Study of Cosmic-ray Muon-induced Neutrons at the Baksan Underground Scintillation Telescope

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6-8 June 2017, Nalchik

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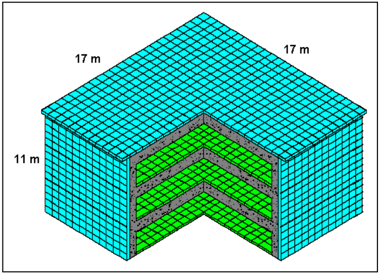
Introduction

- The muon-induced background influences the maximum achievable sensitivity in underground low rate physics experiments.
- 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.
- Reliable neutron flux numbers are an important ingredient in the design of the shielding of new experiments as well as in the analysis of experimental data.
- The neutrons from muons have relatively high energies and penetrate in 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 muon veto system. This is an irreducible background for many underground experiments.
- Fast neutrons produced by cosmic ray muons can fake signals from rare events by elastically scattering on target nuclei. For example, since muon-produced fast single or multiple neutrons can mimic the signature of inverse neutron beta decay, searches for neutrino burst from a core-collapse supernova must cope with this source of background.

Baksan Underground Scintillation Telescope

The registration of electron antineutrinos at the Baksan Underground Scintillation Telescope (850 m.w.e.) made mainly through the inverse beta-decay reaction of electron antineutrinos on protons. 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.



The detector and its operation is described in detail in Ref*. Briefly, the apparatus consists of 3184 scintillation counters, each 70 x 70 x 30 cm^3. These counters are filled with liquid organic scintillator. The **internal counters** is surrounded by the outermost layer of **external counters** which used as an active muon veto. The threshold of the pulse discriminators for the horizontal planes is 8 and 10 MeV for the vertical ones. The scintillator has an aggregate mass of 330 tons. Since the cross sections of reactions with neutrinos are relatively small, all possible reactions with neutrons effectively mimic signals from neutrinos. At the same time, inelastic neutron-induced reactions with the carbon of the scintillator allow to estimate the neutron flux with sufficient accuracy.

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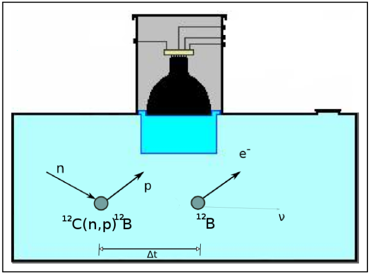
* *Alexeyev E.N. et al. Proc. of 16 ICRC, Kyoto, 1979, V.10, P.276.*

Neutron background

Double events

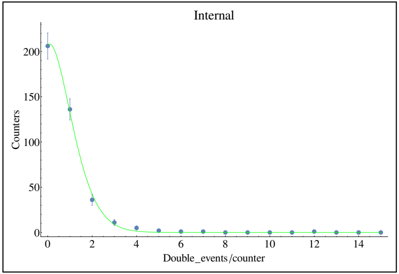
During the passage of the neutrons through the scintillator unstable radioactive isotopes are generated (Ref.[*]). The prompt signal from the proton and the delayed signal from the electron from the unstable isotope beta decay constitute the double signature. The B.U.S.T. can detect unstable radioactive isotope formation and its subsequent beta decay (see Fig.).

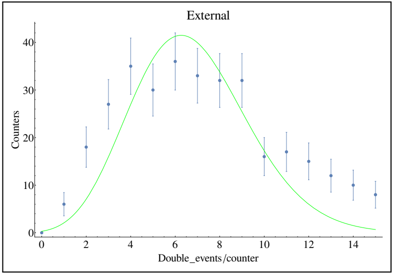


A large number of such pairs of signals allow to construct the distribution of the time intervals between the signals in the pair. The maximum likelihood method which in this case is reduced to the calculation of the average value, allows to determine the lifetime of the unstable isotope (in our case it was ^{12}B with $\tau_B = 29.1 \cdot 10^{-3} s$). 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 is given by
$N_{isot} = n \cdot f \cdot t \cdot \int \sigma(E) \cdot j(E) dE$,
where N and n are the numbers of the isotope and target nuclei, respectively, f - the detection efficiency, σ - the (n,p) cross section, t - the live time of detector.

* *P. Žugec et al., Nucl. Instrum. Meth. A* **760**, *57 (2014)*

Preparation of data and analysis

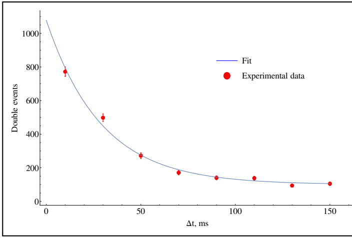




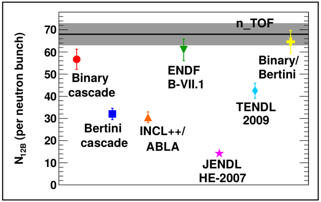
To estimate the neutron flux, the B.U.S.T. data collected from 2002 to 2015 were used (live time $\simeq$ 12.75 years). Only those events that appear as two consecutive signals from the same counter in the absence of any signal from the other counters (double events) were selected. The time interval between a pair of signals was chosen to be less or equal to 5 livetimes of ^{12}B isotope.
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. This selecton cut also applied to external counters.

Neutron background

The boron isotope production rate is estimated by approximation the distribution of the time intervals between each pair of signals by the decay curve $F(\Delta t) = A \cdot exp(-\Delta t/\tau_B) + B$. 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



$N_B = n \times f \times t \times \int_{E_{thr}}^{E_{max}} \sigma(E) \times j(E) dE$. There was found some problems with uncertainties on the cross section for the reaction $^{12}B(n,p)^{12}C$. 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 (n_TOF^*) at CERN. Among models used in GEANT4, a relatively good agreement is observed for the Binary cascade model. The best result, within 5% of the experimental value, is obtained by combining the Binary and the Bertini cascade models.



* *P. Žugec et al., Nucl. Instrum. Meth. A* **760**, *57 (2014)*

Neutron background

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

The neutron flux above 10 MeV is roughly inversely proportional to the neutron energy ($j(E) \propto 1/E^*$). In this case, Eq. 1 reduces to:
$N_B = n \times f \times t \times k \times \int_{E_{thr}}^{E_{max}} \sigma(E)/E dE$

This allows one to determine the proportionality factor
$k = N_B/(n \times f \times t \times \int_{E_{thr}}^{E_{max}} \sigma(E)/E dE)$

thus, the differential neutron flux

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

List of parameters:

- live time $t \simeq 12.72$ years (2002-2015);
- registration efficiency $f \simeq 0.28$;
- energy threshold for neutrons $E_{thr} = 28.6$ MeV (qwenching-factor considered)
- $\int_{E_{thr}}^{E_{max}} \sigma(E)/E dE$, calculated for Binary/Bertini model

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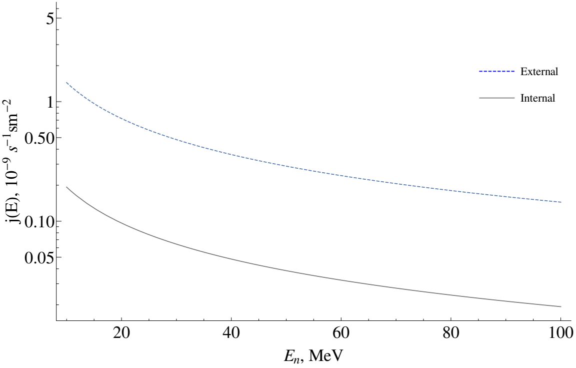
N. Agafonova, Phd thesis, P.91

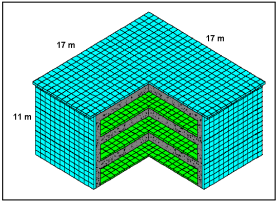
Results ($28.6 \leq E \leq 100$ MeV)

The differential neutron flux (Binary/Bertini model):

$$j(E) = \frac{N_B}{n \times f \times t \times \int_{28.6}^{100} \sigma(E)/E dE} \times \frac{1}{E}$$



Results ($28.6 \leq E \leq 100$ MeV)



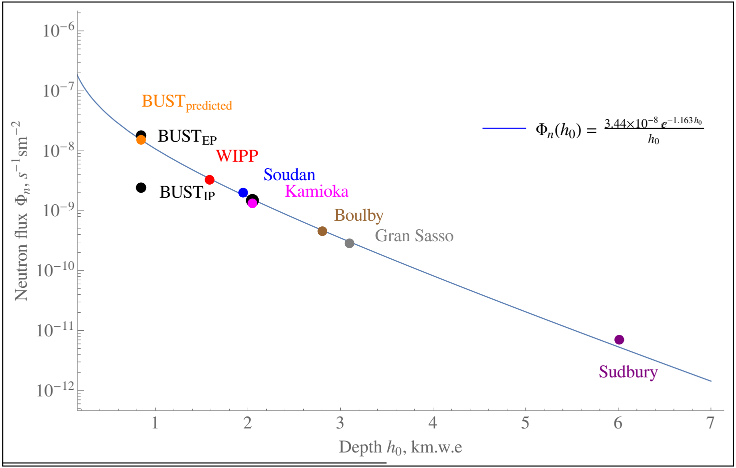
Total neutron flux

group of counters	bkg	^{12}B	n, 10^{29}	Binary, 10^{-9} $cm^{-2}s^{-1}$	ENDF, $10^{-9}cm^{-2}s^{-1}$	Bin/Ber, $10^{-9}cm^{-2}$
external	323	5805	3.73	28.2	10.3	21.5
internal	41	796	4.61	3.2	1.2	2.4

in conclusion...

The total muon-induced neutron flux for the various underground sites (FLUKA based)*:

$$\Phi_n(h_0) = P_0 \times (P_1/h_0) \times e^{-h_0/P_1}$$



*D-M. Mei and A. HimePhys. Rev. D73, 053004 (2006)