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Measuring Low Neutron Fluxes at the Modane Underground Laboratory Using Iodine-Containing Scintillators

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Abstract—The first results of neutron-flux measurements at the LSM underground laboratory (Modane, France) using a new sensitive method are presented. Neutrons are detected by counting delayed $\gamma\gamma$ coincidences in the $^{127}I(n, \gamma)^{128}I$ reaction. It is shown that this approach makes it possible to measure thermal-neutron fluxes at a level of 10^{-6} neutron cm^{-2} s^{-1}.

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INTRODUCTION

In modern physics, the search for rare events in low-background experiments performed in deep underground laboratories, where significant suppression of the background due to cosmic rays is achieved, is an important area of research. These experiments include numerous neutrino experiments, the search for a neutrinoless double-beta decay mode, and the search for dark-matter particles and superheavy elements in nature. An important task that must be performed when searching for rare processes consists in determining the contribution of neutrons to the total result of measurements. At the same time, the main experimental difficulty is the necessity to detect neutron fluxes at a level below 10^{-5} neutron cm^{-2} s^{-1}. When fluxes are as low as these, the number of neutron events detected by even the most sensitive ^{3}He counters does not exceed a few counts per hour [1]. Therefore, it is necessary that the intrinsic background of such detectors be taken into account and suppressed. At the same time, due to the high cost and limited supply of ^{3}He, such detectors are not easily accessible today.

An alternative to ^{3}He detectors are, e.g., scintillators loaded with gadolinium [2] or ^{6}Li [3]. The main experimental difficulty encountered when scintillators are used to detect rare neutron events is their high sensitivity to the background of γ rays and muons.

The method discussed in what follows makes it possible to discriminate neutron events and therefore can be used to detect low neutron fluxes in underground laboratories. In this paper, we present the first results of the experimental test of this method at the LSM underground laboratory (Modane, France) near the site of the EDELWEISS experiment [4], which consists in directly searching for weakly interacting massive particles (WIMPs) of non-baryon dark matter. Precise information about the neutron background is the basis for correct interpretation of data obtained in this experiment [5].

EXPERIMENT

A new sensitive method for detecting neutrons is based on the use of iodine-containing scintillators. Capture of a thermal neutron by an iodine nucleus (the reaction cross section is 6.2 b [6]) contained in a NaI(Tl) detector results in production of a ^{128}I nucleus in an excited state with an energy of 6.8 MeV. Upon de-excitation to the ground state, a significant fraction of decays proceed through the level of 137.8 keV with the half-life period $T_{1/2}$ = 845 ns [6], which makes it possible to detect neutrons by counting the number of delayed $\gamma\gamma$ coincidences. The use of the technique of delayed coincidences with a time interval of a few microseconds makes it possible to discriminate between neutron and background events with high efficiency. Taking the fact into account that the background of random coincidences exhibits an almost quadratic dependence on the total background, the use of this method becomes particularly efficient when making low-background measurements. This method was described in more detail in [7].

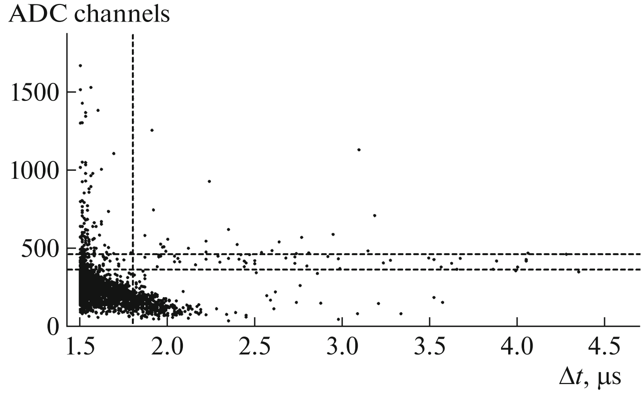

Fig. 1. Delayed events (dots) detected by the NaI(Tl) detector in the presence of a neutron source: (Δt) delay time. The dashed line indicates the region of interest in the range from 1.8 to 5.0 μs. A large number of events below the region of interest are the afterpulses of the photomultiplier tube.

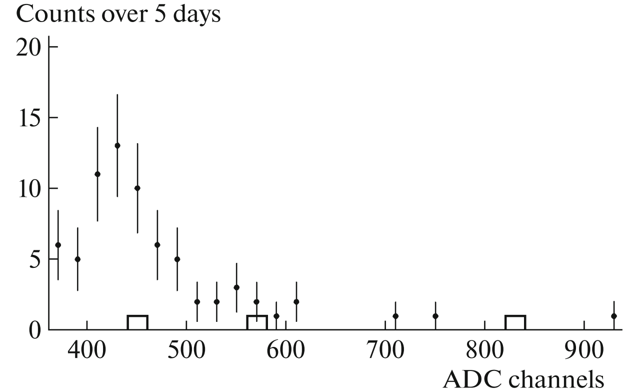

Fig. 2. Delayed events detected by the NaI(Tl) detector over 5 days of measurements in the presence of a weak neutron source. Dots with errors indicate events with a sampling window of 1.8–5.0 μs. The solid line shows the delayed coincidences with a window of 11.8–15.0 μs. The channel range of 380–460 corresponds to the energy of 137 keV.

The test measurements of the neutron flux using this method started at the LSM underground laboratory in April 2017. The NaI(Tl) detector used for this purpose had a mass of 720 g and was placed in a copper–lead shield. The energy scale was calibrated by γ-ray peaks in the spectrum of Th from a thorium-containing wire. The criteria for the selection of the delayed γγ coincidences (i.e., neutron events) were obtained using a low-intensity AmBe source with an activity of 20 neutron/s (Fig. 1). The event of neutron detection was determined as a delayed event with an energy of 137 keV, which corresponded to channels 380–460 (Fig. 2) of the analog-to-digital converter (ADC). In this interval, 39 (~50%) of the total number of 75 neutron events detected during the calibration measurements were found, while the preliminarily estimated ratio of the neutron events to the background of random coincidences was 1 : 1. The search for delayed events associated with neutron was carried out in the time interval of 1.8–5.0 μs. As can be seen from Fig. 1, the use of a delay interval starting earlier than 1.8 μs is prevented by numerous afterpulses of a photomultiplier tube. A time slot from 11.8 to 15 μs was used to monitor the background of delayed coincidences.

The direct measurements of the background thermal-neutron flux at the underground laboratory were started on April 3, 2017. By January 2018, the data-acquisition time was 260.45 days.

As a result of the analysis of the acquired data, 70 delayed events were found in the region of interest (Fig. 3). The background value of random coincidences for a 3.2-μs time slice can be experimentally estimated from the number of delayed events in a time slot that was significantly (for many half-life periods of the level) shifted from the prompt event. Thus, 37 events were detected in the array of acquired experimental data in the interval of delays from 11.8 to 15.0 μs. This result is in full agreement with the value (34 events) calculated from the number of single events in the entire spectrum and in the region of the 137-keV peak. The high background value of random coincidences can be attributed to the presence of ^{40}K in the used NaI(Tl) detector at a level of ~3 Bq, which is a common problem of the early generations of such detectors (which was available at the time of the presented test measurements). This problem has already been eliminated.

In view of the difference between the total number of delayed events and the background value, as well as the detector efficiency [7], the measured thermal-neutron flux was $(2.1 \pm 0.5) \times 10^{-6}$ neutron cm^{-2} s^{-1}. The decisive contribution to the uncertainty of the

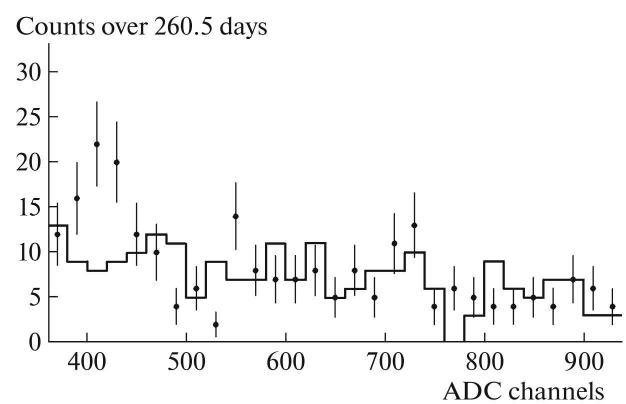

Fig. 3. Delayed events detected by the NaI(Tl) detector when measuring the background. The channel range of 380–460 corresponds to the energy of 137 keV. Dots with errors indicate events with a sampling window of 1.8–5.0 μs. The solid line shows the delayed coincidences with a window of 11.8–15.0 μs.

obtained value was made by the low count rate of neutrons at a high background of random coincidences.

The results were verified by making the above measurements simultaneously with measuring the neutron fluxes in the immediate vicinity of the measurement point using two low-background ^{3}He detectors [1]. The fluxes measured over the entire measurement period were $(2.3 \pm 0.1^{stat} \pm 0.2^{sys}) \times 10^{-6}$ and $(3.1 \pm 0.1^{stat} \pm 0.3^{sys}) \times 10^{-6}$ neutron cm^{-2} s^{-1}. It is important to note that the detector that measured the highest neutron flux was located closer to the laboratory wall, the residual natural radioactivity of the materials of which is the dominant neutron source in the underground laboratory. Generally, there is satisfactory agreement, in terms of the measurement errors, between the neutron fluxes measured by the NaI(Tl) and ^{3}He detectors.

CONCLUSIONS

The measurements results have shown that it is possible in principle to use iodine-containing scintillators to detect low neutron fluxes at a level of 10^{-6} neutron cm^{-2} s^{-1}. When using the low-background detector with a lower ^{40}K content and a mass of approximately 100 kg, it is possible to measure the neutron flux below 10^{-8} neutron cm^{-2} s^{-1}.

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