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Determination of Yield Functions of Neutron Counters at the South Pole from Monte-Carlo Simulation

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Neutron monitors (NM64) are ground-based cosmic ray detectors that measure the flux of primary cosmic rays at the GeV-energy range by counting (primarily) secondary neutrons in atmospheric cascades. They have a lead producer to generate evaporation neutrons that are moderated before being detected in a $^{10}BF_3$ or ^{3}He gas-filled proportional counter. By omitting the lead, a so-called "bare detector" responds to lower energy particles on average and can be used in coincidence with NM64 detectors to estimate the primary cosmic rays' energy spectrum. This research uses the FLUKA Monte Carlo simulation package to refine our understanding of two types of bare neutron detector and three NM64 units located inside and outside, respectively, of the Amundsen-Scott station at the South Pole. One bare design uses paraffin and wood to moderate high-energy neutrons, and another bare design has no moderator. All bares are mounted together in a single assembly. The bares and NM64 all use ^{3}He gas-filled proportional counters. In our previous work, the energy-dependent effective area (yield function) of the paraffin-moderated bares was directly determined from a ship-borne latitude survey in 2009 - 2010. The influence of the container and the environment on the ship significantly affects the measured yield function. In this work, we use simulations to relate the measured yield functions to the actual configuration at the South Pole to study spectral variations of solar energetic particles during Ground Level Enhancements.

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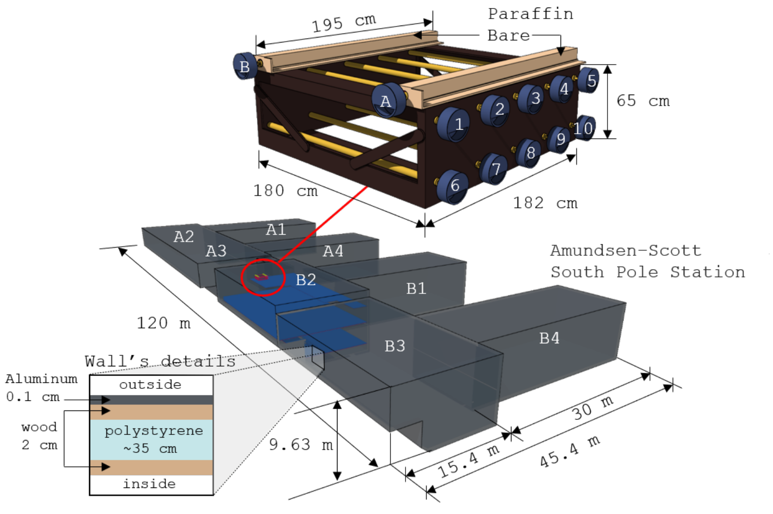
1. Introduction

Cosmic rays are highly energetic particles, mainly protons and alpha particles and electrons propagating through space, entering Earth's atmosphere. Their origins are multiple: (i) from the Solar System, mainly solar flares, (ii) from our Galaxy, possibly from supernovae remnants, and (iii) from outside the Galaxy, possibly Active Galactic Nuclei. At GeV energies, propagation of Cosmic rays in the solar system is strongly influenced by the solar-wind plasma embedded in the interplanetary magnetic field. The Earth's magnetosphere also affects propagation to the atmosphere. Thus, the "primary" cosmic ray flux entering the upper Earth's atmosphere depends on time variations of solar activity. This dependency is rigidity (momentum per charge) dependent. When primary cosmic rays arrive at Earth and collide with nuclei in the Earth's atmosphere, they produce a cascade of "secondary" particles (SPs). Some of the SPs can reach the ground and they can be observed with neutron monitors. Neutron monitors (NMs) are the premier ground-based instruments for precise measurements of the time variations of GeV-primary cosmic rays. It is crucial to know the energy-dependent effective area or yield function (YF) of the monitor, which depends on the detector type, altitude, and location. The standard design neutron monitor (NM64) was introduced in 1964 by Hatton and Carmichael [1] and is used worldwide to study the time variations of the Galactic Cosmic Rays (GCR). Bare neutron detectors, a type of lead-free neutron monitor, are more sensitive to lower energy primary particles than an NM64 however they are more sensitive to environmental effects [2–5]. As there is no standard design for a bare neutron detector, each installation must be analyzed and calibrated individually since the performance may vary with construction technique.

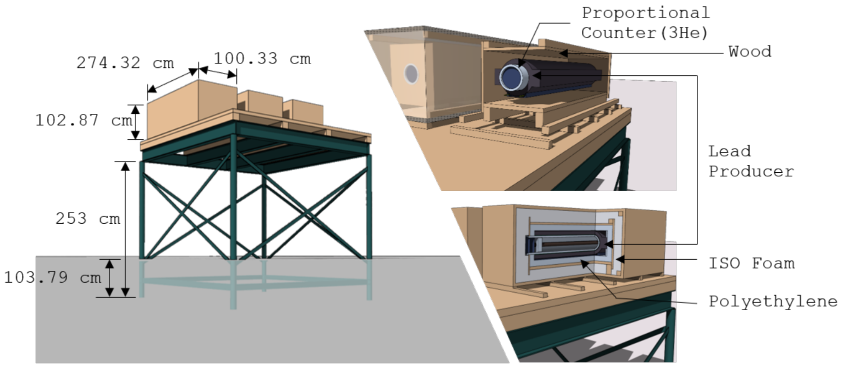
In [6], we derived the YF from a direct measurement from a latitude survey in 2009 – 2010 for two paraffin-moderated bare neutron detectors. After finishing the survey, those two detectors were installed in December 2010 as part of an array of 12 bare detectors at the South Pole, where a standard NM64 is also operated. The yield function of the bare derived from [6] was measured at sea level, while the South Pole station is at a high altitude of about 2,835 meters above sea level. Therefore the YF measured at the sea level will differ from that at the station. Using FLUKA, one of the paraffin detectors was simulated both inside and on top of the container used for the survey. We found that the container has a huge influence on the energy response. The simulated bare count inside the container due to incident particles at higher energy than 100 MeV is higher than that outside by roughly one order of magnitude. In this work, we investigate the YF of the neutron counters at the South Pole using FLUKA 4-1.1, an open-source particle physics Monte Carlo simulation package [7, 8]. DPMJET (rQMD) interaction models have been used [9, 10].

2. South Pole Neutron Detectors

The neutron monitor at Amundsen–Scott South Pole station was reactivated in February 2010 later equipped with an enhanced array of "bare" neutron detectors [11]. The configuration of South Pole bares and three separate NM64 (3NM64) with surroundings are shown in Figure 1 (a) and (b), respectively. Both detectors use ^{3}He filled proportional counters that detect neutrons via the fission reaction n + ^{3}He → p + ^{3}H. The array of twelve bare detectors is located on the mezzanine in the B2 Science Lab. Ten of these detectors are completely unmoderated, while two detectors



(a) Bare neutron detector



(b) Neutron monitor

Figure 1: (a) Bare neutron detector array at South Pole. Ten unmoderated detectors are mounted in a stacked array with the two paraffin moderated detectors on top. (b) Three single NM64s placed in a row (3NM64) are on the platform located outside the station about 100 meters from the nearest structure [11, 12]. The renderings are created by Flair 3.1 [13], which is an advanced user–friendly interface for FLUKA 4-1.1.

have paraffin moderators. The 3NM64 has proportional counters embedded in layers of lead and polyethylene. Their count rates are dominated by ~100 MeV neutrons that interact with lead rings to produce multiple low-energy "evaporation" neutrons that "thermalize" in the polyethylene and are ultimately detected by the proportional counters.

To better measure the spectral index of relativistic solar ions it was our original intent to install an array of bare neutron detectors with statistical precision approximately equal to that of the 3NM64 ($\approx$ 300 total counts per second). Based on our prior experience with BP-28 detectors this would require approximately twelve units, mounted outside the station. To minimize the problems of shipping hazardous materials we decided to use LND25373 ^{3}He detectors similar to those in the 3NM64 operated at the station. We also planned to use compact moderators to minimize the size of an insulated enclosure required to operate outside the station. We took the opportunity to carry two detectors with compact monitors on a latitude survey to determine their yield functions. To our surprise, tests revealed that the compact moderators increased the counting rates only slightly, and there was little difference operating inside or outside the station. As a result we decided not to proceed with an outside insulated enclosure and to instead operate with the array of ten unmoderated and two moderated detectors indoors.

3. Response of the South Pole detectors

3.1 Bare neutron detector tests

We collected data in various locations and configurations to study the effect of materials used as detector moderators on counting rates. The test results are summarized in Table 1. In all cases, the counting rates are expressed as counts per second per detector. The high rate at the South Pole is mostly due to the high altitude. The rates presented are not corrected for barometric pressure or modulation level but the dates when the data were taken are recorded for possible interpretation in that context.

Location	Moderator	Rate	Date
South Pole, Antarctica			
B2	None	13.492(4)	2012
B2	Paraffin	14.862(5)	2012
B2	Donut	13.82(2)	2010-01-23
Snow	Donut	12.88(9)	2010-01-26
University of Delaware, USA			
Patio	None	1.487(4)	2010-08-26
Patio	Paraffin	1.727(5)	2010-08-27
Patio	Donut	1.448(4)	2010-08-27
Patio	Standard	2.585(5)	2010-08-30
Shop	None	0.844(1)	2010-08-31
Shop	Paraffin	0.889(1)	2010-08-27
Shop	Donut	1.111(1)	2010-08-27
Shop	Standard	1.257(1)	2010-08-31

Table 1: Bare ^{3}He Neutron Detector Tests

Location “B2” is the primary science staging area inside the Amundsen-Scott station at the South Pole. “Snow” refers to a location outside the station approximately 100 meters from the nearest structure with the detectors resting on the snow surface. “Patio” is a paved outdoor area adjacent to Sharp Laboratory on the University of Delaware Campus, while “Shop” is inside the electronics shop in Sharp Laboratory – located in the basement, largely under the “Patio”. Tests were made interchanging detectors and moderators, but differences were minimal so only representative results are included in the table.

In Table 1 “Paraffin” refers to the moderators carried on the survey. No significant difference was seen between the two moderators. “None” refers to no moderator at all. “Standard” refers to the moderator used in a standard NM64 neutron monitor. It is a polyethylene cylinder with an inner diameter of 20.5 cm, an outer diameter of 24.5 cm, and a length of 2.27 m. “Donuts” are annular polyethylene supports used to mount LND25373 detectors, which have an outer diameter of only 6 cm, in NM64 moderators. Tests were also made with the detector supported by the donuts but otherwise bare. The “None” and “Paraffin” values for B2 are long term averages over the year 2012 when mounted in the array as shown in Figure 1.

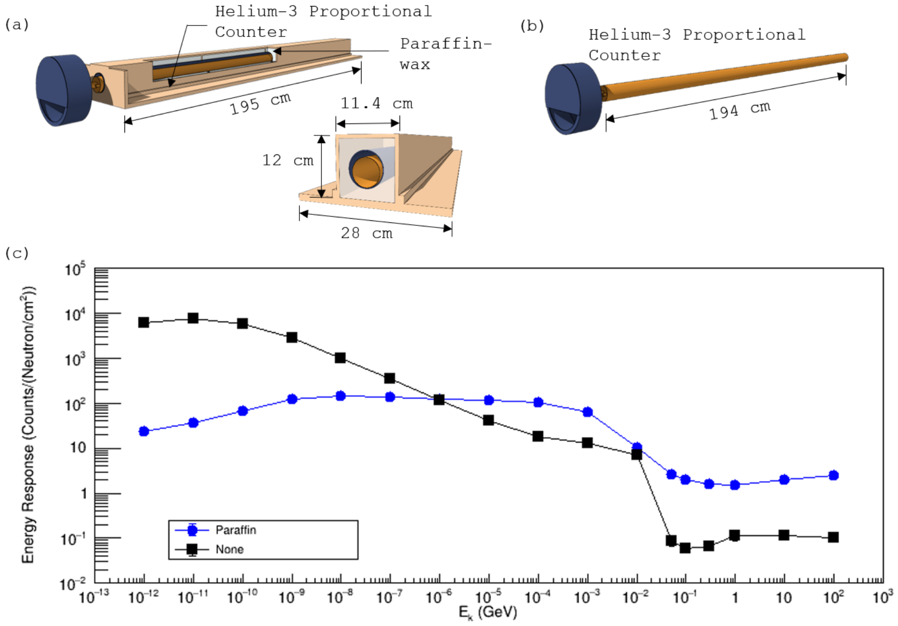


Figure 2: (a) Rendering of an end view and cutaway oblique view of Paraffin-moderated bare detector, and (b) that of the side view of unmoderated bare neutron detector or concisely called “None” in this work. (c) Their simulated energy response. In all cases, the estimated error is smaller than the plot symbol.

3.2 Bare neutron detector simulations

We used simulations to understand the origin of the differences due to location and configuration. Figure 2 (c) shows the preliminary result from the simulation of vertical neutrons. At 100 MeV, the best estimation for comparing with the counting rate [14–16], the energy response for Paraffin moderated bare is slightly higher than unmoderated bare (None), but the details are quite dependent on energy.

3.3 Energy Response of the Ratios

The neutron monitor at the South Pole is uniquely suited to observing solar energetic particles due to its high altitude and low geomagnetic cutoff. Each type of detector has a different YF function and if the same type of detector is installed at different altitudes, the YF function is not the same. We can estimate the spectral index of cosmic rays from the Bare/3NM64 ratio [5, 17]. Figure 3 shows simulated results for 10None/3NM64, 2Paraffin/3NM64, and 2Paraffin/10None energy response ratios.

4. Yield Function of the South Pole Neutron Detectors

While the energy response to neutrons is instructive, the measurement of the particle spectra also depends on propagation in the atmosphere that is contained in the yield function. Ultimately it is only the yield function that matters. Our simulations began by generating libraries of SP (neutrons, protons, muons±) produced by the interaction of primary protons and alpha particles (from 1 GV

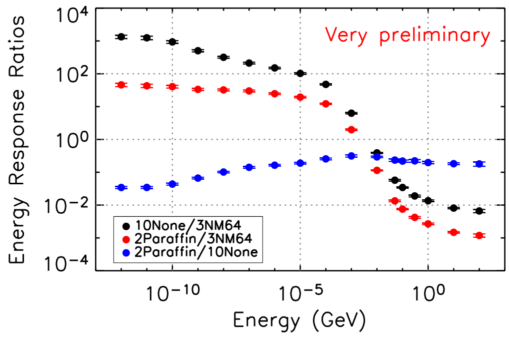


Figure 3: Energy response ratios in a logarithmic scale. Black symbol indicates 10None/3NM64 ratio. Red symbol indicates 2Paraffin/3NM64 ratio. Blue symbol indicates 2Paraffin/10None ratio. Here, we inject a vertical beam of neutrons at a height 100 cm above the detectors in the FLUKA. We apply 20 μs deadtime to our analysis. The vertical error bar represents the error propagation of the ratio that combines uncertainties from two variables; all cases the error bar is smaller than the plot symbol.

to 200 GV) in the atmosphere. The atmospheric profile at the South Pole was based on the Global Data Assimilation System (GDAS) and Naval Research Laboratory Mass Spectrometer, Incoherent Scatter Radar Extended model (NRLMSISE-00) following the method described in [18]. Two million of each primary particle were injected at the top of the atmosphere with a rigidity spectrum following Rig^{-1}. We obtained 1,888,793 neutrons, 244,818 protons, and 3,429,332 muons for the secondary libraries. In the second step, the recorded SPs were injected into the detector simulation and re-sampled with random positions above the detector. Two hundred million "detector" events were simulated for the 3NM64 and the 12-bare detector for neutrons and protons. Only 80 million cycles were simulated for the 12-bare detector for muons and up to two hundred million cycles for the 3NM64. We applied the measured deadtime (in μs) in the simulation for ten unmoderated bares and two Paraffin moderated bares: 20.4, 29.3, 28.4, 29.5, 29.0, 28.6, 29.4, 20.6, 29.4, 29.6, 28.1, 18.8 and for 3NM64: 28.0, 28.0, and 20.0.

4.1 Comparison of Bare Designs

Despite the evident statistical limitations of these preliminary results it is possible to simply compare the ratios of the observed count rates at the South Pole for the two types of configuration and the ratios of the simulated yield functions. The comparison is shown in Figure 4. The orange line indicates the ratio of the count rates of the 2 paraffin bares and the 10 unmoderated bares for 11 days of May 2021: 0.2186. The current agreement between the simulation and the observation is very encouraging and gives us confidence in our methodology.

4.2 Comparison with Previous Results

Figure 5(a) shows our preliminary results of the simulated YF for protons and alphas of the 12 bare detectors at the South Pole. First, we observe that the YF of the protons and the alphas cross over at $\sim$3 GV (a typical neutron counter YF feature) but at higher energy the YF of the alphas becomes 2-3 times larger than the YF of the protons. Below 5 GV, the current statistical uncertainty of our results is above 20%. More simulation will be performed to achieve better precision in this crucial range in rigidity for the investigation of GLE properties. Figure 5 (b) shows the alpha and proton YF for the two Paraffin bares compared with the YF that was derived by measurement in the latitude survey at sea level in 2009-2010 [6] and the YF used in several studies of particle spectra [17]. All have been arbitrarily normalized at 17 GV. The results are encouraging but far more simulation required to improve the precision of our estimates at low rigidity. As [17] showed, the

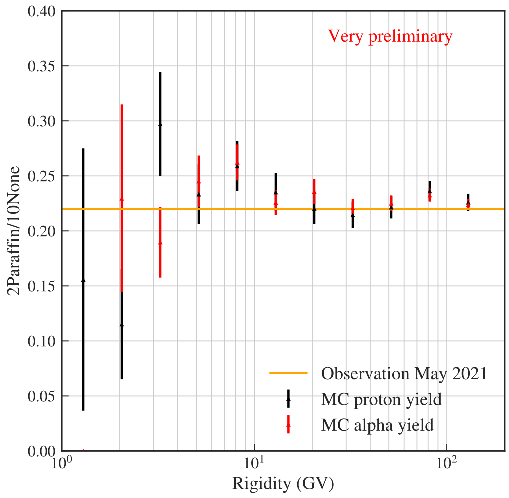


Figure 4: The ratio of the observed count rates at the South Pole for the two types of configuration (orange horizontal line) and the ratios of the simulated yield functions (red and black markers).

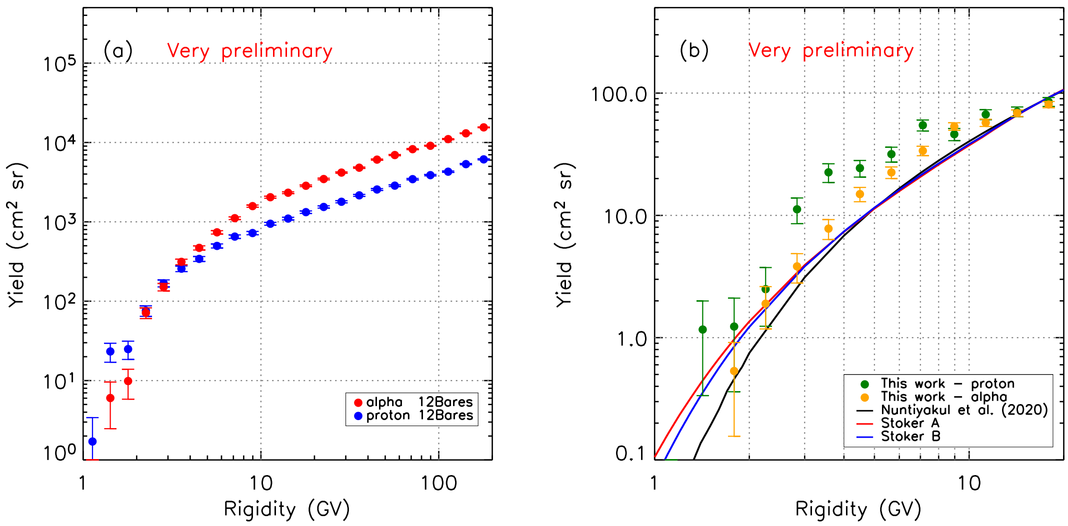


Figure 5: (a) Simulated YF for protons and alphas of 12 bare counters at the South Pole. (b) YF of the two Paraffin bares from this work compared to the determination of [6] and [17].

difference between the red and blue curves is quite significant due to the very steep energy spectrum characteristic of solar particle events.

5. Conclusions

Accurate simulations are required to determine the yield functions of the neutron detectors at the South Pole. We have presented an overview of our work on the energy responses of three types of neutron detectors at the South Pole. We obtained preliminary results of the yield functions of the 12-bare array. Their current agreement of the ratios of the yield functions for two types of bares with the observation is encouraging but more statistics are needed to refine the results and compare them to more observations. The determination of the YF of the 3NM64 located outside the station is a work in progress. We will continue our effort to improve the precision and accuracy of the simulation to better determine the spectral index of the Solar Energetic Particle during Ground Level Enhancement using South Pole neutron monitor data.

6. Acknowledgments

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