in the volume of the detector was $\sim 250\,\mu$s). Events of multiplicity 1 and 2 were regarded as candidates for reactions (1) and (2), while events of higher multiplicity arose only in background processes and were recorded for the purposes of monitoring the experiment. The pulses from the anticoincidence system blocked the collection of useful events for a time $T_{\mathrm{bl}} = 1000$ μs, while the background events detected after the time T_{bl} were recorded separately, to check on the background of the detector.

The amplitude spectrum of the events in the counters has a pronounced peak ($Q = 764$ keV), corresponding to complete dissipation of the energy of the products of the reaction ...into the gas, and low-energy part, due to a wall effect. Events around the

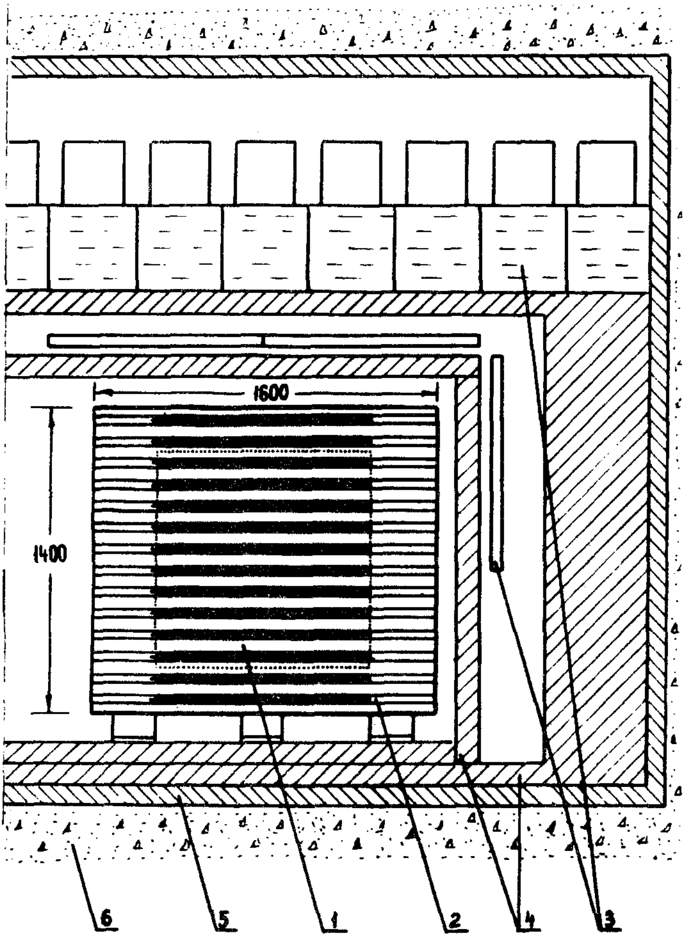

FIG. 1. Diagram of detector. 1) Frame of the detector, with heavy water; 2) horizontal channels with ^{3}He counters; 3) anticoincidence shield; 4) polyethylene; 5) steel; 6) concrete.

absorption peak were sampled. The amplitude coefficient of the sampling in the detection of single events was $\gamma^{(1)} = 0.683$ and for detecting double events, $\gamma^{(2)} = 0.427$.

For reasons associated with the background, data from only the central part of the detector, containing 10×10 counters (the region shown by the dotted lines in Fig. 1), was used in the analysis of the single events. The entire detector was used in the analysis of the double events.

The efficiencies of detection of events of reactions (1) and (2) were determined with the use of an SbBe neutron source of activity 20.1 ± 0.4 neutrons per second. This source was moved sequentially in 100-mm steps throughout the volume of the detector, simulating the uniform creation of neutrons. At each position of the source the counting rate at each of the counters was measured.

The efficiency of the detector as a whole and of its central part were determined by summing over the counters and averaging over all the points of neutron creation. In these measurements amplitude selection was not used. The following values were obtained for the efficiency of detecting neutrons created uniformly over the entire volume.

–both neutrons of reaction (2) in the entire detector $\langle \epsilon^2 \rangle = 0.236$;

–both neutron of reaction (1) in the central part $\langle \epsilon_{\mathrm{II}} \rangle = 0.261$;

–one of the neutrons of reaction (2) in the central region when the second one is not detected: $\langle 2\epsilon_{\mathrm{II}} (1 - \epsilon) \rangle = 0.201$.

We estimate the error in these values of the efficiency to be 6%. It is due to the difference between the energy of the source (24 keV) and the energies of the neutrons of reaction (1) and (2) ($\overline{E}_n \sim 150$ keV) and was estimated from analogous measurements with a PuBe source, having a considerably harder neutron spectrum.

4. The measurements were carried out during the time the reactor was shut down (for the background) for a time of 15.4×10^5 s = 17.8 days, and after the reactor was up to power (for the background + effect) for 23.1×10^5 s = 26.7 days. The average power of the reactor in this period was 1195 MW. The following results were obtained.

The number of interactions in the entire detector, $N_d^{CC}CC$ in the channel of reaction (2) was found from the relation $n_2 = N_d^{CC} \langle \epsilon^2 \rangle \gamma^{(2)}$ with $\langle \epsilon^2 \rangle \gamma^{(2)} = 0.101$, from which we have

$$N_d^{CC} = 170 \pm 67 \text{ in } 10^5 \text{ s}. \tag{7}$$

From the number of single events recorded in the center, $n_{1c} = 126 \pm 23$, we calculated the following: a) the contribution from the reaction $\tilde{\nu}_e + p \rightarrow n + e$ from hydrogen impurities in the heavy water and the influx of hydrogen-containing material from outside is $\Delta_1 = 10 \pm 8$ in 10^5 s; b) the contribution from events of reaction (2) with one neutron detected in the central part and the other not detected: $\Delta_2 = 23 \pm 9$ in 10^5 s. After subtracting these corrections we obtained $n'_{1c} = 93 \pm 26$ in 10^5 s. The total number of interactions N_d^{NC} in the neutral current channel in the detector was

Table I. Number of events in 10^5 s.

Event multiplicity	Background	Background + effect	Effect
	$W = 0$	$W = 1195$ MW	
1 – Center	4757 ± 18	4884 ± 14	$n_{1\mathrm{II}} = 126 \pm 23$
2 – Entire Detector	412.8 ± 5.2	430.1 ± 4.3	$n_2 = 17.3 \pm 6.7$
⩾ 3 – Entire Detector	112.0 ± 2.7	114.0 ± 2.2	2 ± 3.5

found from the relation $n'_c = N_d^{NC}\langle\epsilon_c\rangle\gamma^{(1)}$, with $\langle\varepsilon_c\rangle\gamma^{(1)} = 0.178$:

$$N_d^{NC} = (522 \pm 146) \text{ за } 10^5 \text{ с}. \tag{8}$$

We determined the cross section from (8) and (7) in the usual way (in units of 10^{-44} cm^2 per fission):

$$\sigma_d^{NC} = 3.2 \pm 0.9 \pm 0.3; \quad \sigma_d^{CC} = 1.0 \pm 0.4 \pm 0.1. \tag{9}$$

The first error in (9) is statistical, and the second is a systematic error. The results (9) within the limits of these large errors agree with the cross sections¹⁾ published in Ref. 1; $\sigma_d^{NC} = 2.33 \pm 0.55$, $\sigma_d^{CC} = 0.92 \pm 0.25$, and with the results of Ref. 2: $\sigma_d^{CC} = 1.1 \pm 0.3$.

Comparing the experimental value (9) with relations (4) and (5), we can find the value of the axial constant of the weak nucleon current:

$$g_A^{NC} = 1.25(1.06 \pm 0.16)g_F,$$

which is in agreement with the predictions of the standard model.

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¹⁾ The authors of Ref. 1 give the cross section in units of "cm$^2/\tilde{\nu}_e$." To convert these units to cm^2/fission, we multiply by a factor of 6.14, i.e., the number of $\tilde{\nu}_e$ that accompany a fission event.

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