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STUDY OF REACTOR ANTINEUTRINO INTERACTION WITH PROTON AT **BUGEY** NUCLEAR POWER PLANT

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Abstract

We report on a high precision measurement at 15m from a 2800 MWth reactor in which 300 000 events of electron antineutrino interactions with proton have been detected using an integral method. The cross section of the neutron inverse beta-decay process has been measured with an accuracy of 1.4%. The ratio of measured cross section to the expected one in the standard V-A theory of weak interactions is :

$$\sigma_f/\sigma_{V-A} = 98.7\,\% \pm 1.4\,\% \pm 2.7\,\% = 0.987 \pm 0.030$$

Keywords: Neutrinos - Weak interactions - Neutrino oscillation - Neutron detector - Nuclear power plants

Résumé

La section efficace de la réaction de capture de l'anti-neutrino éléctronique sur proton a été mesurée avec une précision de 1.4%. Cette mesure a été éffectuée auprés d'un réacteur nucléaire de 2800 MWth. Dans cette expérience où seul le neutron issu de la réaction était détécté, 300000 événements ont été enregistrés. Le rapport de la section efficace mesurée sur celle attendue dans la théorie standart V-A des interactions faibles est :

$$\sigma_f/\sigma_{V-A} = 98.7\,\% \pm 1.4\,\% \pm 2.7\,\% = 0.987 \pm 0.030$$

1 Introduction

More than 40 years have passed since the first experiment in which the free neutrino was observed by Reines et al. [1], using a nuclear reactor as a strong electron antineutrino source from beta decaying fission products. For the detection of $\bar{\nu}_e$ the neutron inverse beta-decay process was used

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

During the last 10 years new experiments were carried out near nuclear reactors at Bugey [2], Gösgen[3], Krasnoyarsk [4], Rovno [5] and Savannah River [6] to investigate neutrino properties, to study reaction (1) and to test our knowledge of a power reactor as a source of electron antineutrinos.

In addition to experimental suggestions of ν exotic properties (solar neutrino deficit[7], atmospheric ν anomaly[8]) the search for a massive ν is still an important field of physics. Among experimental methods ν oscillation search is the most sensitive if mixing occurs, and low energy reactor ν are particularly well suited for disappearance experiments.

The inverse neutron beta-decay is the fundamental reaction for semileptonic processes in the first generation of elementary particles. The cross section of reaction (1) is related to the weak interaction coupling constants. In the standard V–A theory both vector and axial vector currents are involved in the corresponding coupling constants G_V and G_A. The improved accuracy of reactor ν experiments gives us important data which supplements the information from free neutron lifetime measurements [9].

A new study of the inverse beta decay reaction (1) was completed at the Bugey nuclear power plant using an integral type detector. In such a detector the total number of neutrino interactions is measured by detecting only the neutron from reaction (1). The detector was installed at 15 m from the pressurized light water reactor (PWR) having a thermal power of 2.8 GW. In a previous experiment, conducted by the Rovno group [10], the same detector was running at 18 m from the 1.4 GW PWR of the Rovno nuclear power plant during two annual cycles of reactor operation. The total cross section for reaction (1) per fission[1] of the reactor fuel was measured with an error of 2.8 %. The main uncertainty of this result (2 %) was connected with the reactor thermal power measurements.

The motivations of this new study were :

Independent measurements near the same type of reactors (PWR) may allow a decrease of systematic errors on thermal power data.

The flux of neutrinos was increased by a factor 3. So it was possible to improve the statistical accuracy and to analyse the stability of detector operation more carefully.

Direct measurements of the reactor neutrino flux at Bugey and a comparison with different results are useful for previous and future experiments at the Bugey site and for the long baseline oscillation experiments, planned now at a distance of 1 km from the Chooz PWR's [11].

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[1] The cross section in cm^2/fission depends only on measured quantities with small errors. To obtain the usual cross section it must be combined with the neutrino yield per fission. This last quantity is partly theoretical and has larger errors. See section 6 for discussion.

2 The $\bar{\nu}_e$ spectrum and reaction cross section

The spectrum of reactor ν_e above the 1.8 MeV threshold for reaction (1) is formed as the result of the beta decay of fission fragments of four isotopes : ^{235}U, ^{239}Pu, ^{238}U and ^{241}Pu. We used the results of Ref.[12] for ^{235}U, ^{239}Pu, ^{241}Pu and Ref.[13] for ^{238}U to compute this spectrum. The number of fissions was calculated from the reactor thermal power and the energy released per fission Ref.[14]. The fissile isotope evolution was calculated for each day using the data on fuel burn up given by the reactor services. The parameters used in our calculations are listed in Table 1.

isotopes	^{235}U	^{239}Pu	^{238}U	^{241}Pu
Fission amount α_i	53.8 %	32.8 %	7.8 %	5.6 %
E_i , MeV/fission	201.8 ± 0.5	210.3 ± 0.6	205.0 ± 0.7	212.6 ± 0.7
σ_i	6.39 ± 1.9 %	4.18 ± 2.4 %	8.88 ± 10 %	5.76 ± 2.1 %

Table 1 : Parameters used in the calculation of the neutrino flux
σ_i - in units of 10^{-43} cm^2 / fission.

The cross section of reaction (1) is connected with vector and axial coupling constants of beta decay, G_V and G_A. In the standard V–A theory of weak interactions we obtain [15] :

$$\sigma(E_\nu) = (\pi c^3 \hbar^4)^{-1}(G_V^2 + 3G_A^2)p\,E(1 + \delta(E_\nu)) \qquad (2)$$

where p and E are respectively the momentum and energy of the positron from reaction (1), and $\delta(E_\nu)$ is a small term taking into account the recoil effect, weak magnetism and radiative corrections.

The coupling constants are related to the free neutron lifetime by :

$$\tau^{-1} = (\ln 2/K)f^R(G_V^2 + 3G_A^2) \qquad (3)$$

with $K = 2\pi^3\hbar^7 \ln 2/m^5c^4 = 1.2306 \times 10^{-120}\mathrm{J}^2\mathrm{m}^6\mathrm{s}$, $f^R = 1.71465(15)$ [16]

and $\tau = 887.4 \pm 1.7\mathrm{s}$ [9]. The value of the weak coupling constant from neutron lifetime data is equal to :

$$({G_V}^2 + 3{G_A}^2) = 1.1668(23)10^{-123}\mathrm{J}^2\mathrm{m}^6 \qquad (4)$$

3 Experimental set–up

The Bugey nuclear power plant, located near Lyon in the south of France, has been used for a long time to search for neutrino oscillations [2]. The present experiment was carried out in the Bugey 5 reactor area, especially equipped for the previous measurements. This laboratory was located at a distance of 15 m from the reactor core with an overburden of 25 mwe (30 muons /m^2/s). No neutron flux associated with reactor operation has been found in the previous experiments [17].

The detector was installed into the existing shield made of successive layers consisting of, from outside to inside, 10 cm of lead to stop γ, 25 cm of water followed by 4 mm of B_4C to slow down and capture fast neutrons, and finally 10 cm of liquid scintillator to tag μ passing through the detector(172/s).

The detector is a stainless steel tank of 130×130×120 cm^3 filled with distilled water in which 252 ^{3}He counters used to detect neutrons produced in reaction(1) are immersed.

They are arranged in a square 16 × 16 matrix with a step of 70 mm. The counters have 32 mm external diameter, about 1 m length and are filled with ^{3}He(4 atm.) and Ar(0.7 atm). The sensitive length of the counters (920 mm) is accurately defined by cadmium tubes (1 mm thick) installed at the ends of the counters[10].

The neutron detection is made by measuring the energy (765 keV) released by the n capture products (p, ^{3}H) in a ^{3}He nucleus. The trigger was simply built up by requiring a pulse above threshold (130 keV). The electronics and the trigger (readout delayed by 400 μs) were designed to allow the recording of multiple neutrons (up to 4) and the history of the neutron candidates on several msec. To reduce the noise we used 20 MHz FADC's allowing pulse shape analysis [18].

The mean neutron lifetime in the detector was measured ($96.6 \pm 0.6 \mu s$). Muon correlated events, i.e. events within a $400 \mu s$ time window with respect to a μ tag, were monitored separately to check the background and counters calibration. Neutrino events from reaction (1) were selected as single neutron events.

4 Detector calibration

The calibration of the detector is the most important task in absolute cross section measurements. The simplicity of our detector allows an accurate determination of the needed parameters: number of target protons and neutron detection efficiency. Details of the procedure used in the previous experiments at ROVNO can be found in [10]. From this work the total number of protons in the fiducial volume (14 × 14 counters) at the working temperature of 25°C is: $N_p = 4.953\ 10^{28} \pm 0.5\ \%$.

During this experiment we have studied extensively the neutron detection efficiency in the real working conditions of the detector. The detector was calibrated once a week with 25 Pu-Be neutron sources homogeneously spread into the target. In addition, cosmic ray induced neutrons (7810 ± 9/day) were also recorded together with ν candidates. The neutron capture energy spectra were analysed on-line and off-line in order to test the stability of the detector operation and of the analysis chain.

To get the value of the absolute neutron detection efficiency, measurements were made with a ^{252}Cf spontaneous fission source placed at the center of the target. Fission was tagged using the signal from a solid state detector in contact with the source. It is assumed that the average number of prompt neutrons per fission is 3.757 ± 0.010 [19]. The leakage of neutrons being negligible, the neutron detection efficiency from fission is equal to the efficiency of neutron from reaction(1). Small corrections to account for efficiency variation connected with the neutron energy difference (1.004 ± 0.003 Monte Carlo estimate) and for pulse shape discrimination losses (hardware 1.0092 and software 1.0021) have been applied. Finally the absolute neutron detection efficiency is : $\epsilon = 0.549 \pm 0.003$.

An example of a reconstructed neutron spectrum is illustrated in fig. 1. Events with an energy deposit inside the window (600-849) keV were accepted. The proportion of real neutrons falling inside this cut was stable during the experiment and its mean value $\gamma = 0.749 \pm 0.003$.

5 Data analysis

The detector was running from the middle till the end of a reactor annual cycle and during the reactor shutdown. For simplicity we selected data during nominal power periods. The small contribution coming from $\bar{\nu}_e$ emitted by other reactors (d = 95.1 m, 259.8 m and 345.3m) has been taken into account. In Table 2 are listed the results corresponding to the fiducial volume of the target (196 ^{3}He counters) during the reactor ON and OFF periods.

	Reactor ON	Reactor OFF
W_{eff}	2800.6 MWth	65.9 MWth
t	88.17 days	38.57 days
N events per day	5621.2 ± 8.0	2599.0 ± 8.2
N_α	1617.2 ± 4.3	1608.7 ± 6.5

Table 2 : Reactor power, event and backgroud rates during reactor ON and OFF data taking periods.

Fig. 2. presents the accepted event rate as a function of time with respect to the thermal power of the reactor.

As it can be deduced from Table 2, the value of the signal/background is equal to 2.2 since we only detect the neutron from reaction(1). So it is important to demonstrate the stability of the background measured during the reactor OFF periods. We can show the excellent agreement between the measurements made during the 3 short shutdown periods interleaved with the reactor ON periods (2597 ± 22 evts/day) and the main shutdown period at the end of the experiment (2599 ± 9 evts/day).

This background is made of 2 components: α-particles from internal radioactive contaminations of the counters (1600/day) and neutrons from the natural radioactivity of materials and cosmic radiation (1000/day). The α component is measured permanently by selecting events in an energy window higher than the neutron capture energy window (fig. 1.). We corrected for the small variation of this α component due to ^{3}He counters exchange (8.5 ± 10.0 evts/day). Another small correction (−7 ± 7 evts/day) is due to some variation in the μ flux in the experiment during the main shutdown period due to the dismounting of very heavy equipments in the reactor building. The value has been obtained by studying the correlation between the μ flux, muon correlated events and the background signal.

After these corrections the ν_e signal corresponding to an effective reactor power of 2734.6 MWth is:

$$n_\nu = (3022.3 \pm 16.1) - (8.5 \pm 10.0) - (-7 \pm 7) = (3020.8 \pm 20.2)\mathrm{day}^{-1} \qquad (5)$$

As an example of the quality of the experiment control we measured the decrease of the ν_e flux due to the isotopic composition evolution in the reactor (burnup effect) : 2.4 ± 0.8 %.(fig. 2.) to be compared with the expected value : 3.0 %

6 Results and discussion

6.1 Experimental cross section

The number of neutrino events per day, n_ν, in Eq. 5 corresponds to the average composition of the nuclear fuel in the reactor core and is related to the cross section per fission, σ_f measured in the experiment, by

$$n_\nu = (W_{eff}/E_f)(4\pi\ R^2)^{-1}(N_p \gamma \epsilon)\sigma_f \qquad (6)$$

The nuclear fuel composition, the thermal power W_{eff}, the energy E_f absorbed in the reactor core per fission and the geometric factor R were deduced from the data provided by the technical branch of EdF (French Electricity Company). These parameters are determined below :

$W_{eff} = 2734.6 MW \pm 0.6\,\%$ obtained from measurements on the secondary water loop of the reactor with small corrections (for more detail see [20]),

$E_f = 205.4$ MeV $\pm$ 0.3 % including both prompt and delayed energy release [14],

$R = 14.882$ m $\pm$ 0.3 % is the ν_e path length taking into account the thermal power distribution inside the reactor core.

The measured cross section for the composition of the fuel is:

$$\sigma_f = 5.750\ 10^{-43}\ \mathrm{cm}^2/\ \mathrm{fission}\ \pm 1.4\,\% \qquad (7)$$

to be compared with the expected cross section:

$$\sigma_{V-A} = \Sigma\alpha_i\sigma_i = 5.824\ 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}\ \pm 2.7\,\% \qquad (8)$$

To compare the results, it is convenient to fix a relation independent from α_i contributions :

$$X = \sigma_f/\sigma_{V-A} = 0.987 \pm 1.4\,\% \pm 2.7\,\% = 0.987 \pm 0.030 \qquad (9)$$

where the first error refers to the experimental value σ_f , and the second to σ_{V-A};

In Table 3, the results of present work are presented together with the results of measurements performed in Rovno [10] with the same detector, and results comparison [21] of measurements at Gösgen, Krasnoyarsk and Rovno has been made and the average value has been found for the cross section of the reaction (1).

σ_f	σ_{V-A}	$X = \sigma_f/\sigma_{V-A}$	Ref.
5.90 ± 3.0 %	5.95 ± 2.7 %	0.992 ± 3.0 % ± 2.7 %	[21], 1988
5.85 ± 2.8 %	5.94 ± 2.7 %	0.985 ± 2.8 % ± 2.7 %	[10], 1991
5.752 ± 1.4 %	5.824 ± 2.7 %	0.987 ± 1.4 % ± 2.7 %	present work

Table 3 : Results of reaction (1) cross section measurements
σ - in units of 10^{-43} cm^2 / fission.

It can be seen from Table 3 that the results agree very well with each other. The experimental accuracy was improved and now it is twice as good as the theoretical prediction.

6.2 Fundamental constants of weak interaction

From Eq. 2 and the result of measurements, the combination of constants is:

$$({G_V}^2 + 3{G_A}^2) = 1.152(35)10^{-123}\mathrm{J}^2\mathrm{m}^6 \qquad (10)$$

and we can conclude that weak coupling constants of the inverse beta decay reaction (1) and the beta decay of neutron (4) agree with each other within the V-A theory of weak interaction.

Using the value of the vector constant from superallowed $0^+ - 0^+$ nuclear beta decay [9] $G_V = 1.4153(10)10^{-62}$Jm^3 we obtain :

$$G_A = 1.781(33)10^{-62}\mathrm{Jm}^3 \text{ and } G_A/G_V = 1.258(22) \qquad (11)$$

6.3 Limit for the helicity of ν_e

If we assume both left-handed and right-handed neutrinos can be produced and absorbed in weak interactions, the value of ν_e helicity H_ν in our experiment follows from the equation: $X = 1/2(1 + H_\nu^2)$ [21,22]. The limit is:

$$H_\nu > 0.96(68\,\%\,\mathrm{C.L.}) \tag{12}$$

Now this is the best experimental limit for ν_e.

6.4 Neutrino oscillations

In the previous paragraph we assumed no neutrino oscillations, now we can derive the sensitivity of the experiment to oscillation parameters. Two cases are considered:

- vacuum oscillations. For large mass parameters we find $X = 1 - 1/2\sin^2 2\theta$, where θ is the mixing angle of neutrinos with masses m_1 and m_2. Then we obtain

$$\sin^2 2\theta < 0.086(68\,\%\,\mathrm{C.L.})\ \text{for}\ | m_2^2 - m_1^2 | > 2\mathrm{eV}^2. \tag{13}$$

- Heavy ν admixture. We assume that ν_e are produced with a small mixing probability of a heavy neutrino. Then for the mixing parameter $| U_{eH} |^2 = 1/2 \,| 1 - X |$ we find the limit (for detail see [23]) :

$$| U_{eH} |^2 < 0.023(68\,\%\,\mathrm{C.L.}) \tag{14}$$

7 Conclusions

The accuracy achieved on cross section measurements for reaction (1) is twice as good as the one calculated on the basis of the fission fragments beta spectra. No experimental indications of disagreement with the V-A model of weak interaction were obtained. We can also conclude that the characteristics of the neutrino flux emitted by PWR reactors is well understood and can be calculated using the parameters of Ref. [12, 13, 14]. The results obtained will be useful for future long baseline oscillation experiments like the one planned now at a distance of 1 km from the Chooz PWR reactor in France, as well as for future experiments at the Bugey Nuclear Power Plant.

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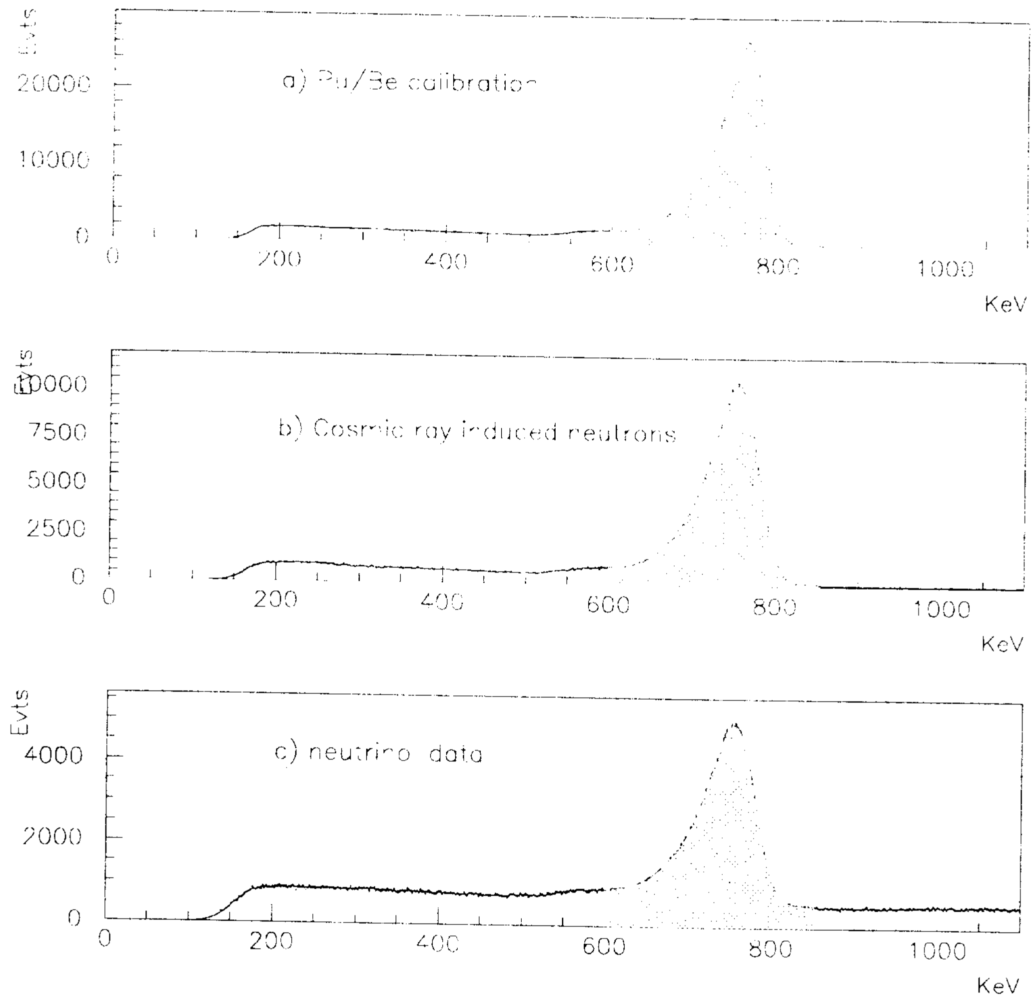

Figure 1: Energy spectrum (all counters added) as measured by ^{3}He counters for various running and data selection conditions: a)Pu/Be source runs. b)tagged cosmic rays induced neutrons and c)ν candidates. The neutron acceptance window corresponds to the dashed area and the α background is estimated in a same width window on the right side of the n capture peak.

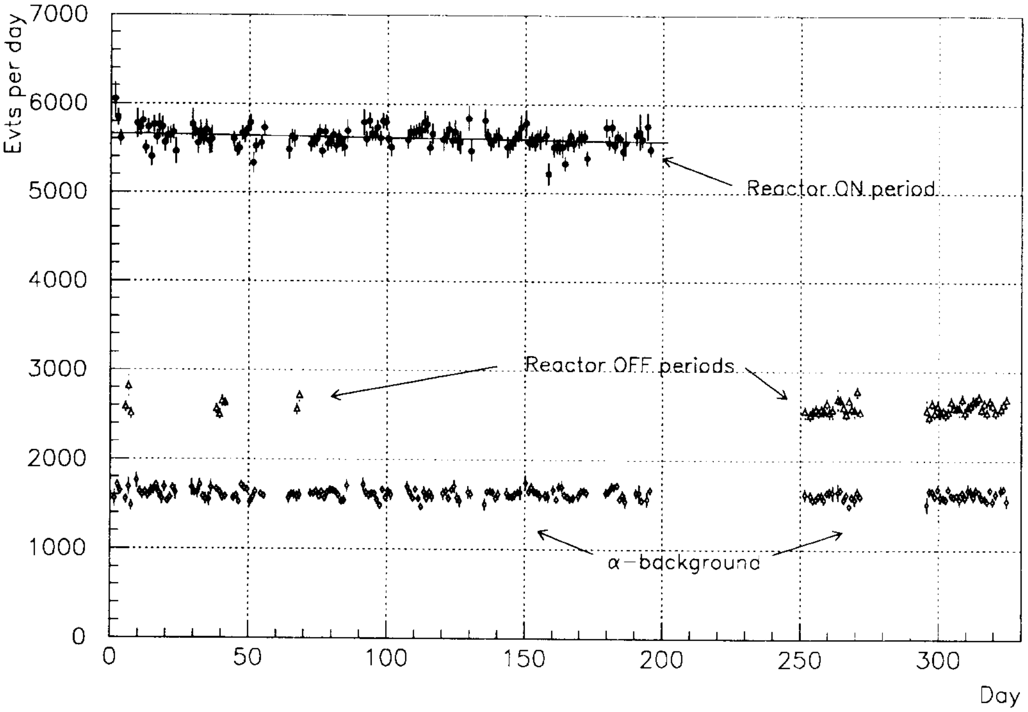

Figure 2: Reactor ON: event rate in (600-849 keV) energy window reduced to nominal 2734.6 MWth reactor power. Solid line indicates the fitted decreasing rate due to fuel burn up effect (2.4 ± 0.8 %) Reactor OFF: event rate in (600-849 keV) energy window. α-background: α-particles rate in (850-1099 keV) energy window.