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NEUTRON FLUX MEASUREMENT USING ACTIVATED RADIOACTIVE ISOTOPES AT THE BAKSAN UNDERGROUND SCINTILLATION TELESCOPE

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Preliminary results of a neutron background measurement at the Baksan Underground Scintillation Telescope (BUST) are presented. The external planes of the BUST are fully covered with standard scintillation detectors, shielding the internal planes and suppressing thus background events due to cosmogenic and local radioactivity. The shielded internal planes were used as targets for the neutron flux registration. The experimental method is based on the delayed coincidences between signals from any of the BUST counters. It is assumed that the first signal is due to inelastic interaction of a neutron with the organic scintillator, while the second signal comes from the decay of an unstable radioactive isotope formed when the fast neutron interacts with the ^{12}C nuclei. Using the Monte Carlo method (GEANT4) we also simulated propagation of neutrons through a layer of scintillator. The experimentally found muon-induced neutron flux is $j = 1.3^{+0.7}_{-0.3} \cdot 10^{-10}$ cm$^{-2} \cdot$ s^{-1} for neutron energies $E \geqslant 22$ MeV, which is in a qualitative agreement with similar measurements of other underground laboratories as well as with predictions of the GEANT4 program.

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INTRODUCTION

Underground experiments studying rare processes (searching for Dark Matter, neutrinoless double beta decay, core-collapse neutrinos) are located at deep underground to reduce the background of cosmic rays. These experiments require precise knowledge of the muon-induced background from surrounding rock. Background from muon-induced neutrons is one of the most important limitations

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to detector sensitivity for rare event searches. The fast neutrons, from (α, n) reactions and fission decays in the surrounding rocks are lower in energy than muon-induced neutrons and thus easier to be shielded. Cosmic ray muon shielding materials serve as targets for neutron production. It is difficult to suppress background constituted by the fast neutrons with energy above 10 MeV, so that they contribute to the total background for an experiment. Neutrons are able to travel considerable distances in matter before reaching the counter. Energies of the fast neutrons may be as high as a few GeV. Measurements of muon-induced neutron rate are important for estimating the sensitivity of an experiment and constructing future detectors for rare event searches. Experimental and theoretical studies of muon-induced neutron background on different targets have been carried out by a number of laboratories [1–10]. The KamLAND collaboration has presented muon-induced neutron rates for various target isotopes [11]. The EDELWEISS Dark Matter search experiment has reported the measurements of germanium recoils in coincidence with muon signals in scintillator [12]. The LVD experiment at Gran Sasso has also investigated neutron-induced background with recoil energies up to 300 MeV in liquid scintillator [13]. Direct measurements of neutron energy spectrum by 12-l liquid scintillation detector at the Soudan underground laboratory have been done in [4]. In organic scintillators, a high-energy neutron can be detected through a double signature: the first pulse is generated by the proton from neutron inelastic interaction with carbon, while the second pulse is due to the electron from the beta decay of an unstable radioactive isotope formed when the fast neutron interacts with the carbon nuclei.

In this paper, we present an estimation of the muon-induced neutron background using data of the BUST experiment collected during the period from 2001 to 2014 at the depth of 850 m water equivalent (m.w.e.).

1. EXPERIMENTAL SETUP

The BUST [14, 15] is a liquid scintillation detector whose major purpose is the investigation of cosmic ray muons and neutrinos. To shield cosmic ray background, the BUST experiment is located in an excavation under the slope of Mt. Andyrchy (North Caucasus, $43.28°$ N and $42.69°$ E) at the depth of about 300 m (see Fig. 1) or 850 m.w.e. The walls of the excavation are covered with low radioactivity concrete and lined with steel sheets. The experimental setup depicted in Fig. 2 consists of an array of 3186 scintillation counters distributed over eight planes (4 vertical and 4 horizontal). Six of the eight planes form a parallelepiped structure, the other two are located in it at equidistant from each other. The distance between the neighboring horizontal planes is 3.6 m. The frame of the facility is a metallic carcass of steel beams and channels. The inner part of the parallelepiped is framed in the form of a vertical wall of low radioactivity concrete

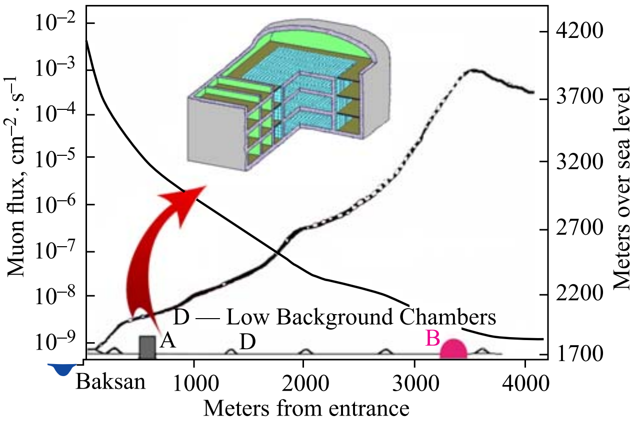

Fig. 1. Schematic illustration of the location of the Baksan Underground Scintillation Telescope

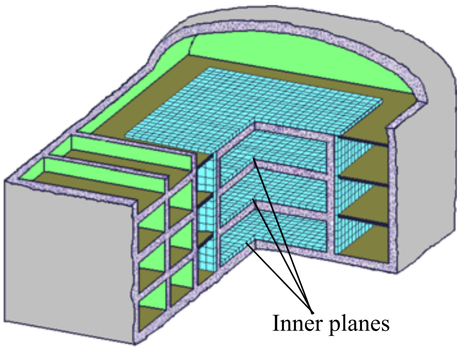

Fig. 2. Schematic illustration of the structure of the Baksan Underground Scintillation Telescope

blocks and two storeys. Each storey consisting of an iron sheet and a layer of low radioactivity gravel is covered with concrete. The counters of the horizontal planes are placed on the concrete layers. The upper horizontal plane consists of 24×24 scintillation counters, the rest three horizontal planes accommodate 20×20 counters each. Three vertical planes have 15×24 counters and one vertical plane is built of 15×22 counters. The upper horizontal plane and all vertical planes serve as an active shield for the internal planes. The total mass of the liquid scintillator contained in 3186 counters is 330 t. The internal planes have the effective target mass of 130 t and are used for monitoring the Galaxy to study neutrino bursts from gravitational stellar collapses [16]. A standard

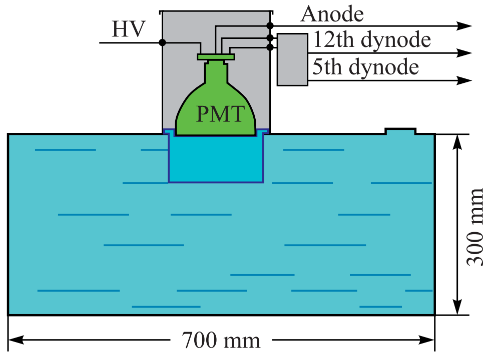

Fig. 3. Standard scintillation counter of the Baksan Underground Scintillation Telescope

scintillation counter of the BUST (see Fig. 3) is an aluminium parallelepiped container with sizes $0.7 \times 0.7 \times 0.3$ m viewed from the top by a 15 cm diameter photomultiplier (PMT) through an organic glass illuminator. A PMT is placed in an iron protective casing. The pulse discriminator–shaper and LC-converter are attached to the surface of the protective casing. The LC-converter is designed to provide information on the energy deposition in the counter if it exceeds 500 MeV by converting the pulse amplitude from the 5th dynode of the PMT to the output pulse duration. The BUST liquid scintillator is a mixture of hydrocarbons (C_9H_{20}) also known as white spirit. The design of the BUST allows one to monitor the operation and to process data from each counter. This is useful for a wide range of problems like the study of muon groups or the neutrino signal registration. For registration of rare events such as neutrino from gravitational stellar collapses, the internal planes of the telescope are used. The coordinate information of a triggered counter is constituted by an output signal from the pulse discriminator, which is based on a signal from the 12th dynode of the PMT. The threshold of the pulse discriminators for the horizontal planes is 8 MeV and 10 MeV for the vertical ones. On each plane the anode signals are integrated through a chain of summators. This scheme allows one to get information about the energy deposition in the plane and to measure the time of flight of muons as well as to reconstruct their trajectories. Since 2001, the facility is operating in the continuous data acquisition mode using a passive and active shielding to reduce backgrounds. The scintillator serving as a passive hydrogen-rich shielding and the counters as the active charged-particle detectors are used to moderate neutrons and veto muon-induced events, respectively. In this paper, we exploit the technique, which allows us to estimate the neutron background by measuring the frequency of decays of unstable radioactive isotopes in the target of the detectors.

2. NEUTRON BACKGROUND

Cosmic ray muons penetrate deep underground and produce neutrons in the volume of the detector or in the rock surrounding the facility. The background from the neutrons produced in the scintillator is controlled by external detectors of muons, which are located at some distance from the main detector covering the latter completely. Contrary, it is difficult to suppress the neutrons produced in the rock because they have a greater penetrating power and the impossibility to fix the primary muon. The background of neutrons generated by muons in deep underground is a few orders of magnitude lower than natural radioactivity from neutrons with energies less than 10 MeV. At the same time, the neutrons from muons have relatively high energies and penetrate the ground. They can travel far from the muon track or their point of origin reaching detectors from large distances and reducing the efficiency of an anticoincidence system. This is an irreducible background for many underground experiments.

In experiments searching for rare events, signals from neutrons have the same signature as the useful signal. In particular, the registration of electron antineutrinos at the BUST is made mainly through the inverse beta-decay reaction of electron antineutrinos on protons $\overline{\nu}_e + p \to e^+ + n$. The signal from the positron appears as a single operation of one of the counters installed at the one of the internal planes, at the absence of signals from the other counters [16]. Since the cross sections of reactions with neutrinos are relatively small, all possible reactions with neutrons effectively mimic signals from neutrinos. For example, neutrons produce background via elastic scattering off protons. At the same time, inelastic neutron-induced reactions with the carbon of the scintillator allow one to measure the neutron flux with sufficient accuracy. During the passage of the neutrons through the scintillator, unstable radioactive isotopes are generated. The prompt signal from the proton and the delayed signal from the electron from the unstable isotope beta decay constitute the double signature. The BUST can detect unstable radioactive isotope formation and its subsequent beta decay as, for example, the following reaction:

$$^{12}\mathrm{C}(n,p)^{12}\mathrm{B}, \tag{1}$$

which has been exploited in the present analysis (see Fig. 4). A large number of such pairs of signals allow one to construct the distribution of the time intervals between the signals in the pair. The maximum likelihood method, which in this case is reduced to the calculation of the average value, enables one to determine the lifetime of the unstable isotope. The approximation of distribution of the time intervals between the signals in the pair by a decay curve makes it possible to estimate the frequency of radioactive isotope production during the observation time. The connection between the number of isotope nuclei and the neutron flux

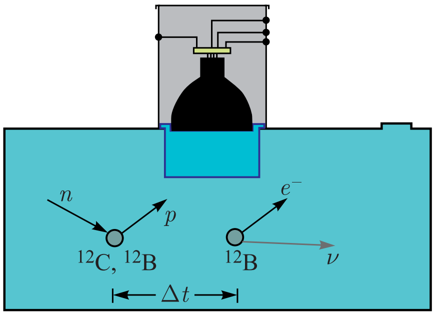

Fig. 4. Schematic view of the mechanism of production of ^{12}B which gives a pair of signals in a counter of the BUST through the reaction $^{12}C(n,p)^{12}B$. The first signal is generated by the outcoming proton, while the second one is registered later due to the β decay of ^{12}B

is given by

$$j = \frac{N}{nf\sigma t}, \tag{2}$$

where N and n are the numbers of the isotope and target nuclei, respectively; f is the detection efficiency; σ is the cross section of the reaction; t is the observation time.

3. ANALYSIS AND RESULTS

To estimate the neutron flux, the BUST data collected from 2001 to 2014 were used (live time data taking was 11 yr). Only those events that appear as two consecutive signals from the same counter in the absence of any signal from the other counters were selected. In addition, only the data from the internal planes of the BUST were used to suppress muon background. From each counter, we get information which includes the coordinate of the triggered counter, energy deposition in the volume of the counter, and the time information. To have the decay of a ^{12}B nucleus with high probability, the time interval between a pair of events was chosen to be equal to 5 half-lives of ^{12}B.

We fitted the distribution of the signal pairs per counter by the Poisson distribution throughout the observation time. The counters which gave the number of signals pairs exceeding that predicted by Poisson distribution were excluded from the data processing (see Fig. 5). The presence of the radioactive boron is indicated by fitting the distribution of the time intervals between each pair of signals by the decay curve $\propto a\exp(-\Delta t/\tau) + b$ (τ is the mean lifetime of ^{12}B) shown in Fig. 6. From the parameter a we obtain the number of ^{12}B isotopes, while b gives the level of background events. The chi-square distribution minimization method was applied to fitting. Subsequently, the number of the produced ^{12}B nuclei was converted into the neutron flux according to (2). For the BUST, $n = 6 \cdot 10^{30}$, $N = 380^{+16}_{-12}$, $t = 11$ yr, $f = 0.28$, for the cross section we adopted $\sigma = 5^{+20}_{-3} \cdot 10^{-27}$ cm^2 [18]. The uncertainty in the determination of the

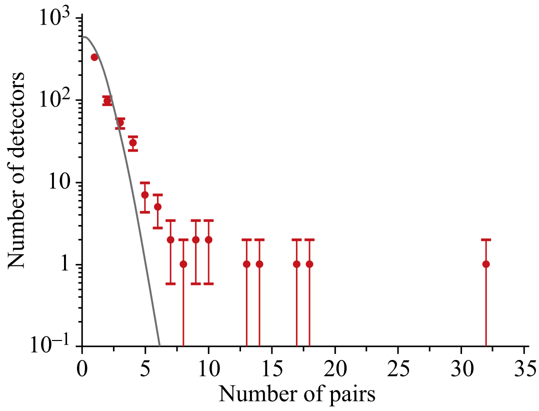

Fig. 5. Distribution of the signal pairs per counter (points). The solid curve represents the Poisson distribution

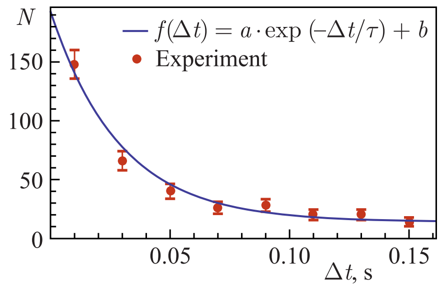

Fig. 6. Distribution of the time delays between the signals at the BUST. The solid line is the fit by the decay curve with $\tau = 29.1$ ms (mean lifetime of ^{12}B)

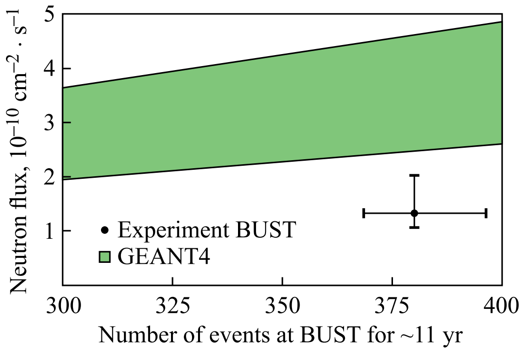

Fig. 7. Dependence of the neutron flux on the number of the signal pairs at the BUST. The shaded area is the prediction of the GEANT4 program. The point with error bars is the experimental result obtained by using the BUST data (the live data taking time is 11 yr)

neutron flux is due to existing uncertainties on the cross section for the reaction $^{12}\mathrm{C}(n,p)^{12}\mathrm{B}$ in the considered energy range [18].

Using the GEANT4 package [17], the propagation of neutrons through a layer of the scintillator was simulated for different scintillator thicknesses varying from 30 to 70 cm, according to the sizes of an individual counter. The energy of the neutron beam was taken to be in the range from 20 to 500 MeV. The analysis indicates the presence of the reactions with radioactive isotopes such as $^{12}\mathrm{B}$ nuclei. Based on the GEANT4 data, we plotted the expected flux of neutrons depending on the number of registered signals from $^{12}\mathrm{B}$ (see Fig. 7).

CONCLUSIONS

Preliminary results of a neutron background measurement at the Baksan Underground Scintillation Telescope exploiting the reaction $^{12}\mathrm{C}(n,p)^{12}\mathrm{B}$ are presented. The external planes of the BUST are fully covered with standard scintillation detectors shielding the internal planes and suppressing thus background events due to cosmogenic and local radioactivity. These shielded internal planes were used as targets for neutron flux registration. The experimental method is based on the delayed coincidences between two signals from any of the BUST counters. It is assumed that the first signal is due to inelastic interaction of a neutron with the organic scintillator, while the second one comes from the decay of an unstable radioactive isotope formed when the fast neutron interacts with the $^{12}\mathrm{C}$ nuclei. Using the Monte Carlo method (GEANT4) we simulated propagation of neutrons through a layer of scintillator. The experimentally found muon-induced neutron flux is $j = 1.3^{+0.7}_{-0.3} \cdot 10^{-10}$ cm$^{-2} \cdot$ s^{-1} for neutron energies $E \geqslant 22$ MeV, which is in a qualitative agreement with similar measurements of other underground laboratories [1–10] as well as with predictions of the GEANT4 code.

The study of other cosmogenic beta-decaying isotopes such as $^{8}\mathrm{He}$, $^{9}\mathrm{C}$, $^{9}\mathrm{Li}$, $^{11}\mathrm{Li}$, produced by neutrons in the scintillator of the BUST, is in progress now.

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