Precise measurement of the cross section for the reaction $\tilde{\nu}_e + p \rightarrow e^+ + n$ at the Bourges reactor

V. N. Vyrodov, Yu. V. Kozlov, V. P. Martem'yanov, I. N. Machulin,
L. A. Mikaélyan, M.D. Skorokhvatov, S. V. Sukhotin, and A. V. Étenko
Institute of General and Nuclear Physics, Kurchatov Institute Russian Science Center, 123183 Moscow, Russia

Y. Declais
Laboratoire d'Annecy-le-Vieux des Physique des Particules, F-74941 Annecy, France

H. de Kerret, B. Lefievre, and M. S. Obolensky
College de France, F-75231 Paris, France

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With the help of an integrated detector at a distance of 15 m from the Bourges-5 reactor, ~300 000 events of the reaction $\tilde{\nu}_e + p \rightarrow e^+ + n$ were detected. The error in the measured cross section $\sigma_{\rm exp}$ has been reduced by a factor of 2. This cross section is now known within an error smaller than the expected cross section σ_{V-A}: $\sigma_{\rm exp}/\sigma_{V-A} = 0.987 \pm 0.014$ (experimental) ± 0.027 (theoretical). The result is used to test the minimal model of the electroweak interaction. The result is of metrological value for several directions in the physics of reactor antineutrinos $\tilde{\nu}_e$. *© 1995 American Institute of Physics.*

INTRODUCTION

The cross section for inverse β decay,

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

plays a special role in the physics of reactor antineutrinos, since a value of this cross section as accurate as possible is required for solving many fundamental and methodological problems.

1. In the standard model of the $V-A$ interaction, the cross section for reaction (1), like the lifetime of a free neutron, is determined by the combination $G_V^2 + 3G_A^2$ of vector and axial β constants, and the measured cross section $\sigma_{\rm exp}$ is used to determine these constants.[1,2]

Effects which lie outside the initial positions of the minimal model of the electroweak interaction may cause the cross section to be smaller than the expected value σ_{V-A}. For example, if both left-hand and right-hand antineutrinos are emitted in β decay, and the degree of their polarization thus satisfies $H_\nu < 1$, we would have the following expression according to Refs. 2 and 3:

$$X = \sigma_{\rm exp}/\sigma_{V\text{-}A} = 1/2(1 + H_\nu^2) < 1. \tag{2}$$

In the case of $\tilde{\nu}_e \rightarrow \nu_x$ oscillations we would have the following result at distances from the reactor which are large in comparison with the length of these oscillations:

$$X = 1 - 1/2\sin^2(2\vartheta), \tag{3}$$

where ϑ is the mixing angle.

2. In order to carry out the analysis mentioned above, we need to know the energy spectrum of reactor $\tilde{\nu}_e$'s, i.e., $\rho(E_\nu)$. We recall that the cross section σ_{V-A} is given by

$$\sigma_{V\text{-}A} = \int dE_\nu \rho(E_\nu) \sigma(E_\nu),$$

where $\rho(E_\nu)$ is the spectrum of $\tilde{\nu}_e$'s, and $\sigma(E_\nu)$ is the cross section for the reaction in the case of monoenergetic neutrinos.[4,5] The spectrum of reactor $\tilde{\nu}_e$'s above the reaction threshold is formed as the result of β decay of fission fragments of ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu: $\rho = \Sigma \alpha_i \rho_i$, $\sigma_{V-A} = \Sigma \alpha_i \sigma_i$, where α_i is the contribution of isotope i ($i = 5,9,8,1$) to the total number of fission events.

For ^{235}U, ^{239}Pu, and ^{241}Pu, we use the $\tilde{\nu}_e$ spectra found in Refs. 6 and 7 through conversion of measured β spectra of a mixture of fragments of the fission of these isotopes. In the case of ^{238}U we use the results calculated in Ref. 8. Here are the expected values (in units of 10^{-44} cm^2/fission) of the cross section σ_i of reaction (1) in the $\tilde{\nu}_e$ spectra of these isotopes: for ^{235}U, $63.9 \pm 1.9\%$; for ^{239}Pu, $41.8 \pm 2.4\%$; for ^{238}U, $88.8 \pm 10\%$; and for ^{241}Pu, $57.6 \pm 2.1\%$.

In the calculations of the cross sections σ_i we used the β constants corresponding to the neutron lifetime[9] $\tau = 887.4 \pm 0.2\%$. The resultant error in the cross section σ_{V-A} calculated in this manner is estimated to be 2.7% (68% CL).

3. When a highly accurate value is available for σ_{exp}, it can be used in other experiments with reactor $\tilde{\nu}_e$'s, as a sort of metrological standard. The effect is to improve the accuracy and (in our opinion) to help substantially in making the analysis of the results self-consistent. A distinctive feature of this standard is that when it is used in practice one must consider the differences in the composition of the fissile isotopes in the reactor core. The corresponding corrections usually do not exceed 1.0–2.0%.

The cross section σ_{exp} has been used[10,11] for an absolute normalization of the $\tilde{\nu}_e$ spectrum found from measurements of the positron spectrum of reaction (1). Positron spectra are measured[10,12] by spectrometers which operate on the basis of delayed coincidences between the products of reaction (1). The absolute characteristics of such instruments have so far been determined within an error $\sim 4\%$, so a normalization of the spectrum to the value of σ_{exp} is useful.

The cross section σ_{NC}^d for the splitting of the deuteron, $\tilde{\nu}_e + d \to \tilde{\nu}_e + n + p$, is being measured at reactors in Krasnoyarsk,[13] at the Rovno nuclear power station,[14] and in Bourges (G. Sobel *et al.*, private communication). Since the ratio $R = \sigma_{\text{NC}}^d / \sigma_{\text{exp}}$ is far less sensitive than the cross sections themselves to uncertainties in the $\tilde{\nu}_e$ spectrum,[10,11] the use of σ_{exp} as a standard is justifiable.

Certain future experiments, in particular, a search (presently in preparation) for oscillations at a distance of 1 km from the reactors at Chose, France, may use σ_{exp} instead of σ_{V-A} to calculate the expected count rate of events in the absence of oscillations, since the former is now known more accurately.

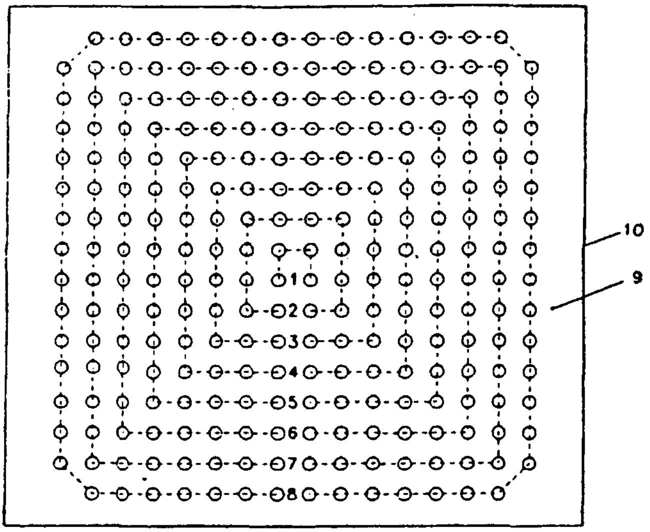

FIG. 1. Schematic diagram of the VIND detector (plan view). 1–8—"Rings" of counters with ^{3}He; 9—target (water); 10—130× 120-cm housing.

4. In the present study we used the VIND integrated detector, which has been used previously for measurements at a reactor of the Rovno nuclear power station.[15,16] This circumstance has made it possible to carry out an accurate comparison of the neutrino fluxes from two different reactors and thus to continue a study of the properties of a reactor as a neutrino source (this study has been in progress for several years).[17]

THE DETECTOR AND THE DETECTION OF EVENTS

The VIND integrated detector was positioned 15 m from the center of the core of the fifth unit of the Bourges nuclear power station, in a laboratory room which had previously been used in a search for neutrino oscillations.[12] The detector was inside a shield chamber consisting of a liquid scintillator (anticoincidences, 10 cm), a layer of B_4C (4 mm), water (25 cm), and lead (10 cm).

Events of reaction (1) in the integrated detector[15,16] were detected solely on the basis of the neutrons produced in the reaction, with the help of proportional counters filled with the gas 4 atm $^3\mathrm{He}+0.7$ atm Ar. Distilled water poured into a tank with dimensions of 130 ×130× 120 cm served as a target for $\tilde{\nu}_e$'s and also as a neutron moderator. The counters, with an outside diameter of 32 mm and a length ~1100 mm, were inside the water, forming a 16× 16 square matrix with a period of 70 mm (Fig. 1). Useful events were selected on the basis of the heights of the signals corresponding to total absorption of the energy of the products of the reaction $^3\mathrm{He}(n,p)T+765$ keV in the gas. The number of useful events, divided by the total number of neutrons absorbed in the helium, was monitored with the help of neutron sources. It turned out to be $\gamma=0.749\pm0.003$. The average neutron lifetime in the detector was 96.6 ± 0.6 μs. Neutrons were detected for

TABLE I. Number of neutrino events detected in the various "rings" (per counter per day).

Ring number	1+2	3	4	5	6	7	8
Number of $\bar{\nu}_e$'s	15.53	15.26	15.19	15.55	15.42	15.48	16.70
Error	0.20	0.16	0.15	0.14	0.13	0.11	0.12

400 μs after the passage of the muon, assigned to a separate group, and used to monitor the experiment in progress.

CALIBRATION OF THE DETECTOR

The VIND detector was designed in such a manner that its basic parameters (the number of protons in the target, N_p, and the neutron detection efficiency ϵ) could be determined very accurately by an experimental method, without the need for numerical simulation.[15,16] Accordingly, conditions were arranged such that the leakage of neutrons from reaction (1) out of the working volume of the detector was offset by the influx of neutrons from the exterior. This working volume includes the 14×14 matrix of inner counters and is bounded at its ends by cadmium tubes, which cover the ends of the counters. The number of hydrogen atoms in this volume at a 25°C working temperature of the water was $N_p = 4.953 \times 10^{28} \pm 0.5\%$.

The distribution of neutrino events detected with respect to the "rings" of counters verifies that the compensation conditions hold well in the inner part of the detector (rings 1–7 in Fig. 1), while at the periphery (ring 8) the influx of neutrons is considerably greater than the neutron leakage.

The efficiency at which the neutrons are detected in the working volume (with an amplitude selection coefficient $\gamma = 1$) was determined with the help of a ^{252}Cf source, for which the average number of prompt neutrons per spontaneous-fission event is[18] 3.757 ±0.010. This source was positioned on a semiconductor fission-fragment detector at the center of the detector. As a result of these measurements, we made corrections of 0.3 ±0.3% for the leakage of ^{252}Cf neutrons from the working volume and 0.004 ±0.001% for the difference between the energies of the neutrons from reaction (1) and of fission neutrons. The final result was $\epsilon = 0.549 \pm 0.003$.

MEASUREMENTS

The measurements were carried out from the middle to the end of a reactor run and then continued after the reactor was shut down (Fig. 2). While the reactor was operating, the count rate of neutrino events was observed to fall of by ~80 events/day. This decrease corresponds to that resulting from the buildup of plutonium isotopes in the reactor core.

Table II shows a summary of the results, referred to the working volume of the detector (the 196 inner counters). The other reactors at the nuclear power plant which made a contribution (~100 events/day) operated at a constant power level.

A reactor power of 2734.7 MW thus corresponds to a neutrino-event count rate of 3022±16 per day.

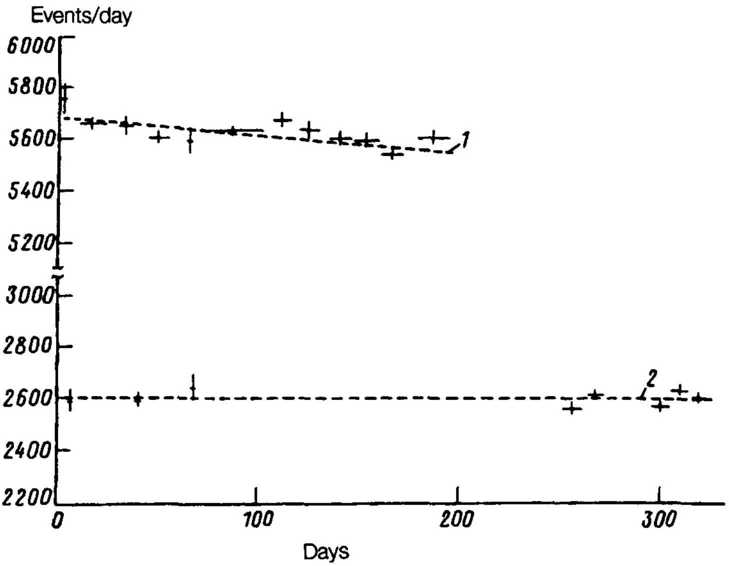

FIG. 2. Average daily count rate of the detector. 1—Reactor operating; 2—reactor shut down.

The background consisted of a neutron component associated with cosmic rays and natural radioactivity (1000 events/day) and a background of α particles from the radioactivity of the counter material (1600 events/day). A correction of 1.5 ± 12 events/day was made for the variations in these components. The final result found for the count rate of neutrino events N_ν is

$$N_\nu = 3021 \pm 20 \ \text{day}^{-1} \ \text{for a power } W = 2735 MW. \qquad (4)$$

This result corresponds to the following contributions α_i of the fissile isotopes:

$$\alpha_5 = 0.538, \quad \alpha_9 = 0.328, \quad \alpha_8 = 0.078, \quad \alpha_1 = 0.056. \qquad (5)$$

RESULTS AND DISCUSSION

1. The reaction cross section σ_{exp} was found from the relation

$$N_\nu = (W/E_f)(4\pi R^2)^{-1}(N_P \gamma \epsilon)\sigma_{\text{exp}} . \qquad (6)$$

Here $W = 2735$ MW ± 0.6% is the average thermal power, $E_f = 205.4$ MeV ± 0.3% is the energy absorbed in the reactor per fission event for fuel composition (5) (Ref. 19), and

TABLE II.

Reactor power, MW	2734.7	0
Measurement time, days	88.47	38.57
Count rate, events/days	5621±11	2599±12

the quantity $(4\pi R^2)^{-1}$, where $R = 14.882$ m ± 0.3% is the effective solid angle, was found with the help of the distribution of the energy evolution over the volume of the reactor core. As a result, we found

$$\sigma_{\text{exp}} = 5.750 \times 10^{-43}\text{cm}^2/\text{fission} \pm 1.4\% \quad (68\% \quad \text{CL}), \tag{7}$$

while the expected cross section for fuel composition (5) is

$$\sigma_{V-A} = 5.824 \times 10^{-43}\text{cm}^2/\text{fission} \pm 2.7\% \quad (68\% \quad \text{CL}). \tag{8}$$

We would like to stress that the ratio of these cross sections,

$$X = \sigma_{\text{exp}} / \sigma_{V-A} = 0.987 \pm 1.4\% \pm 2.7\%, \tag{9}$$

is independent of the contributions α_i.

Results of measurements of the cross section for reaction (1) which have been published previously, namely the "worldwide average,"[2]

$$\sigma_{\text{exp}} = 5.90 \times 10^{-43}\text{cm}^2/\text{fission} \pm 3.0\%, \quad X = 0.992 \pm 3.0\% \pm 2.7\%,$$

and the cross section found at the Rovno nuclear power station with the help of the same detector,[15]

$$\sigma_{\text{exp}} = 5.85 \times 10^{-43}\text{cm}^2/\text{fission} \pm 2.8\%, \quad X = 0.985 \pm 2.8\% \pm 2.7\%,$$

agree well with results (7) and (9) of the present study.

2. From (2) and (9) we find the following result for the degree of polarization H_ν of the electron antineutrinos:

$$H_\nu > 0.96 \quad (68\% \quad \text{CL}). \tag{10}$$

3. From (3) and (9) we find limitations on the mixing parameters for neutrinos with masses m_1 and m_2,

$$\sin^2(2\vartheta) < 8.7 \times 10^{-2} \quad (68\% \quad \text{CL}) \quad \text{for} \quad |m_1^2 - m_2^2| > 2\text{eV}^2, \tag{11}$$

and on an admixture $|U_{eH}|^2$ of "heavy" neutrinos,[20]

$$|U_{eH}|^2 < 2.2 \times 10^{-2} \quad (68\% \quad \text{CL}). \tag{12}$$

4. The reactor characteristics (the thermal power, the instantaneous isotopic composition of the fuel, etc.) furnished by the staff of the power station are used directly in the experiments. They influence the results of the experiment and the interpretation of results. There is accordingly the question of how well these characteristics are supported by data found from the neutrino experiment itself. This problem has been the subject of several special studies over the past decade (see Ref. 17 and the papers cited there). We restrict the discussion in the present letter to the reactor power.

Replacing σ_{exp} in (6) by σ_{V-A} from (8), and treating the result as an equation, we can find the power W_B^ν and compare it with the thermal power W_B measured by the standard reactor control facilities:

$$W_B^\nu + (2700 \pm 80)\text{MW}, \quad W_B = (2735 \pm 17)\text{MW}.$$

The superscript ν means that the reactor power was determined through a measurement of the intensity of the neutrino emission of the reactor.

Working from data found previously at the Rovno nuclear power station,[15,16] we can make a direct comparison of the reactor power levels at Rovno (R) and Bourges (B):

$$W_B^\nu/W_R^\nu = 1.003 \times W_B/W_R \pm 1.9\%.$$

We note in conclusion that the results found in the present study, the description of reaction (1), the description of the decay of a free neutron on the basis of the $V-A$ interaction, and the understanding of the properties of the reactor as a source of $\tilde{\nu}_e$'s all agree with each other within the specified errors.

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