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Neutron flux measurement using fast-neutron activation of ^{12}B and ^{12}N isotopes in hydrocarbonate scintillators

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We measured the production of ^{12}B and ^{12}N in the organic liquid scintillator. The delayed coincidence method has been used to determine the production of unstable isotopes. These isotopes are critical in understanding background in underground detectors used for rare events search. They are produced by cosmogenic-neutron interactions in the detectors. The production rates were measured at Baksan Underground Scintillation Telescope (BUST). Then we use the measured isotope production rate to estimate the cosmogenic neutron flux. Some preliminary results and comparisons with the Monte-Carlo simulations are presented.

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1. Introduction

Deep underground sites provide a unique opportunity to explore the rare events (dark matter, neutrinoless double beta decay, core collapse neutrinos etc.). Most of underground experiments are located at deep underground to reduce the background of cosmic rays. As high-energy muons can penetrate deep underground and generate background to physics experiments, these experiments require precise knowledge of the muon-induced background from surrounding rock. Cosmic ray muons can be easily vetoed and they do not directly constitute a serious problem. But, the high-energy muons can induce spallation neutrons at the rock surrounding experimental setup. These spallation neutrons have a very broad spectrum that extends up to several GeV in neutron energy. They can travel a long distance into the detector and are difficult to tag. Neutron scattering and capture within the target can restrict experimental sensitivities or bring false positive signals in the studies of rare events. Background from muon-induced neutrons is one of the most important limitations to detector sensitivity for rare event searches. The fast neutrons, from (α, n) reactions and fission in the surrounding rocks, are lower in energy than muon-induced neutrons and thus easier to be shielded. It is difficult to suppress background constituted by the fast neutrons with energy above 10 MeV so that they contribute to the total background of an experiment. Measurements of muon-induced neutron flux are important for estimating the sensitivity of an experiment and constructing future detectors. There are the estimation of muon-induced neutrons in an organic liquid scintillator at the depth 850 m water equivalent. In general, such estimation require detailed and experiment-specific Monte Carlo simulations to correct for the neutron contribution from rock, but this is difficult, in particular for the older experiments. In this paper, we present the results of a study of muon-induced fast neutrons from rock for the BUST experiment.

2. Detector and measurements

The BUST [1] 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, $43.28^0 N$ and $42.69^0 E$) at the depth of about 300 m or 850 m.w.e. The walls of the excavation are covered with low radioactivity concrete and lined with steel sheets.

The experimental setup 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 blocks and two storeys. Each storey consisting of an iron sheet and a layer of low radioactivity gravel is covered by 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 are serving as an active shield for the internal planes. The total mass of the liquid scintillator contained in 3186 counters is 330 tons. The internal planes have the effective target mass 130 tons and are used for monitoring the Galaxy to study neutrino bursts from gravitational stellar collapses [2]. A standard scintillation counter of the BUST is an aluminium parallelepiped container with sizes $0.7 \times 0.7 \times 0.3$ m^3 viewed from the top by a 15 cm diameter photomultiplier (PMT) through a 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 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 spirite. The design of the BUST allows 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 to get information about the energy deposition in the plane and to measure the time of flight of muons as well as to reconstructtheir 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 used to moderate neutrons and veto muon-induced events, respectively.

In experiments searching for rare events, signals from neutrons have the same signature as the useful signal. In particular, the registration of electron anti-neutrinos [2] at the BUST 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 internal counters, at the absence of signals from the other counters. Since the cross sections of reactions with neutrinos are relatively small, all possible reactions with neutrons effectively mimic signals from neutrinos. Neutrons produce background via elastic scattering on protons. At the same time, inelastic neutron-induced reactions with the carbon of the scintillator allow to measure the neutron flux with sufficient accuracy. During the passage of the neutrons through the scintillator unstable radioactive isotopes are generated.

Neutron induced reactions in organic scintillator are interest due to possibility to get information about neutron background. Significant in this respect are the reactions leading to the emission of charged particles. Among them the $^{12}C(n,p)^{12}B$ reaction leads to the emission of protons and energetic electrons above the threshold of BUST counters. 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. The $^{12}C(n,p)^{12}B$ reaction has been exploited in the present analysis. Theoretically ^{12}N isotope is known to be not directly produced by the primary neutron, but rather the recoil proton ($n + p \to n + p$) interacting with the ^{12}C: $^{12}C(p,n)^{12}N$. The ^{12}N decay has the same signature as the ^{12}B decay reaction, so this background events can only be statistically substracted from the data.

A large number of pairs of signals allow to construct the distribution of the time intervals between the signals in the pair. The approximation of distribution of the time intervals between the signals in the pair by a decay curve makes it possible to estimate the number of radioactive isotopes produced during the observation time. The produced number of ^{12}B nuclei neutrons N_B related to the neutron flux $j(E)$ through the following expression:

$$N_B = n \cdot f \cdot t \cdot \int_{E_{thr}}^{E_{max}} \sigma(E) \cdot j(E)\, dE, \tag{2.1}$$

where n the numbers of target nuclei, f is the detection efficiency, $\sigma(E)$ is the differential cross section of the reaction, t is the observation time. The energy range covered by the integral spans from the counter threshold for neutrons up to highest neutron energy E_n.

The values of the cross section largely vary depending on the selected model. We use as a benchmark for the predictions of the model calculations the integral measurement of the $^{12}C(n,p)^{12}B$ reaction performed at the neutron time-of-flight facility [3] at CERN. The best evidence for the $^{12}C(n,p)^{12}B$ cross-section comes from n_TOF experiment. The n_TOF result has been compared with evaluated cross-sections used in GEANT4. Among models in GEANT4 good agreement is noticed only with a combined Bertini/Binary cascade model. In this work the neutron flux was estimated on the basis of the cross-section from the Binari/Bertiny model evaluation up to 100 MeV. The neutron flux from the rock above 10 MeV is roughly inversely proportional to the neutron energy [4]. In this case, equation 2.1 reduces to

$$N_B = n \cdot f \cdot t \cdot k \cdot \int_{E_{thr}}^{E_{max}} \sigma(E)/E\, dE \tag{2.2}$$

This allows one to determine the proportionality factor k. Thus, the differential neutron flux can be written as:

$$j(E) = \frac{N_B}{n \cdot f \cdot t \cdot \int_{E_{thr}}^{E_{max}} \sigma(E)/E\, dE} \cdot \frac{1}{E} \tag{2.3}$$

Because of the quenching of the proton light yield in scintillator [5], and taking into account the detector energy threshold ($E = 8$ MeV), the neutrons with the double signature have energies greater than 28.6 MeV (i.e. $E_{thr} = 28.6$ MeV).

3. Data analysis and results

To estimate the neutron flux, the BUST data collected from 2001 to 2017 were used. 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. 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 6 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. 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 $F(t) = a\exp(-\Delta t/\tau_B) + a_N \exp(-\Delta t/\tau_N) + b$ (τ_B and τ_N is the mean lifetime of ^{12}B and ^{12}N respectively).

From the parameter a we obtain the number of ^{12}B isotopes, while b and a_N 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 equation 2.3. The responce function f of individual counter to double event reactions has been evaluated using Monte Carlo code. All the involved processes, including energy loss, multiple scattering etc., have been taken into account.

The counters of BUST are commonly divided into two groups: the inner counters (for search neutrino signal from supernova remnants) and the outer counters (used as an active muon veto). We calculated the average neutron flux for external group of counters using the equation 3. After taking into account the above mentioned considerations, the total neutron flux with 28.6 to 100 MeV is $\Phi_n \simeq 2.33 \cdot 10^{-9}\, cm^{-2}\, s^{-1}$ for the experimental hall of BUST detector. Due to Monte Carlo estimation of registration efficiency, we obtain a more accurate result in comparison with previous data processing [6].

According to Monte-Carlo modelations [7] the following equation predicts the muon induced neutron flux as a function of depth:

$$\Phi_{pred}(h_0) = P_0 \times (P_1/h_0) \times e^{-h_0/P_1}, \tag{3.1}$$

where h_0 is the equivalent depth in km.w.e relative to a flat overburden, and P_0, P_1 are the fitting parameters. The muon-induced neutron flux at the 0.85 km.w.e. (BUST) was obtained using a scailing method $\Phi_{pred}(0.85) = 15.1 \cdot 10^{-9}\, cm^{-2}\, s^{-1}$. The value $\Phi_{pred}(0.85)$ is in qualitative agreement with our results.

4. Conclusions

The experimental data collected by the BUST detector were used to estimate the neutron flux at the external counters of facility. 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 signal comes from the decay of an unstable radioactive isotope formed when the fast neutron interacts with the ^{12}C nuclei. The experimentally found muon induced neutron flux (for neutron energies $E \geq 28.6$ MeV) is in a qualitative agreement with predictions of the Monte-Carlo (FLUKA) models.

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