PROCEEDINGS OF SCIENCE

A Simulation Study of the Response of the Princess Sirindhorn Neutron Monitor and Bare Counters to Solar Neutrons

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The Sun can occasionally accelerate particles to become solar energetic particles, some of which may collide with the Earth's atmosphere and produce secondary air showers that ground-based neutron monitors can detect. This work investigates the Princess Sirindhorn Neutron Monitor (PSNM) response to solar neutrons originating from solar activity, such as solar flares and coronal mass ejections. The PSNM, located at an altitude of 2560 m near the equator with a high geomagnetic cutoff rigidity of 16.7 GV, is particularly suited for this study, as it can potentially detect lower energy (sub-GeV) solar neutrons against a background of higher energy charged cosmic rays because neutrons are not affected by the geomagnetic field. Furthermore, since the start of operations in 2007, PSNM has deployed bare counters without surrounding lead or polyethylene. These bare counters are more sensitive to low-energy atmospheric neutrons and may be used to distinguish showers from solar neutrons versus those from Galactic cosmic-ray ions. This research employs Monte Carlo simulations to model the interactions of solar neutrons with the Earth's atmosphere and the response of PSNM to solar neutrons. We simulate neutron showers across a range of energies at different zenith angles. This study provides useful insights into the capabilities of neutron monitors, together with bare counters, for solar physics research and contributes to advancing our understanding of solar neutron detection.

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1. Introduction

The Sun is a dynamic star that occasionally undergoes explosive events, such as solar flares and coronal mass ejections. During these events, particles can be accelerated to high energies, forming solar energetic particles [1]. These energetic particles, consisting primarily of charged particles, are ejected into interplanetary space. Solar neutrons, in particular, are produced through nuclear interactions in the solar atmosphere, predominantly via proton-proton collisions in the photosphere, resulting in a broad energy spectrum ranging from a few MeV to several GeV [2, 3]. Lower energy neutrons produced in the photosphere are captured by protons, emitting detectable gamma rays (2.223 MeV) observed by spacecraft, whereas moderate energy neutrons escaping the solar atmosphere undergo beta decay into detectable protons and electrons; consequently, only relativistic solar neutrons of high energy can survive the $\approx$880 s mean lifetime of free neutrons to traverse the 1 AU distance to Earth, initiating atmospheric showers detectable by ground-based neutron monitors (NMs). Numerous solar neutron events have been recorded since the first detection in 1982 [4–7].

The detection efficiency of solar neutrons by ground-based NMs is strongly influenced by factors such as atmospheric depth, the geographical location of the NM station, the relative geometry between Earth and the Sun, and the angular distribution of the incoming neutrons [2, 8]. Previous studies have indicated that NMs located at high altitudes and lower latitudes are particularly well suited to detect solar neutrons [2]. The Princess Sirindhorn Neutron Monitor (PSNM), located near the equator at an altitude of 2560 m with a high geomagnetic cutoff rigidity (momentum per charge of a particle) of 16.7 GV, stands out as a potentially suitable station for such observations. Its equatorial location and high cutoff rigidity offer the advantage for potentially detecting sub-GeV solar neutrons, which are unaffected by the Earth's magnetic field, against the background of higher-energy charged cosmic rays.

This study focuses on investigating the response of the PSNM to primary neutrons using computer simulations. A unique feature of the PSNM is its 3 bare counters (BCs) along with 18 standard NMs (18NM64) [9], which have been operational for nearly 100% of the time since 2007. Unlike the NM64 design, BCs do not have the surrounding lead producer and polyethylene moderator. The BCs typically exhibit an enhanced sensitivity to lower-energy primary cosmic rays compared to that of NMs. Therefore, we expect a higher ratio of the count rate from BC to that of NM (BC/NM) for showers from lower-energy particles, such as solar neutrons, as compared to the BC/NM ratio from showers of higher-energy charged particles at PSNM. To better understand the response of NM and BC at PSNM, we performed Monte Carlo simulations of neutron showers with energies ranging from 0.1 to 10 GeV, arriving with zenith angles from 0° to 75°. This study provides valuable insights into the capabilities of NM stations that are equipped with BCs to advance solar physics research.

2. Methodology

This research employed a two-stage Monte Carlo simulation approach using the FLUKA4-4.0 software package [10] to investigate the interaction of solar neutron with the Earth's atmosphere and their subsequent detection at ground level.

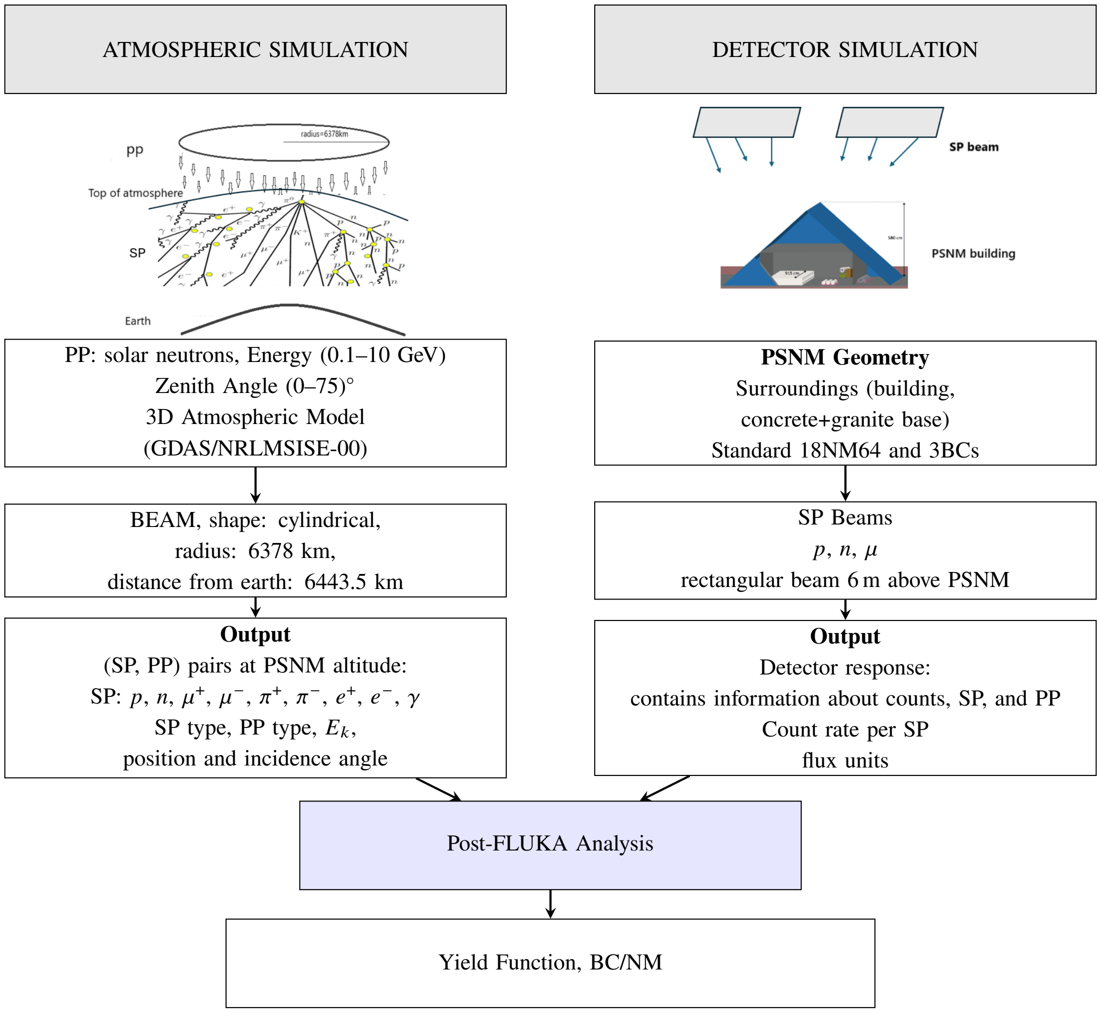

Figure 1: Methodology of Monte Carlo simulation for the Princess Sirindhorn Neutron Monitor (PSNM), in Thailand, using 3 steps: modeling of atmospheric showers, detector simulations, and post-FLUKA analysis. Here, PP and SP stand for primary and secondary particles, respectively.

The first stage involved detailed atmospheric simulations to model the cascade initiated by solar neutrons with energies ranging from 0.1 to 10 GeV. We use the cylindrical-shaped beam of neutrons distributed uniformly across the cross-sectional area of the beam with a 6378-km radius. This mimics the case of particles arriving from a random sky direction. To accurately represent the atmospheric conditions at the PSNM station (latitude: 18.59°N, longitude: 98.48°E, altitude: 2565 m), a 3D spherical atmospheric model was constructed by linearly interpolating data from the GDAS (Global Data Assimilation Database)[1] for altitudes up to 26 km and the NRLMSISE-00 (Naval Research Laboratory Mass Spectrometer, Incoherent Scatter Radar Extended Model) [11] for altitudes from 26 km to 72.5 km. For the beam of primary particles, 10^5 neutrons for each of 15 discrete energy values (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 2.0, 4.0, 6.0, 8.0, 10.0 GeV) are simulated to interact with our Earth's atmospheric model (see the top left illustration in Figure 1). The output of this stage comprised pairs of primary and secondary particles (PP, SP) at the PSNM

[1] http://ready.arl.noaa.gov/gdas1.php

altitude, including all the relevant information of PP and SP, such as the zenith angle of PP. This allows us to separate the PP into five zenith angle bins from 0° to 75°.

The second stage was to observe the response of NM and BC at PSNM to the resulting SP fluxes from the atmospheric simulations in the previous stage by generating a ≈1300 m^2 rectangular beam (which can be extended to ≈1700 m^2 depending on the position and incident angle) of SPs at the top of the PSNM model (as illustrated at the top right of Figure 1). We simulated only 3 types of SP (neutrons, protons, and muons) because they contribute to more than ≈97% of the NM count rate [12]. A total of 225 simulations have been performed to study the detector's response. The detailed geometry of the 18NM64, including its surrounding building, concrete base, and three BCs at PSNM, was carefully modeled as described in [13]. Simulations were performed for a large number of input particles $\sim 10^6$ for each SP type, energy level, and zenith angle range. For each simulation, we get the counts separately for the BC and NM. Subsequent post-FLUKA analysis was performed to derive the yield (Y) of BC and NM as a function of primary neutron kinetic energy (E_k) and zenith angle (θ_z) as

$$Y(E_k, \theta_z) = \frac{C}{L(E_k, \theta_z)}, \tag{1}$$

where C is the number of counts detected by BC or NM and L is the beam luminosity defined as the number of PP per cross-sectional area [14].

3. Simulation Results and Discussion

This section presents the key findings from our two-stage Monte Carlo simulations regarding the response of the PSNM and BC to solar neutrons across a ranges of energies and zenith angles. We present the derived yield function and BC/NM, and discuss their implications for solar neutron detection and discrimination.

3.1 Yield Function

The key results from our simulations are the NM and BC yield functions calculated from Equation 1. Figure 2 shows the simulated yield for 18NM and 3BC at PSNM as a function of primary neutron kinetic energy (E_k) for different θ_z ranges. We also compare our NM yield to the results from [8] for similar θ_z.

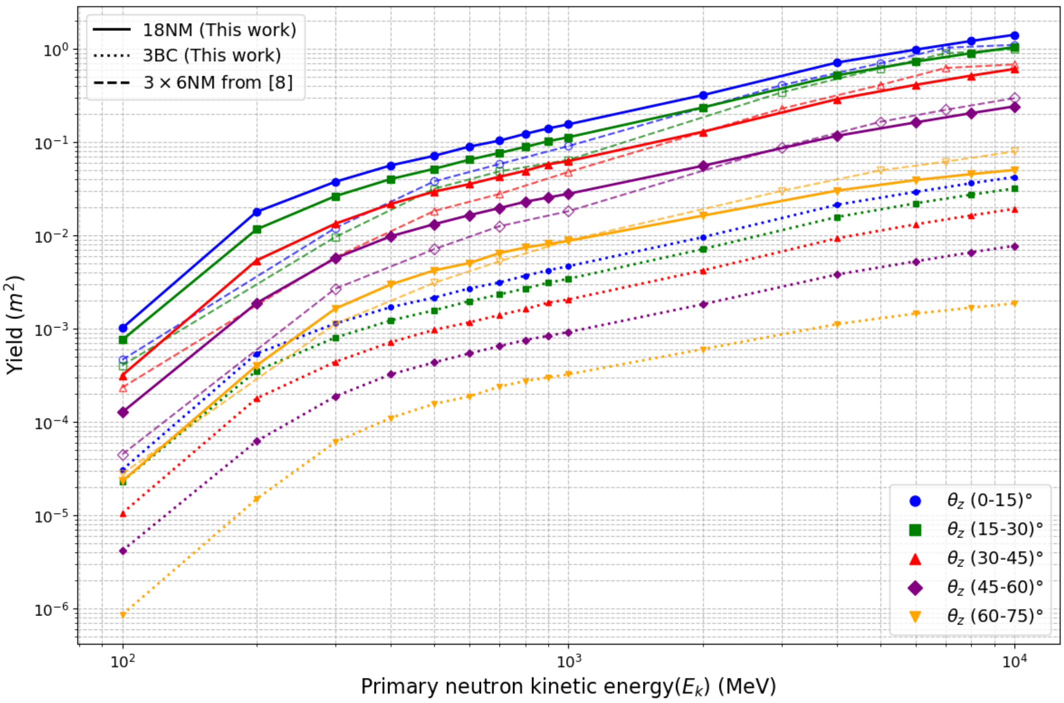

Figure 2: Simulated yield functions of the 18-counter neutron monitor (18NM) and 3 bare counters (3BC) at PSNM for different solar neutron energies E_k and solar zenith angles θ_z. Our simulated NM yield functions are compared with calculations from [8].

Previous studies and empirical observations suggest that one NM should provide a count rate that is approximately a factor of six of that for one BC at PSNM [15]. Our simulated results shown in Figure 2 for 18NM and 3BC at low zenith angles (which dominate the count rate) are roughly consistent with this expectation, indicating a factor of ∼35 for the 18NM yield compared to the 3BC yield at 10 GeV. Although our results are specifically for primary neutrons, at high energies (much greater than a proton's rest mass), we expect similar interactions with cosmic-ray protons. However, we do not clearly observe the enhanced sensitivity for BC at low energies compared to NM, as expected and reported by [16]. We will investigate this discrepancy. Our simulated NM yields at different θ_z agree reasonably well with the results from [8] without arbitrary scaling, especially at high energies. Although results from [8] are for a general NM station and not specifically for PSNM, this approximate agreement supports the validation of our simulation approach.Some differences of our results with [8] at lower energies may arise from various factors, such as the atmospheric depth (results from [8] is for 700 g/cm^2 while it is approximately 770 g/cm^2 at PSNM), atmospheric models, detector geometry, and environmental effects. Note also that the plots from [8] in Figure 2 are for specific values of zenith angle (0°, 15°, 30°, 45°, and 60°), which are the lower bounds of the zenith angle ranges for our results.

3.2 Bare Counter to Neutron Monitor Ratio

Since it is a ratio, the BC/NM is not sensitive to the change in the absolute normalization of the solar neutron spectrum, but the value should change with the spectral index and θ_z of solar neutrons.

Using a spectral model with an index of 4 (i.e., Flux $\propto E_k^{-4}$) and the yield functions obtained from our simulations, we calculated the number of counts detected by BC and NM. Figure 3 shows the ratio of (3BC/18NM) during a solar neutron event (SN) as compared to the average value of the ratio from Galactic cosmic rays (GCR) at PSNM during 2020 for different θ_z.

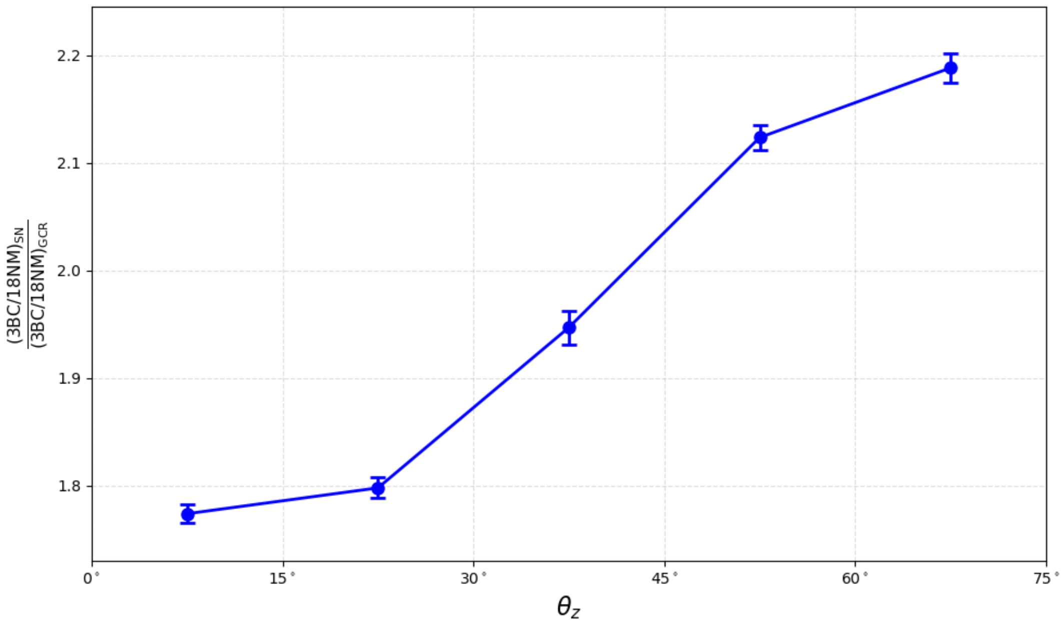

Figure 3: Simulation results of the fractional increase of (3BC/18NM) ratio at PSNM during a solar neutron (SN) event with the power-law spectral index of 4, as compared to the average value of the ratio from Galactic cosmic rays (GCR) at PSNM in 2020.

Figure 3 indicates that, for an SN event with a power-law index of 4 between 0.1 and 10 GeV, the (3BC/18NM) ratio at PSNM would change significantly as compared to the average value of $(3BC/18NM64)_{GCR}$ = 0.017 due to GCRs, and thus the $(3BC/18NM)_{SN}/(3BC/18NM)_{GCR}$ ratio is greater than 1. This is true for all θ_z of the arriving solar neutron flux, with the small error bars reflecting the high statistical precision of our simulations.

4. Conclusion

This study used Monte Carlo simulations to characterize the response of NM and BC at PSNM to solar neutrons ranging from 0.1 to 10 GeV at different θ_z. We derived the energy-dependent yield function for both the standard NM and BC, demonstrating the overall detection efficiency and validating our model against previous work. The preliminary results of our simulations revealed that the BC/NM ratio for solar neutrons is consistently higher than the observed background ratio of GCR for a solar neutron event with a power-law index of 4, for all θ_z. This indicates that we can use this ratio as a confirmation for solar neutron detection at PSNM. This is particularly useful for PSNM, given its high geomagnetic cutoff, and encourages us to search for the signal of solar neutrons in the real PSNM data using our novel (BC/NM) technique.

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