Fast neutrons in the Baksan Underground Scintillation Telescope: the background for core-collapse supernova searches

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Abstract We report on the measurement of the flux and spectra of the fast neutron background at BUST with a rock overburden of about 850 m w e, using a special method for the neutron flux estimation based on neutron activation analysis. The neutron-induced events are identified by a two-pulse signature of neutron inelastic scattering process.

Keywords: Neutron Background, Core Collapse Supernovae, Underground Physics, Neutrino

1. Introduction

In experiments searching for rare events, signals from neutrons have the same signature as a useful signal. In particular, the registration of electron anti-neutrinos at the Baksan Underground Scintillation Telescope [1] (BUST) made mainly through the inverse beta-decay reaction of electron antineutrinos on protons $\tilde{\nu}_e + p \rightarrow e^+ + n$.

The signal from the positron appears as a single operation of one of the internal counters, at the absence of signals from other counters [2]. 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 measuring the neutron flux with a sufficient accuracy. During the passage of neutrons through the scintillator, unstable radioactive isotopes are generated.

We have estimated the fast neutron flux (up to some 100 MeV) in the BUST experiment (Figure 1) which has been excavated at a depth of 300 m (850 m w e) under the slope of Mt. Andyrchy (North Caucasus, 43.28°N and 42.69°E).

The aim of the measurement is:

1) To assess as precisely as possible the neutron contribution to the total counting rate in the detector in view of its use for core-collapse supernova search experiments.

2) To evaluate the spurious events and background produced by cosmic ray induced neutrons in the detectors that will be installed in the underground laboratories for experiments in particle physics and astrophysics.

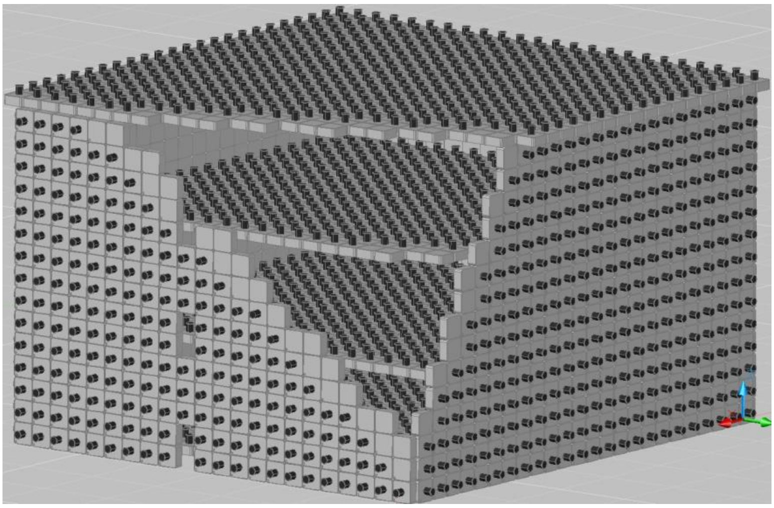

Fig1. *The layout of the Baksan Underground Scintillation Telescope of BNO INR RAS.*

2. Measurements

Neutron-induced reactions in organic scintillator are interesting due to a possibility to get information about the neutron background. Significant in this respect are the reactions leading to emission of charged particles. The ^{12}C(n, p)^{12}B reaction is among them.

The ^{12}B reaction leads to 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, the ^{12}N isotope is known to be not directly produced by the primary neutron, but rather the recoil proton (n + p → 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 these background events can only be statistically subtracted from the data.

A large number of signal pairs allows constructing distribution of time intervals between the signals in the pair. The approximation of distribution of time intervals between signals in a pair by the 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) is obtained from the following expression:

$$N_B = n \cdot f \cdot t \cdot \int_{E_{thr}}^{E_{max}} \sigma(E) \cdot j(E) dE \quad (1)$$

where *n* is the number of target nuclei, *f* is the detection efficiency, *σ(E)* is the differential cross section of 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 at CERN. The best evidence for the ^{12}C(n, p)^{12}B cross-section comes from the n_TOF experiment [3]. 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 basis of the cross-section from the Binary/Bertini 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 (1) reduces to

$$N_B = n \cdot f \cdot t \cdot k \cdot \int_{E_{thr}}^{E_{max}} \sigma(E)\,/E dE \tag{2}$$

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

$$j(E) = \frac{N_B}{n \cdot f \cdot t \cdot \int_{E_{thr}}^{E_{max}} \sigma(E)/E dE} \cdot \frac{1}{E} \tag{3}$$

Because of the quenching of the proton light yield in scintillator, 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).

2.1. Data analysis

To estimate the neutron flux, the BUST data collected from 2001 to 2018 were used (the live time data taking was 16.35 years). 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 the ^{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 signal pairs per counter by the Poisson distribution (Figure 2) 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.

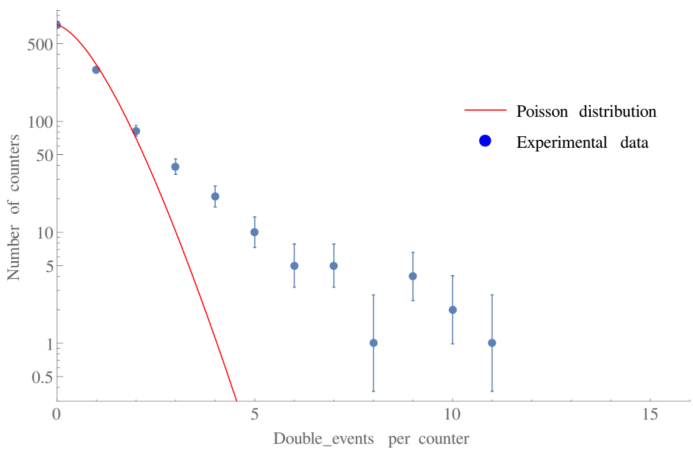

***Fig2**. Distribution of the signal pairs per counter (points). The solid curve represents the Poisson distribution.*

The presence of the radioactive boron is indicated by fitting the distribution of the time intervals between each pair of signals (Figure 3) by the decay curve $F(t) = a \cdot exp(-\Delta t/\tau_B) + a_N \cdot exp(-\Delta t/\tau_N) + b$ (τ_B and τ_N is the mean lifetime of ^{12}B and ^{12}N respectively).

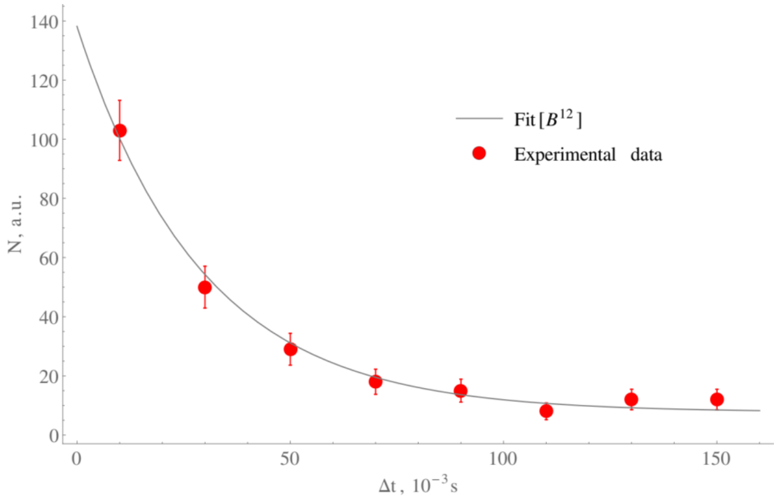

***Fig3**. Time delay distribution between the signals at BUST. The solid line is the fit by the decay curve.*

From the parameter *a* we obtain the number of ^{12}B isotopes, while *b* and a_N give 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 (3). The response function *f* of the individual counter to double event reactions has been evaluated using the Monte-Carlo code. All involved processes, including energy loss, multiple scattering etc., have been taken into account.

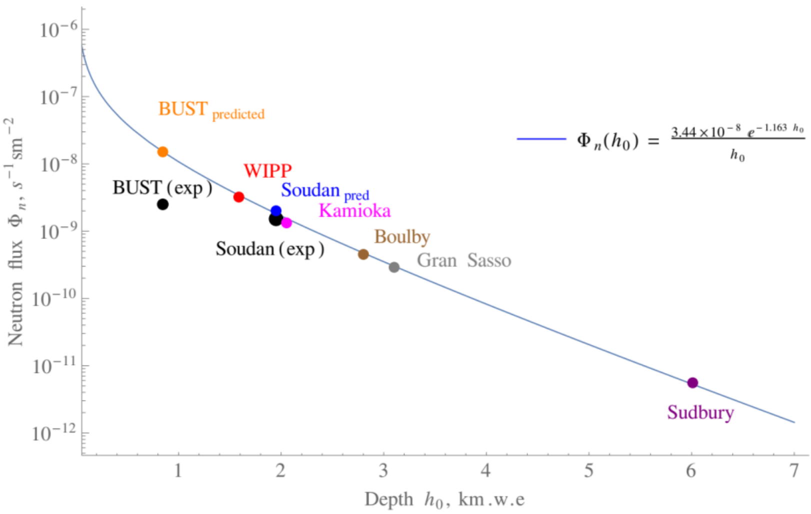

***Fig 4.** Comparison between experimental results and Monte-Carlo (Mei&Hime) predictions*

The BUST counters are commonly divided into two groups: the inner counters (for search neutrino signals from supernova remnants) and the outer counters (used as an active muon veto). We calculated the average neutron flux for an internal group of counters using equation (3).

After taking into account the above-mentioned considerations, the total neutron flux with E_n from 10 to 100 MeV is $\Phi_n = (2.5 \pm 5) \cdot 10^{-9}$ cm^{-2}s^{-1} for the internal counters of the BUST detector. According to Monte-Carlo simulations [5] the following equations predict the muon-induced neutron flux as a function of depth:

$$\Phi_{pred}(h_0) = P_0 \cdot (P_1 / h_0) \cdot e^{h_0/P_1} \tag{4}$$

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 the scaling 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.

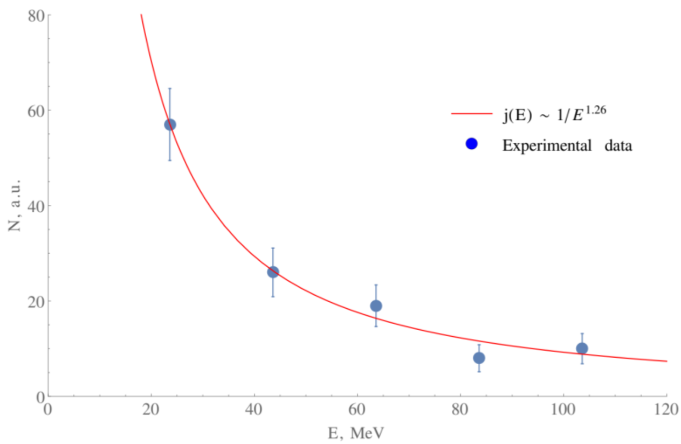

Fig 5. *Neutron energy spectra measured with BUST using the delayed coincidence method.*

The neutron energy distribution is derived from energy release data in selected double events. The calculation does not take into account the energy resolution of the counters. Fitting the distribution with a power function (Figure 5) gives us a spectral index of 1.26. This value is close to the results obtained in the LVD, KARMEN and Soudan experiments [6].

3. Conclusion

The experimental data collected by the BUST detector (16.35 years of live time) 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 $E \geq 10$ MeV) is in a qualitative agreement with predictions of the Monte-Carlo models.

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