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Cosmic-ray-induced ship-effect neutron measurements and implications for cargo scanning at borders

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Abstract

Neutron measurements are used as part of the interdiction process for illicit nuclear materials at border crossings. Even though the natural neutron background is small, its variation can impact the sensitivity of detection systems. The natural background of neutrons that is observed in monitoring instruments arises almost entirely from cosmic-ray-induced cascades in the atmosphere and the surrounding environment. One significant source of variation in the observed neutron background is produced by the "ship effect" in large quantities of cargo that transit past detection instruments. This paper reports on results from measurements with typical monitoring equipment of ship effect neutrons in various materials. One new result is the "neutron shadow shielding" effect seen with some low neutron density materials.

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1. Objectives

Quantifying the background effects of cosmic radiation is usually a task associated with high-precision measurements in basic nuclear and particle physics research. However, cosmic rays can also affect relatively simple, low-count detector applications, such as the passive neutron screening performed by radiation portal monitoring (RPM) systems deployed over the last several years at international border crossings [1–3]. The neutron background seen in these detection systems is a fairly constant, low rate of events (with some diurnal variation [4]), and occasional, fraction-of-a-second, spikes [5]. These apparently anomalous spikes are the subjects of this paper, where evidence is presented to show that they can be largely attributed to the "ship effect" due to cosmic ray interactions in the surrounding vehicles and environment.

The intent of this study is to gain a better understanding of the magnitude of the observed signal in standard RPM instruments from cosmic-ray-produced neutron backgrounds, and to evaluate methods for better distinguishing these neutron backgrounds from signals of interest. In particular, if the impact of ship effect neutrons can be reduced through data algorithms, the sensitivity of deployed detection systems would be improved. To this end, several aspects of neutron detection and the ship effect have been investigated. A model was produced for the neutron detection system utilized in this study, and it was validated with experimental measurements. A study was undertaken to determine the size of the ship effect from several materials. An examination was also made of the temporal distribution of the neutron background and ship effect neutrons to determine if such information could be used to reduce ship effect produced backgrounds.

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2. Cosmic radiation at Earth

Cosmic radiation incident upon the upper atmosphere consists primarily of charged particles with energies typically above 300 MeV. Primary cosmic particles are about 85% protons, 13% alpha particles, and the remainder other charged particles with masses up to Fe nuclei being common, traces of heavier element nuclei, and about 0.1% gamma radiation [6–8]. Upon arrival at the Earth's atmosphere, the primary cosmic rays undergo nuclear interactions during collisions with atmospheric nuclei to produce secondary particles, which in turn produce further cascades. Five main factors affect the number of secondary particles reaching the surface of the Earth: latitude, the Earth's weather, solar activity, diurnal cycle, and barometric pressure (including altitude effects). Since primary and secondary particles interact with the atmosphere, longer paths through the atmosphere reduce the flux reaching the ground, resulting in lower background radiation levels at greater atmospheric depths. Cosmic radiation, and its secondary products, is thus highly dependent on elevation, with higher backgrounds at higher elevations.

The cosmic-ray-induced neutron flux at ground level results from a series of interactions starting in the upper atmosphere. Most of these "background" neutrons (at sea level at an atmospheric depth of 1033 g/cm^2) are produced by secondary neutrons, including multiplication through further collisions, and with a small contribution from mesons [9,10]. As discussed in these and other references, muons also produce neutron spallation events, but the neutron spectrum and attenuation characteristics observed, as well as modeling results, indicate that it is the secondary neutrons that dominate the production of the observed neutron flux.[1] The basic shape of the energy distribution of these background neutrons is largely independent of depth in the atmosphere that evolves in a predictable manner as a function of depth [11]. As discussed next, a reasonable value for this background neutron flux at ground level is ~120 n/(s m^2). Note that this is comparable to the average background flux of muons, which are the most abundant cosmic-ray-induced secondary *charged* particles reaching sea level with an average flux being about 170 muons/(s m^2) out of a total of 240 charged particles/(s m^2) [12,13].

Many researchers have measured the neutron flux near sea level, and they report a range of values. Yamashita et al. [14] report a value of about 72 n/(s m^2) near the surface from calculations and 40 n/(s m^2) from measurements. Lindstrom et al. [15] report the fast neutron background arising from cosmic rays at sea level is about 200 n/(s m^2). Sheu et al. [16] report a total flux at sea level of about 51 and 29 n/(s m^2) near the surface of water. O'Brien et al. [9] give about 64 n/(s m^2) near the air–ground interface, 31 n/(s m^2) near the surface of water, 210 n/(s m^2) near an air–aluminum interface, and 770 n/(s m^2) near an air–iron interface. Gordon et al. [17] report about 134 n/(s m^2) at Yorktown Heights (altitude of 167 m), which results in about 120 n/(s m^2) at sea level, while Goldhagen [18] gives about 122 n/(s m^2), and Wiegel et al. [19] state about 125 n/(s m^2). The differences in these values may be explained because the measurements were made in different locations near different materials and with different instruments. A value of about 120 n/(s m^2) appears to be a reasonably current value to assume at sea level.

The neutron background around 1 MeV has a large contribution due to the nuclear evaporation process, while higher energy neutrons arise from various direct reactions, including a knock-on bump between 10 and 100 MeV [6]. Recent modeling of the cosmic ray flux at sea level has been performed that shows these spectral features [20]. Neutrons are moderated by collisions in the atmosphere and eventually, collisions with the ground that reflect neutrons back and contribute to the low-energy flux near the surface. Many moderated neutrons are absorbed by nitrogen in the atmosphere, while others comprise the lower energy part of the observed neutron spectrum. All of these many effects of production, scattering, and moderation combine to produce the measured neutron spectrum.

Hess et al. [6] give the differential flux of neutrons at the Earth's surface as a function of energy (E) as proportional to E^{-1} below 0.1 MeV and proportional to $E^{-1.4}$ above 1 MeV. Other authors similarly report the neutron spectrum as having a shape depending upon E^{-n}, where n is 1.25 [21], 1.74 [22], 1.16 [23], or 1.24 [24], for the 1–10 MeV part of the energy range. Roesler et al. [25] state that a function proportional to $E^{-0.92}$ is a reasonable fit to the data from 1 eV to 1 GeV. Gordon et al. [26] give a more complex functional fit to the neutron spectrum above 0.1 MeV. As shown in Fig. 1, a reasonable approximation of the experimental data shown for the differential flux from 1 eV to 1 GeV (in n/(s cm^2 GeV^1) is the function 0.001 E^{-1}, where E is in GeV, though it overestimates the higher energy part of the spectrum. For the purpose of the simulation work reported here, this functional form is adequate. The figure shows this function as a solid line compared to two sets of experimental data from Refs. [6,26]. The experimental data show the presence of broad bumps in the thermal region, in the region around 1 MeV, and around 100 MeV. The thermal bump is associated with thermalization of higher energy neutrons by the ground or other matter. The 1 MeV bump, which is present at all altitudes, originates from nuclear knock-on and spallation, while the bump around 100 MeV arises from energetic reactions in the atmosphere and diminishes with decreasing altitude. The log–log plot of Fig. 1 does not show the significance of these features, which contain the majority of the neutron flux of interest here. Fig. 2 depicts these three features by showing a plot of energy times the differential flux at an altitude of 167 m (data extracted from Ref. [26]).

[1] There seems to have been a long-standing belief by some that muons are responsible for the ship effect, but this does not appear to be consistent with more recent results [12,13].