PROCEEDINGS OF SCIENCE

Monte Carlo Simulation of the Neutron Monitor and Position-Dependent Bare Neutron Counter Yield Functions at Mawson Station, Antarctica

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Neutron monitors (NMs) are ground-based detectors that are widely used to detect secondary particles produced by the collisions of primary cosmic rays (CRs) and air molecules in the Earth's atmosphere. Bare neutron counters (BCs), operated without the lead producer and polyethylene reflector, are more sensitive to CRs of lower energy. Thus the ratio of BC to NM enhancements has proven useful for determining the spectral index of relativistic solar particles during ground level enhancements. Recently, a unique array of 6 BCs has been installed along with the 18-counter NM at the Cosmic Ray Laboratory at Mawson Station, Antarctica. The BCs are placed at different locations relative to the laboratory wall and the NM, allowing measurements of the effect of the surrounding environment on the BC response and validation of Monte Carlo (MC) simulation techniques. We use the FLUKA software to simulate atmospheric CR interactions above the station and investigate the NM and position-dependent BC yield functions at Mawson. The results show that secondary neutrons interacting in the environment over 1 kilometer away can affect the BC yield function. The results will provide a better understanding of the yield functions, their position dependence, and the use of the BC to NM ratios to determine the spectral index of relativistic solar particles.

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1. Introduction

Neutron monitors (NMs) are utilized worldwide as ground-based detectors of secondary particles produced by collisions of primary cosmic rays (CRs), which mostly are high-energy protons and alpha particles from space, and air molecules in the Earth's atmosphere. Components of the standard NM64 design [1] include the lead producer, in which secondary CRs interact to produce low-energy neutrons, and outer polyethylene reflector, which reflects such neutrons back to the neutron-sensitive proportional counters. The moderator, also made of polyethylene, helps reduce the energy of neutrons to enhance detection in the proportional counters. Bare counters (BCs) which are fitted in polyethylene moderator without lead producer are suitable for low energy neutron detections [2, 3]. Each proportional counter tube is filled with BF_3 gas enriched to $\sim 95\%$ ^{10}B, which absorbs low-energy neutrons by the induced nuclear fission reaction $n + {}^{10}\mathrm{B} \longrightarrow {}^{4}\mathrm{He} + {}^{7}\mathrm{Li}$ and the characteristic signal due to ionization of the gas by the reaction products.

The Mawson Neutron Monitor is located at -67.60° S in latitude and 62.88° E in longitude in Mawson Station, Antarctica. It is one of the stations installed in a polar region where Earth's magnetic field does not block access the relevant CRs. To be specific, the geomagnetic cutoff rigidity (momentum per charge) is about 0.2 GV, and the detection threshold is instead determined by an atmospheric cutoff of ~ 1 GeV nucleon^{-1}. This detector continuously monitors the flux of Galactic CRs, and is also sensitive to occasional bursts solar energetic particles (SEPs), which have a very much higher flux at low rigidity. In 2020, the firmware (microcontroller code) in the electronics of counters was upgraded to the 800 series for measuring time delays between successive neutrons [4]. In addition, six BCs were installed, and their positions were swapped twice for investigating counter efficiency and effects of the counter position and environment on the count rates. Now, the BC/NM count rate ratio at this station could be used to indicate the SEP spectral index [5–7], which is a key motivation for this study. To interpret such measurements, it is important to know the yield function or energy-dependent effective area of BCs and the NM since they depend on the location, altitude, and environment of the detectors.

2. Monte Carlo Simulation

We used the FLUKA 2022 version 4.3.2 software [8, 9] for Monte Carlo simulations of particle transport and interactions with in matter for different particles such as neutrons, protons, muons, etc. We divide our simulations into 3 steps as follows [10–12]:

2.1 Air shower development

We simulate the air shower profiles by simulating the collisions of primary CRs and the air molecules using Monte Carlo simulation. We applied the 3D spherical model and the Global Data Assimilation System database (GDAS), which includes moist air at low altitude and the Naval Research Laboratory Mass Spectrometer, Incoherent Scatter Radar Extended model (NRLMSISE-00), which provided profiles of temperature, density, and pressure of the air at each altitude for this step of the analysis [13–16]. The boundary of this simulation is a sphere surrounding the Earth. In this work, we created a library of secondary particles by interactions of primary protons and alpha particles with spectral index equal to 1 in the atmosphere [11]. The results provided the products

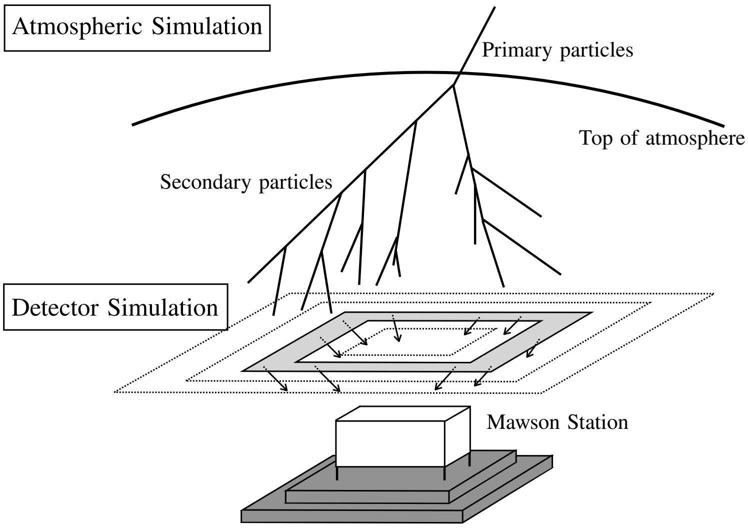

Figure 1: Schematic of Monte Carlo simulation for Mawson Station, Antarctica.

of secondary CRs (especially neutrons, protons, and muons) at the low cutoff rigidity, altitude, and atmospheric profile of Mawson Station.

2.2 Detector simulation

We designed the simulation geometry of neutron detectors and the surrounding environment at Mawson Station. Dimensions of the building are 20 meters in length by 10 meters in width and 3 meters in height. It is covered by expanded polystyrene (EPS) walls, floor, and roof. The construction is located on solid rock about 30 meters above sea level. There are 18 NM counters and 6 BCs set up inside the building. The NM is divided into 3 sections with 6 counter tubes per section as shown in Figure 2. Each section is placed on steel plate form laid on concrete poles at different heights above the floor of the building. Four BCs are placed on the floor parallel to the NM counters, and two others are placed perpendicular to the other tubes.

The entire building is raised on stilts above the underlying rock, in order to avoid snow accumulation against the walls. In summer, the wind keeps this region clear. Under and around the building, the geometry comprises granite rocks up to varying heights, to realistically characterize the topography based on photographs from various angles. The deepest part is under the center of station, with an air gap of about 1.5 m, while at the sides it ranges from 0.45 to 1.0 m. The geometry also includes the wooden slabs and aluminum rods that support the weight of the station. Three sets of Geiger counter muon telescopes are also included. The outputs from independent detector simulations can reveal the sensitivity of the NM and each BC to the surroundings.

2.3 Count rate estimation

We combined outputs from 2.1 and 2.2 to estimate the yield functions, i.e., geometry factors as a function of primary CR rigidity.

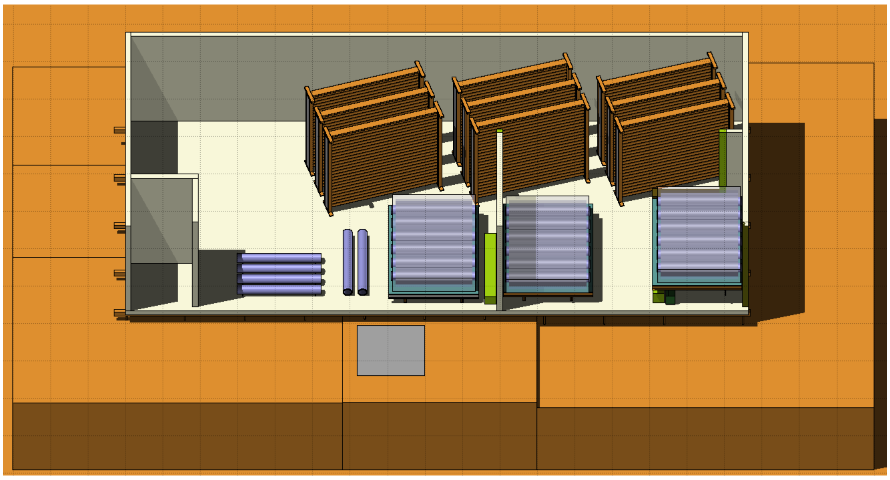

Figure 2: Geometry of neutron detectors at Mawson Station, Antarctica and their surroundings.

3. Results

3.1 Air shower flux

Atmospheric CRs fluxes of particles as a function of kinetic energy at latitude, longitude, and altitude of the detector are shown in Figure 3. The p, n, μ^+, μ^-, π^+, π^-, e^+, e^-, and γ are produced by collisions of Galactic CR protons and alphas at the top of the atmosphere. The MC cuts to remove e^+, e^-, and γ below $\sim$ 7 MeV are clearly visible. Gammas are the most abundant particles arriving at Mawson Station, followed by n, μ^+, and μ^-. Then e^+, e^-, and p have lower fluxes, and π^+ and π^- fluxes are about 3 orders of magnitude lower.

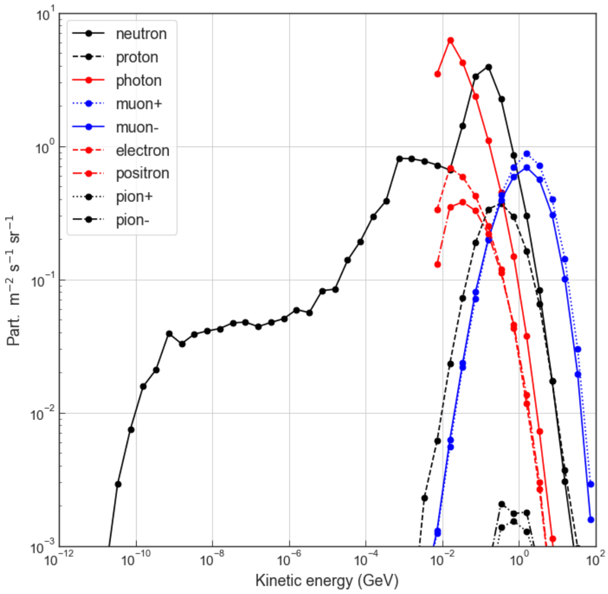

Figure 3: Fluxes of atmospheric secondaries as a function of kinetic energy at Mawson Station.

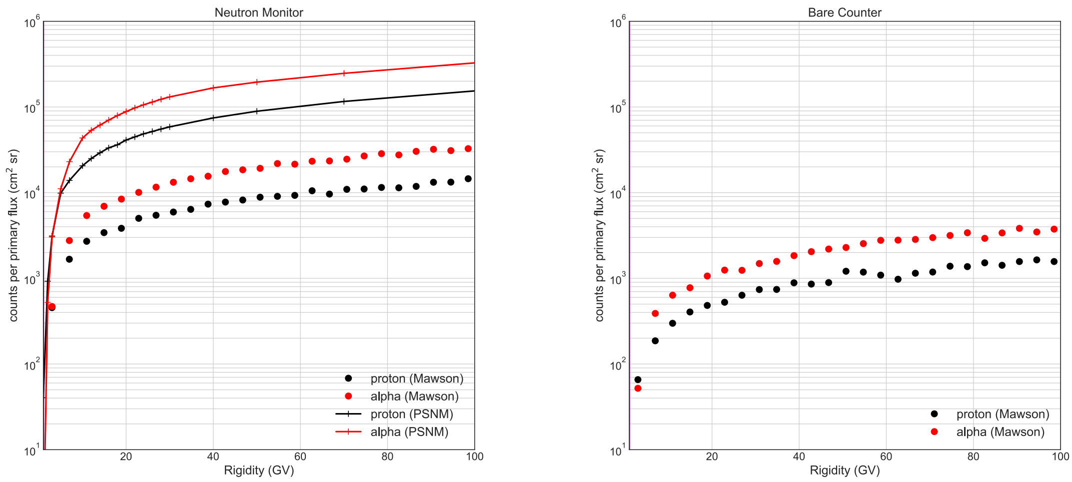

Figure 4: Yield functions (counts per primary flux) of NM (left) and BCs (right). The solid lines are for PSNM in Thailand, at altitude 2560 m, and dots are for the Mawson. NM and BCs in Antarctica, at altitude 30 m. Note that geomagnetic cutoffs are not implemented for this figure.

3.2 Yield Function

We applied the air shower profile as an input in this step, but the detector simulation is performed separately. Since the muon detectors are mainly composed of metals, they are taken into account for this simulation. The detectors recorded counts due atmospheric secondaries that either entered directly or scattered from any surrounding materials. The random direction beam was centered over the building at height 8 meters above the ground with a rectangular area of 20 x 10 m^2. The yield function (count per primary particle flux) of detectors at Mawson station as a function of rigidity (in GV) is represented in Figure 4. The solid lines are for the Princess Sirindhorn Neutron Monitor (PSNM), at 2560 m altitude at Doi Inthanon, Thailand, the station with the world's highest cutoff rigidity, ~ 16.8 GV [4, 17], from primary protons (black) and alphas (red), without implementing the geomagnetic cutoff. It is clearly seen that the yield functions of BCs and NM at Mawson Station lower than those, due to the altitude different between these two stations. The values for the Mawson NM are higher than for BCs by about one order of magnitude.

3.3 Position dependence

The simulations were performed for three types of secondary particles (neutrons, protons, and muons) in the atmosphere above Mawson Station at varying distance from the detectors. We created nested square rings as source regions of secondary particles with random kinetic energies and random directions from the air shower simulation at the level of 8 meters from the ground. Each square ring is centered at the center of the building. Only some secondary particles will interact and lead to counts in the NM and 6 BCs (Figure 5).

We consider the relationship between the cumulative counts and distance of secondary particles, which defined as a center of inner square and outer square, starting the accumulation from a large distance. In the BCs, 11 % of the counts due to secondary neutrons are due to neutrons beyond 100

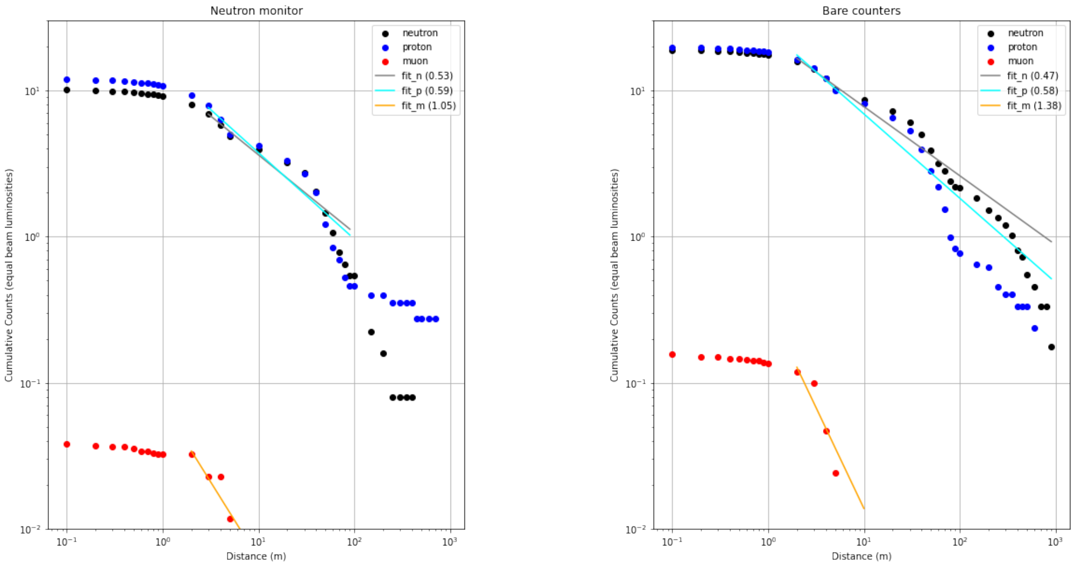

Figure 5: Cumulative counts from multiplying counts in proportion to the area of each ring due to atmospheric secondary particles in the Mawson NM (left) and 6 BCs (right) as a function of distance from the building, starting from a large distance.

m and 3 % are from neutrons beyond 500 m. For comparison, in the NM, 5 % of the counts due to secondary neutrons are due to neutrons beyond 100 m and no neutrons beyond 500 m. We can summarize that the BCs are more sensitive to the distant environment than the NM. Moreover, the slope from the log-log plot of cumulative counts vs. distance are roughly -0.5 either for neutrons or protons yielding counts in either the NM or BCs.

4. Acknowledgements

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