Nuclear Instruments and Methods in Physics Research A 777 (2015) 1–5

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Measurements and simulations of the cosmic-ray-induced neutron background

M.F. Becchetti, M. Flaska, S.D. Clarke, S.A. Pozzi

Department of Nuclear Engineering and Radiological Sciences, University of Michigan, Ann Arbor, MI 48109, USA

ARTICLE INFO

Article history:
Received 21 February 2014
Received in revised form
23 August 2014
Accepted 30 October 2014
Available online 18 November 2014

Keywords:
Neutron background
Liquid organic scintillator
Neutron-scatter camera
CRY
Angular distribution

ABSTRACT

The cosmic-ray-induced neutron background at ground level has been measured and simulated in conjunction with EJ-309 organic liquid scintillators with an approximate deposited energy range of 0.5–6 MeV. Specifically, the pulse height distributions, net neutron count rates, and angular dependences were obtained. The simulations were carried out using the Monte Carlo transport code MCNPX-PoliMi combined with the (Cosmic-Ray Shower Generator) CRY source subroutine that returns secondary particles produced by cosmic rays. A scaling formula from literature was also implemented in the simulation. The angular dependence of the neutron count rate was measured by collimating the liquid scintillator with polyethylene to attain 18° angular resolution from 0° downwards to 72° horizontally. The neutron count rate was measured to be $23.10 \pm 1.69\ h^{-1}\ sr^{-1}$ at 0°, and $7.20 \pm 0.78\ h^{-1}\ sr^{-1}$ at 72°. The simulations and measurements compare well and show similar cosine anisotropy for the angular distribution. The study thus shows that the neutron background response in detector systems can be efficiently and accurately simulated using the procedures described.

1. Introduction

The uncertainty in detecting and locating a weak or distant radioactive source is strongly dependent on the background levels of the radiations being detected. For example, false alarm rates and accuracy of source identification are a function of the background. Thus, accurate modeling of the background is beneficial for simulating and optimizing the real-world performance of a detection system. Liquid scintillators have recently found use in neutron-scatter cameras [1–3]. These systems make use of the angular distribution of neutrons to generate images with the goal of accurately locating radioactive sources, and hence it is important to include an appropriate model of the neutron background that accounts for the angular dependence of the neutron background. This work presents a more detailed explanation of the simulation process used in previous results [4], and updates preliminary results previously reported with sufficient statistics [5].

1.1. Origin of the neutron background

The neutron background arises primarily from radiation of cosmic origin, with negligible contributions from radioisotopes in the local environment. The three naturally occurring terrestrial radioisotopes that emit neutrons (via spontaneous fission) are ^{238}U, ^{235}U, and ^{232}Th. Neutrons are also produced from (α,n) reactions. However, these contributions to the neutron background are negligible due to low rates and natural abundances.

The cosmic-ray-induced neutrons observable on the ground are produced through spallation reactions on primarily nitrogen, oxygen, and argon nuclei in air from high-energy particles consisting of approximately 89% protons, 10% helium ions, and 1% heavier nuclei, with energies up to approximately 1000 GeV [6]. This so-called "primary flux" originates from outside the solar system. There are other types of particles besides neutrons that produce signals in organic liquid scintillators, but especially gamma-rays and muons are of importance because they have a significant fluence. An example of the neutron background energy spectrum at sea level from the MCNPX simulations is shown in Fig. 1.

1.2. Neutron-background dependences

The main parameters affecting the neutron background are the altitude, geomagnetic latitude and longitude, and time. The rate of spallation reactions on air nuclei varies with altitude, as does the attenuation of the neutrons as they propagate towards Earth, with the maximum population of neutrons just above airplane cruising altitudes at 15 km [7]. Ions are deflected by Earth's magnetic field, the degree of which depends on the momentum per unit charge of the ions (magnetic rigidity), and the strength of the geomagnetic field, which depends strongly on latitude and less so on longitude.

http://dx.doi.org/10.1016/j.nima.2014.10.077
0168-9002/© 2014 Elsevier B.V. All rights reserved.

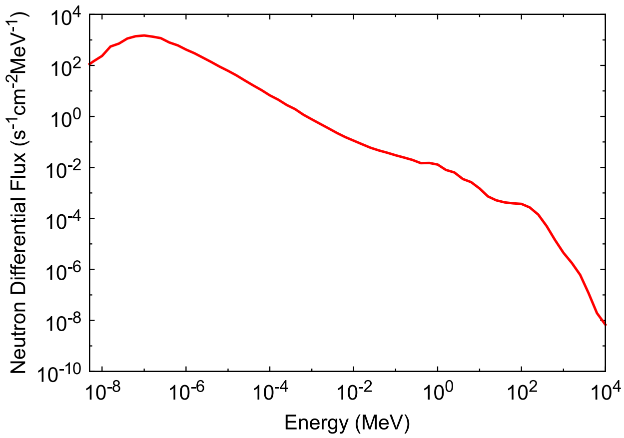

Fig. 1. The neutron background spectrum from cosmic-rays at the Earth's surface at an altitude of 256 m, at coordinates 42°N 83°W (Ann Arbor, Michigan, USA), with no ground scatter, produced from an MCNPX simulation. The distinguishing features are a hump at 100 MeV and 1.5 MeV from nuclear evaporation, a slowing down region, and a thermal peak.

This deflection effectively filters out ions of lower energy from reaching the Earth's atmosphere. The Sun modulates the heliospheric and geomagnetic fields [8]. This activity has been shown to vary with a period of approximately 11 years [9], and is often quantified by the number of sunspots observed on the photosphere of the Sun. Land-based neutron monitors show a change in neutron flux inversely correlated with the Sun's activity.

2. Simulations

Simulations of the neutron background were done using Monte Carlo codes. To account for the dependences described in Section 1.2, simulations usually begin by tracking primary particles at very high altitudes (above 30 km). However, this is too computationally intensive for the multiple simulation runs that optimization and testing of detector systems requires. To avoid this problem a source subroutine was implemented that produces secondary particles, such as neutrons, directly.

2.1. MCNPX-PoliMi and Cosmic-Ray Shower Generator source subroutine

The general-purpose Monte Carlo transport code MCNPX-PoliMi [10] was compiled with the Cosmic-Ray Shower Generator (CRY) source subroutine from LLNL [11] that generates time-correlated cosmic-ray-induced neutrons, as well as other secondary particles, and accounts for altitude, geomagnetic latitude, and the 11-year solar cycle. The neutrons returned by CRY were generated in MCNPX by simulating cosmic primary particles, assumed to be entirely protons, incident on the Earth's atmosphere at an altitude of 33 km, and tracking the resulting cascades through the atmosphere towards Earth's surface. Similar simulations had been done in the past and were shown to be relatively accurate [12]. Using the CRY source subroutine avoids the need to run large simulations starting with primary particles and allows charged-particle tracking to be disabled, thereby decreasing computation time. MCNPX-PoliMi was chosen for its ability to track individual interactions in cells of interest, which is necessary to accurately obtain neutron pulse height distributions (PHDs). The specialized MPPost post-processor then calculates the light output due to neutron scattering interactions in the detector cell(s) [13]. Modifications were made to the post-processor to include high-energy neutron reactions on carbon using additional light-output coefficients for ^{4}He nuclei and deuterons [14].

2.2. Scaling formula

While CRY can generate time-correlated neutrons (such that the rates can be attained), it relies on a simple dipole model of the Earth's magnetic field and ignores contributions from helium ions. Therefore, the simulated tally units were converted into rates by using a scaling formula developed by Gordon et al. [15]. The scaling formula implements vertical geomagnetic cutoff rigidities calculated by Shea and Smart [16] using the International Geomagnetic Reference Field. Vertical geomagnetic cutoff rigidity is the quantity that describes the level of shielding the geomagnetic field provides against vertically incident charged particles. The scaling factor obtained is then multiplied by the provided reference rate to get the expected total neutron rate. The simulated spectrum is then scaled accordingly. To summarize, the spectral shape and the angular dependence of the neutron background in EJ-309 is generated using MCNPX and CRY, and the neutron count rates themselves are calculated by scaling the neutron flux measurement of Gordon et al. to the experiment using their formulas for the dependence on altitude, geomagnetic location, and solar activity.

The two principal cosmic-ray ions responsible for the neutron background are protons and helium ions. The latter are not included in the CRY source subroutine. However, because the scaling formula is derived from measurements, it includes contributions from all primary cosmic-rays. To use the scaled total neutron rates with the MCNPX simulations, it was necessary to ensure that primary cosmic helium ions do not change the shape of the induced neutron spectrum. The neutron background was simulated in MCNPX using primary protons and primary helium ions separately at 33 km vertically incident on the Earth's atmosphere using their known spectra [6], and tracked to the ground level. The spectral shape is similar in both cases, as shown in Fig. 2. This is expected because the energy of the primary helium ions is high enough that their nucleons interact individually [7]. Likewise, the angular distribution of spallation neutrons was found to be similar.

The source parameters specified in the CRY subroutine were adjusted to match the experiment (in Ann Arbor, Michigan, USA), with a latitude and longitude of 42°N and 83°W respectively, and the date was set to October 2012 which corresponds to a relative solar activity of approximately 25% of the maximum. A 5-m layer of soil composed primarily of silica was used in the model. Because

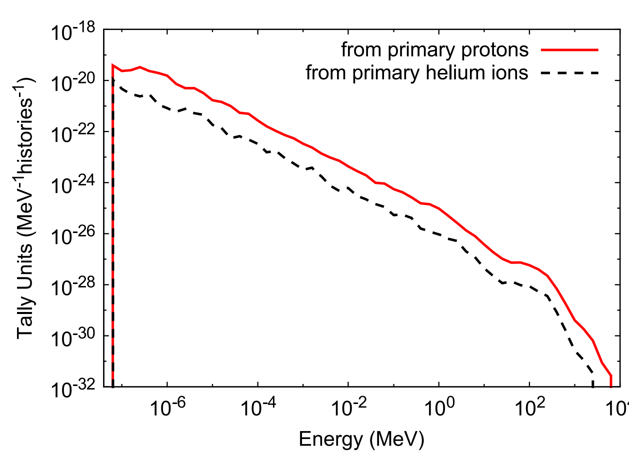

Fig. 2. Simulated neutron background separately from primary protons and helium ions, demonstrating that the spectral shapes are similar. The 1.5 and 100 MeV peaks are visible as in Fig. 1. Uncertainties were below 10%.