Spectrum of electronic antineutrinos from a nuclear reactor and test of the theory of electroweak interaction

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A statistical base of 78 000 events of the inverse β decay detected at the Rovno nuclear power station was used to measure the absolute spectrum of electronic antineutrinos $\widetilde{\nu}_e$. This spectrum must be known to test experimentally the theory of electroweak interaction in the electronic-antineutrino spectrum that has not been studied adequately. Some "recommended" cross sections for the interaction of $\widetilde{\nu}_e$ with the deuterons in the neutral and charged current channels and the cross section for the $\widetilde{\nu}_e$-e scattering are given.

1. The use of nuclear reactors to study weak interactions involving electronic antineutrinos requires an accurate and reliable energy spectrum of $\widetilde{\nu}_e$.

Experiments are currently being prepared to determine the characteristics of the reactions which have not been studied comprehensively and which are described in the theory of electroweak interaction in terms of the Z^0-boson exchange (the neutral currents). The Rovno nuclear power station, for example, has been targeted as the site for measurement[1] of the cross sections of the reactions $\widetilde{\nu}_e + d \rightarrow 2n + e^+$ and $\widetilde{\nu}_e + d \rightarrow n + p + \widetilde{\nu}'_e$, which are determined by the axial constants of the charged and neutral currents, and the cross section of the $\widetilde{\nu}_e$-e scattering,[2] which includes the neutral and charged currents and their interference. Preparations are under way also in the United States to study reactions involving deuterons.[3] Knowledge of the spectra is also essential in the experimental search for neutrino oscillations conducted by several groups[3–7] with use of reactors.

2. Let us define more precisely the spectrum of reactor electronic antineutrinos. We know that this spectrum is formed as a result of the β decay of fission fragments due to the fission of ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu, whose spectra differ from each other. Because of the buildup of ^{239}Pu, the total spectrum of the reactor changes markedly in the course of the operating period.

In practice, however, it turns out that the average composition of the nuclear fuel of a given reactor during the experiment remains nearly constant from one operating period to another, while different reactors of the same type, such as the Rovno nuclear power reactor,[4] Gösgen reactor,[5] and Bourges reactor[6] differ only slightly in their fuel composition (see Table I).

It is therefore legitimate to speak of the reactor spectrum as a standard spectrum, taking into account, where necessary, only the small differences.

These differences can be taken into account by using the $\widetilde{\nu}_e$ spectra obtained by an independent method. The conversion method, which can be used to find the corre-

TABLE I. Contribution (%) of fissile isotopes to the total number of fissions.

Experiment	Year	Distance from the reactor	^{235}U	^{239}Pu	^{238}U	^{241}Pu
Gösgen[5]	81 – 82	37.9 m	62.7	26.5	6.7	4.1
– " –	82 – 83	45.9 m	59.3	29.1	6.8	4.8
– " –	84 – 85	64.7 m	55.1	32.2	7.0	5.7
Rovno[4]	84	18 m	60.6	27.7	7.4	4.3
– " –	85	25 m	55.7	31.3	7.6	5.4
– " –	86	18 m	60.6	27.4	7.4	4.6

sponding $\tilde{\nu}_e$ spectrum from the total spectrum of the beta electrons from the fission fragments of a given isotope, gives the best results. For ^{235}U and ^{239}Pu the converted spectra were tabulated by Schreckeubach *et al.* and Feilitzsch *et al.*[8] For the other two isotopes, calculations based on summing spectra of the individual fission fragments have been carried out.[9]

3. We report here the results of the measurements of the $\tilde{\nu}_e$ spectrum which were carried out at the Rovno nuclear power plant in the reaction

$$\tilde{\nu}_e + p \rightarrow e^+ + n \qquad (1)$$

at distances of 18 m and 25 m from the reactor. We used a scintillation spectrometer to detect delayed coincidences between the positron and the neutron in reaction (1). Since neutrino oscillations have not been detected in the most recent experiments[4,5,7] (see Ref. 6), we took the average of the positron spectra measured at 18 m and 25 m from the reactor. The resultant spectrum $S^{\exp}(E_e)$ (52 000 events) is shown in abso-

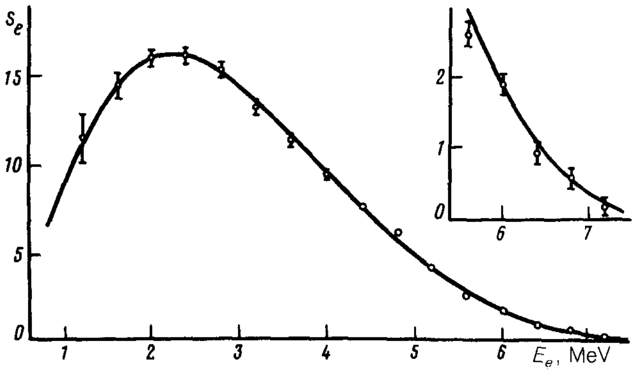

FIG. 1. Positron spectrum from reaction (1) (10^{-44} cm^2·fission^{-1}·MeV^{-1}). The error bars—Experiment; solid curve—calculations based on $\rho_R(E_\nu)$.

lute units in Fig. 1 (points). The other results obtained at the Rovno nuclear power plant were reported elsewhere.[4]

The antineutrino spectrum $\rho(E_\nu)$ was sought by the maximum-likelihood method as an exponential function with a power series in E_ν in the argument of the exponential function. The likelihood function was minimized ($\chi^2_{\min}$ 0.7 per degree of freedom) by using, in addition to the spectrum $S^{\exp}(E_e)$, the total cross section of reaction (1), measured in the same $\tilde{\nu}_e$ flux with an integral detector which recorded only the neutrons in reaction (1) (26 000 events). As a result, we found an expression for the $\rho(E_\nu)$ spectrum, MeV^{-1}·fission $^{-1}$:

$$\rho_R(E_\nu) = 6.78\exp[-(E_\nu/1.342) - (E_\nu/6.868)^2 - (E_\nu/8)^{10}] \quad 2.3 \leqslant E_\nu \leqslant 8.7 \quad (2)$$

and the error matrix.

This spectrum corresponds to the composition of the nuclear fuel:

$$^{235}\mathrm{U} - 59.6\%, \quad ^{235}\mathrm{Pu} - 28.3\%, \ ^{238}\mathrm{U} - 7.4\%, \quad ^{241}\mathrm{Pu} - 4.7\% . \qquad (3)$$

A high power of E_ν in (2) was used in order to reflect the sharp decrease in the positron spectrum at energies $E_e > 5.6$ MeV (Fig. 1). In a narrower energy range the $\tilde{\nu}_e$ spectrum can also be described in terms of a three-parameter Gaussian distribution which was tested for the first time by Nezrick and Reines[10] and more recently by Zacek *et al.*[5] [see expression (4) below]. Spectrum (2) is shown in Fig. 2b and its error margin ($\pm$ standard error) is represented by the hatched section in Fig. 2a.

Spectrum (2) was used to find the cross sections for the interaction of $\tilde{\nu}_e$ with the deuteron: $\sigma^{dCC} = (1.05 \pm 7.3\%) \times 10^{-44}$ cm^2/fission (charged current) and $\sigma^{dNC} = (2.89 \pm 4.9\%) \times 10^{-44}$ cm^2/fission (neutral current), the ratio $\sigma^{dCC}/\sigma^{dNC} = 0.364 \pm 3.6\%$, and the ratio $\sigma(\tilde{\nu}_e + p \to e^+ + n)/\sigma^{dNC} = 20.2 \pm 2.5\%$. These errors take into account only the indeterminacy in the $\tilde{\nu}_e$ spectrum. In the calculations we used the expressions for the cross sections for the interaction of $\tilde{\nu}_e$ with the deuteron, in which the nuclear part of the matrix element was found in the effective-radius approximation.[1] In the experiment[1] which is planned to be carried out at the Rovno nuclear power plant all the quantities mentioned above will be measured simultaneously. We have also found the cross sections of $\tilde{\nu}_e$- e interaction, $\sigma(T > E_n)$ (10^{-45} cm^2 fission^{-1}/electron), where T is the kinetic energy of the electron, and E_n is the detection threshold, in MeV:

$$\sigma(>1.5) = 5.04 \pm 4.3\%, \ \sigma(>2.5) = 1.52 \pm 4.3\%, \ \sigma(>3.5) = 0.46 \pm 5.3\%,$$
$$\sigma(>4.5) = 0.127 \pm 7.3\% .$$

The cross sections of $\tilde{\nu}_e$-d and $\tilde{\nu}_e$-e given above may be viewed as "recommended" cross sections determined in accordance with the minimal model for the electroweak interaction for the "standard" spectrum (2) of the reactor.

Although the errors of the cross sections which were found and their ratios are rather small, the hard part of the spectrum, $E_\nu > 7$ MeV, must be further refined, especially since its contribution to the cross section σ^{dCC} is not that small [see Fig. 2b, which shows an "accumulation" of the cross sections $\int_{E_n}^{E_\nu} \rho(E_\nu) d\sigma(E_\nu)$].

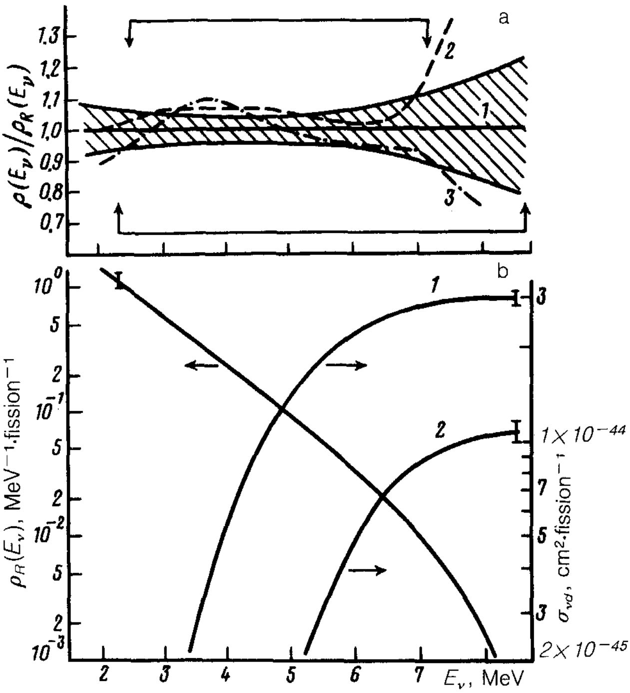

FIG. 2. (a) Ratio of the spectra: 1—The present study; hatching—$\pm$ 1 standard error; 2—$\rho_G(E_\nu)$ (Ref. 5); 3—"converted" spectrum.[8,9] Measurement range: bottom arrows—$\rho_R(E_\nu)$; top arrows—$\rho_G(E_\nu)$. (b) $\rho_R(E_\nu)$—The present study; cross sections $\sigma_{\nu d}$ for the interaction of $\tilde{\nu}_e$ with the deuterons. 1—Natural current; 2—charged current.

4. In their final study (Gösgen, 30 000 events), Zacek *et al.*[5] give the e^+ spectra in the energy range 0.88–5.5 MeV, which were measured at three distances (see Table I) and which are described by the total $\tilde{\nu}_e$ spectrum

$$3.80\times10^{19}\exp(-0{,}571\,E_\nu - 0{,}044\,E_\nu^2)\ \mathrm{MeV}^{-1}\,\mathrm{s}^{-1}$$

for an average reactor power of 2810 MW. Using this result, we easily find ρ_G, MeV^{-1}·fission^{-1}

$$\rho_G(E_\nu) = 5.22\exp(-0{,}571\,E_\nu - 0{,}044\,E_\nu^2) \qquad 2{,}5\leqslant E_\nu \leqslant 7{,}2 \tag{4}$$

for the nuclear fuel composition, in agreement within 1% with (3). We see from Fig. 2a that (4) agrees within mutual errors with spectrum (2) obtained by us.

Taking into account many factors that affect the results, we can assume that the agreement between the independently measured spectra is satisfactory. It should be noted, however, that the three-parameter spectrum of ρ_G cannot be used to determine the total cross sections, since it is not amenable to an extrapolation to high energies.

Figure 2a also shows a "converted" spectrum (see Sec. 2), which is in agreement with the spectrum obtained by us. At very high energies, however, this spectrum apparently falls off more precipitously.

We note in conclusion that the use of the measured $\tilde{\nu}_e$ spectrum in the analysis of the neutrino experiments has the basic advantage that it allows us to express the probabilities for the $\tilde{\nu}_e$ interaction in natural units: a combination of fundamental constants, $g_V^2 + 3g_A^2$ charged currents, which determine the cross section for the reaction of the inverse β decay [reaction (1)].

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