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HIGH-SENSITIVE SPECTROMETER OF FAST NEUTRONS AND THE RESULTS OF FAST NEUTRON BACKGROUND FLUX MEASUREMENTS AT THE GALLIUM-GERMANIUM SOLAR NEUTRINO EXPERIMENT (SAGE)

J. N. Abdurashitov, V. N. Gavrin, A. V. Kalikhov, V. L. Matushko, A. A. Shikhin, V. E. Yants, O. S. Zaborskaia

Institute for Nuclear Research, Russian Academy of Sciences, Moscow

The principle of operation, design, registration system and main characteristics of a fast neutron spectrometer are described. The spectrometer is intended for direct measurements of ultra-low fluxes of fast neutrons. It is sensitive to neutron fluxes of $10^{-7}\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$ and lower. The detection efficiency of fast neutrons with simultaneous energy measurement was determined from Monte-Carlo simulation to be equal to 0.11 ± 0.01. The background counting rate in the detector corresponds to a neutron flux of $(6.5 \pm 2.1)\cdot 10^{-7}\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$ in the range 1.0–11.0 MeV. The natural neutron flux from the surrounding mine rock at the depth of 4600 meters of water equivalent was measured to be $(7.3\pm 2.4)\cdot 10^{-7}\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$ in the interval 1.0–11.0 MeV. The flux of fast neutrons in the SAGE main room was measured to be $2.3 \cdot 10^{-7}\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$ in 1.0–11.0 MeV energy range.

Описываются конструкция, принцип действия, система регистрации и основные характеристики спектрометра быстрых нейтронов. Спектрометр предназначен для измерения ультраслабых потоков быстрых нейтронов. Его чувствительность к нейтронным потокам составляет $10^{-7}\text{см}^{-2}\cdot\text{с}^{-1}$. Эффективность регистрации быстрых нейтронов с одновременным измерением энергии была определена моделированием с использованием метода Монте-Карло и составляет $0{,}11 \pm 0{,}01$. Фоновая скорость счета в детекторе соответствует потоку нейтронов $(6{,}5\pm 2{,}2)\cdot 10^{-7}\text{см}^{-2}\cdot\text{с}^{-1}$ в области 1,0–11,0 МэВ. Измеренный нейтронный поток от окружающей породы на глубине 4600 м в. э. составляет $(7{,}3 \pm 2{,}4)\cdot 10^{-7}\text{см}^{-2}\cdot\text{с}^{-1}$ в области 1,0–11,0 МэВ. В главном помещении галлий-германиевого нейтринного эксперимента измеренная величина потока быстрых нейтронов не превышает величину $2{,}3\cdot 10^{-7}\text{см}^{-2}\cdot\text{с}^{-1}$ в области 1,0–11,0 МэВ.

INTRODUCTION

It is well known that fast neutrons from the surrounding rocks are one of the background sources for an underground experiments, as the solar neutrino flux registration and search for double beta decay. The sources of the fast neutrons are (α, n) reactions on the light elements (C, O, F, Na, Mg, Al, Si). Measurements of fast neutron flux in the laboratory of the Gallium-Germanium Solar Neutrino Telescope (GGNT) and in an unshielded room at the same depth have been performed using a special high-sensitive spectrometer with registration system based on a fast two-channel digital oscilloscope. The laboratory is located under Mt. Andyrchy (Northern Caucasus Mountains, Russia) in a tunnel that penetrates 3.5 km into a mountain, at a depth of 4600 m of water equivalent.

1. DETECTOR STRUCTURE AND OPERATION PRINCIPLE

The neutron spectrometer was designed taking into account requirements for minimizing the background from γ rays and random coincidences. It is a calorimeter based on a liquid organic scintillator-thermalizer viewed by photomultipliers (PMTs) with ^{3}He proportional counters (NCs), uniformly distributed through the scintillator volume [1].

Fast neutrons with $E_n > 1$ MeV entering the scintillator are decelerated down to thermal energy, and diffuse in the detector volume until they are either captured in a neutron counter or captured by scintillator protons or leave the detector. The amplitude of the light scintillations from recoil protons, which are produced during neutron thermalisation, is on average proportional to the initial neutron energy. About 19 of all proportional counters provide a «neutron label» of an event. Such a technique allows us to suppress the external γ-ray background significantly.

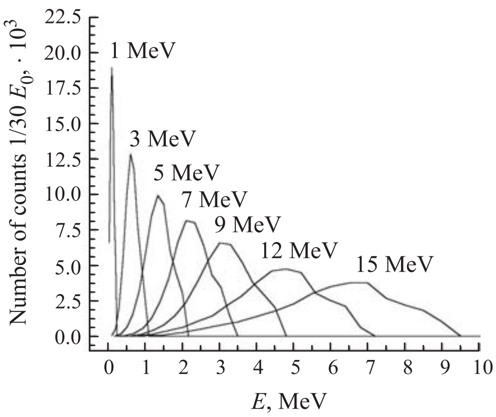
Low-level signal electronics for the spectrometer were designed with signal-to-noise ratio optimization and full pulse shape analysis required for efficient rejection of background events. A data acquisition and processing system is based on a fast (100 MHz) two-channel PC/AT interfaced digital oscilloscope. The acquisition software was written in the C programming language. To simplify the structure of the apparatus, signals from all PMTs and NCs are multiplexed into independent channels called «PMT channel» and «NC channel» respectively. A signal from the NC channel triggers the data acquisition system. The full waveform of events in the PMT and NC channels are registered independently inside selected time intervals before and after the trigger, they are called «prehistory» and «history» accordingly. These time intervals can be adjusted on the basis of calibration measurements. The last generation of the data acquisition system is described in detail in [2].

2. MEASUREMENTS

Three series of measurements were performed with different background conditions. In the first series, the fast neutron flux in one of the additional rooms of GGNT was measured. To suppress the γ-ray background the detector was shielded by an 8 cm thick lead shield. In the second series, the spectrometer without any shielding was situated in the main room of GGNT, which is shielded with special low-background concrete and steel. In the third series, the internal background of the detector was investigated. A shielding of 30 cm of borated polyethylene and 35 cm of water was used.

To calibrate the PMT channel, a ^{60}Co γ source was used [3]. The energy of the centre of the Compton edge was assumed to be equal to 1 MeV on the electron energy scale, which corresponds to ~ 4 MeV of a neutron energy scale.

A Pu-Be source was used to calibrate the NC channel [3]. The spectrum produced by the Pu-Be source has a specific shape due to a wall effect, which distorts the counter event spectrum. In spite of this distortion, the range of energies observed for true neutron events is less narrow compared to the broad background spectrum produced by internal alphas. We used only the events from the «neutron window» coincident with PMT signals in order to suppress the internal background of the detector. The delay time is a specific feature of the detector and depends on the detector design. The acquisition system allows us to measure directly the delay time for neutron events. Such measurements were carried out using a Pu-Be source. A fitting procedure leads to a time constant of $T_{1/2} = 55$ μs.



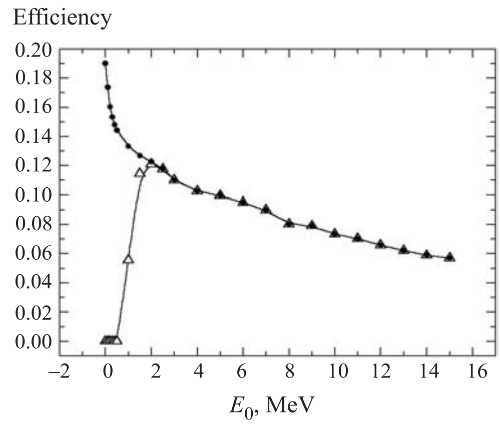


Fig. 1. Responce functions

Fig. 2. Detector efficiency: triangles — $\varepsilon(E_0)$; circles — without threshold of registration influence

Decays of radioactive isotopes of Bi and Po, which can take place in the helium counter walls, have been considered as the main sources of the significant internal background. Beta decay of ^{214}Bi can fire the scintillator, followed by a delayed capture α signal from Po decay in helium counters:

$$^{214}\mathrm{Bi}(e) \to {}^{214}\mathrm{Po}(\alpha) \to ..., \tag{1}$$

thus imitating an actual neutron event. The delay time distribution of the events obtained for the series results in a time constant $T_{1/2} = 164$ μs. It confirms our assumption about the possible origin of the detector internal background.

The detection efficiency depends in a complicated manner on the response function of the detector. The response function for an infinite organic scintillator, calculated using Monte-Carlo simulation, is shown in Fig. 1. The neutron's thermalization process in the detector of the actual geometry was studied also. As a result we have obtained that the total detection efficiency can be expressed as composition of three contributions:

$$\varepsilon_E = \varepsilon_{\mathrm{tot}}(E_n) = \varepsilon \cdot \varepsilon_{\mathrm{th}}(E_n)(1 - \varepsilon_{\mathrm{out}}(E_n)), \tag{2}$$

where $\varepsilon \approx 19\,\%$ is the efficiency of registration of thermalized neutrons by ^{3}He-counters; $\varepsilon_{\mathrm{out}}(E_n)$ is the probability for a neutron to leave the detector; $\varepsilon_{\mathrm{th}}(E_n)$ is caused by the registration threshold. Thus the dependence of efficiency on initial neutron energy has a form that is shown in Fig. 2. Unfolding of obtained spectra was not performed, the mean value of efficiency in 1–7 MeV energy range $\varepsilon_{\mathrm{tot}} = 11\,\%$ was used to calculate the neutron flux.

3. RESULTS OF THE MEASUREMENTS

The conditions of the performed measurements and the values of the calculated rates of counting are shown in the Table, for counting rates: R_γ — in the PMT channel; R_{NC} — in the NC channel; R_{NW} — in the «neutron window» and R_{cor} — for the correlated events.

Table 1. **Fast neutrons background flux measurement (conditions of measurements and rates of counting)** $R_{\rm tot} = R_N + R_{\rm rand} + R_{\rm bkg}, R_{\rm cor} = R_{\rm tot} - R_{\rm rand} = R_N + R_{\rm bkg}$

Conditions	R_γ, h^{-1}	$R_{\rm NC}, h^{-1}$	$R_{\rm NW}, h^{-1}$	$R_{\rm tot}, h^{-1}$	$R_{\rm rand}, h^{-1}$	$R_{\rm cor}, h^{-1}$	$R_{\rm cor}/\varepsilon_E, h^{-1}$
H_2O	21	96.4 ± 0.8	29.5 ± 0.5	1.25 ± 0.4	0.07 ± 0.001	1.25 ± 0.40	11.36 ± 3.78
Mine Rock	140 ± 0.4	106.4 ± 0.3	46.6 ± 0.2	2.96 ± 0.13	0.29 ± 0.17	1.42 ± 0.45	12.91 ± 4.29
SAGE	512 ± 4	74.2 ± 0.2	25.8 ± 0.1	1.93 ± 0.12	1.11 ± 0.17	-0.43 ± 0.45	-3.91 ± 4.11

We consider three contributions to the experimentally measured counting rate $R_{\rm tot}$: the random coincidence rate $R_{\rm rand}$, the internal background counting rate $R_{\rm bkg}$, and «neutron» counting rate R_n, so that

$$R_n = R_{\rm tot} - R_{\rm bkg} - R_{\rm rand}. \quad (3)$$

We assume that the total background γ spectrum has the same shape as the random, coincidences spectrum. To obtain the random coincidences spectrum the total spectrum of the background gammas has been normalized to a calculated random coincidences rate. The maximum rate random coincidences in the case of absolutely independent signals in the PMT and NC channels can be calculated in the following way:

$$R_{\rm rand} = r_\gamma\, r_n^w \Delta t, \quad (4)$$

where r_γ is the γ rate; r_n^w is the neutron counter rate in the determined energy window; Δt is the time window. Applying the subtraction procedure as described, the spectra for each series of measurements were obtained. Figures 3, a, b and 3, c, d give the details of the measured and

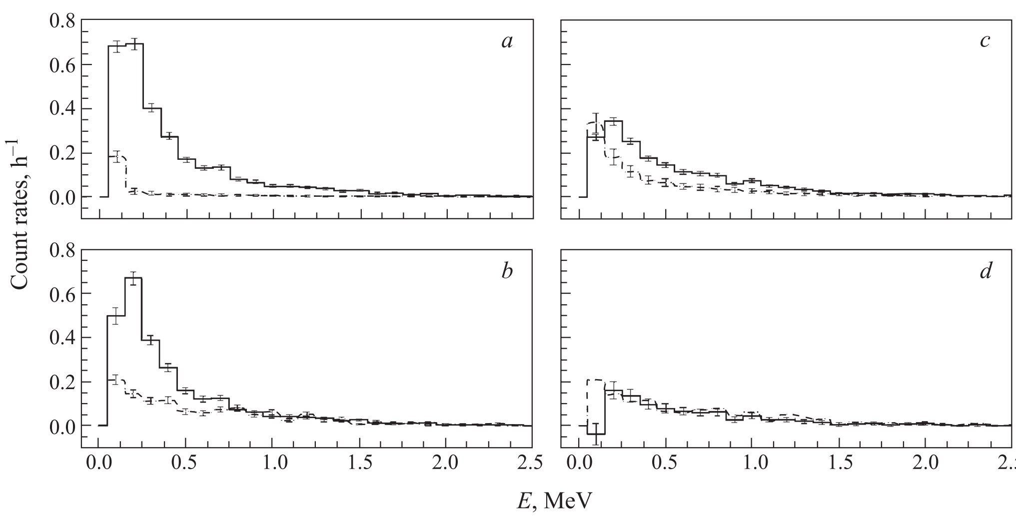


Fig. 3. Fast neutrons amplitude distributions for Mine Rock measurements (electron scale) (a, b) and in the Main SAGE Room (electron scale) (c, d): a, c) solid line — total number; dashed line — random coinciences; b, d) solid line — correlated event; dashed line — background of the detector

calculated spectra. Taking into account the detection efficiency of 0.11 ± 0.01 and detector full square of 6267.5 cm^2, the value of neutron fluxes was obtained as $(7.3 \pm 2.4) \cdot 10^{-7} \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$ for measurements in an additional room of GGNT, $< 2.3 \cdot 10^{-7} \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$ for measurements in the main room of GGNT and $(6.5 \pm 2.1) \cdot 10^{-7} \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$ for measurements in a water shield.

CONCLUSIONS

The main results of the measurements can be summarized as follows. (I) Using the fast neutron high-sensitive spectrometer neutron energy distributions with a resolution of $60\,\%$ are measured. The sensitivity of the detector is estimated as $10^{-7} \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$. The registration threshold was determined as 1 MeV. (II) The efficiency dependence on initial neutron energy was calculated by Monte-Carlo simulations. In calculations of the neutron flux we used the efficiency value of 0.11 ± 0.01. (III) The internal background of the detector was measured in a shield of water and borated polyethylene. The background counting rate in the detector corresponds to a neutron flux of $(6.5 \pm 2.1) \cdot 10^{-7} \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$ in the range 1.0–11.0 MeV. Analysis of the time distribution showed that the origin of the detector background is ^{214}Bi–^{214}Po decay in the walls of the helium counters. (IV) The natural neutron flux from the surrounding mine rock at a depth of 4600 meters of water equivalent was measured to be $(7.3 \pm 2.4) \cdot 10^{-7} \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$ in 1.0–11.0 MeV. The flux of fast neutrons in the SAGE main room was measured to be $< 2.3 \cdot 10^{-7} \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$ in 1.0–11.0 MeV energy range. (V) Based on theoretical calculations [3] one can show that the neutron contribution to effect, measured by SAGE, is negligible [4].

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