Monte-Carlo simulation of the response of bare neutron counters at the South Pole to vertical secondary particles from cosmic rays

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Abstract. Neutron monitors (NM64) are standard ground-based detectors that measure the flux of primary cosmic rays at GeV energies in space by counting secondary particles (mostly neutrons) from atmosphere cascades. The atmospheric neutrons are detected by induced nuclear fission in a gas proportional counter. In the standard design, there is a lead ring to generate evaporation neutrons that are moderated by polyethylene before being detected in the $^{10}$BF$_3$ gas counter. By omitting the lead, so called “bare counters” respond to lower energy particles on average and can be used in conjunction with NM64 to estimate the energy spectrum of the primary cosmic rays. The specific objective of this research is to refine the understanding of the lead-free neutron monitor now installed at the South Pole using Monte-Carlo FLUKA simulations. This design uses paraffin and wood to moderate high-energy neutrons and detects them with $^3$He gas-filled proportional counters. Latitude surveys have shown that they have different detection efficiency from either the NM64 or polyethylene moderated bare counters, but they have never been adequately modelled. Understanding the differences quantitatively is the goal of this work. We will also report the detection efficiency of the paraffin bare for other atmospheric particles.
1. Introduction

Cosmic rays are atomic nuclei such as protons and alpha particles (positively charged particles), as well as electrons (negatively charged particles). The propagation of these particles is influenced by magnetic fields in the solar wind and in the magnetosphere of the Earth. We now know they can originate inside the solar system, mainly solar flares, and outside the solar system from supernovae and other sources. When high-energy "primary" cosmic rays rain down on Earth and collide with nuclei in the Earth's upper atmosphere, they produce a cascade of "secondary" cosmic rays. The sub-atomic particles released from the air collisions can reach the ground. We can detect such particles by using neutron monitors, which are the premier instruments for precise measurements of time variations of primary cosmic rays that have an energy range of 1-20 GeV. The standard design neutron monitor (NM64) was introduced in 1964 by Hatton and Carmichael [1]. We will discuss in detail a variety of neutron monitor designs in the next section.

The activity of the sun affects the cosmic ray spectrum at lower energies than 1 GeV, so studying energies in this range is also interesting. Minimally moderated neutron detectors referred to as "bare counters" have been designed to detect such low energy particles. There are many ways to study the changes of the spectrum. In a latitude survey, neutron monitors and/or bare counters are transported on a ship through a range of geomagnetic cutoff (minimum momentum needed to reach the Earth) which varies with latitude. The variation in counting rate of the neutron monitor as a function of cutoff permits measurement of the cosmic ray spectrum at energies where direct spacecraft measurement is difficult or impossible because of the large detector size required.

We have successfully done a latitude survey on the Swedish icebreaker Oden from Helsingborg, Sweden, to McMurdo, Antarctica, and back from November of 2009 to April of 2010. We transported two bare counters on this trip. The survey data is more complicated to interpret because no NM64 was carried on the voyage. We are required to simulate the energy response of the bare counters to compare with the detection efficiency of the NM64. Our data analysis regarding the bare counters on the voyage in 2009 – 2010 has been published previously in [2]. In this work, we aim to show Monte-Carlo simulation of the response of bare neutron counters from the latitude survey, which were subsequently installed at the South Pole. As an ultimate goal, we plan to compare results from the simulation with the results from the analysis of the data obtained from [2].

2. Neutron monitor

Neutron monitors are ground-based detectors that enable one to indirectly study the flux of high-energy charged particles that strike the Earth’s atmosphere from outer space. These particles interact with the Earth’s atmosphere, generating a cascade of sub-atomic particles that can reach the Earth’s surface. The neutron monitor is mostly sensitive to the neutron component of the cascade. Using simulations allows us to investigate the response of a detector under known conditions enabling us to understand our detectors better to find the energy-dependent effective area or yield function.

There are four main parts of the standard-model neutron monitor (NM64) [1], the reflector, the producer, the moderator, and the proportional counter. The reflector is the outer most layer of the monitor and is made from a proton-rich material, usually polyethylene, to prevent entry of low energy environmental neutrons to the monitor. The energy cross section is similar to the neutron's cross section, which greatly reduces the likelihood that lower energy neutrons will pass through. The reflector also contains the neutrons generated in the lead producer, preventing escape from the monitor. The next part is the producer consisting of 99.99% pure lead that serves as an amplifier, producing multiple evaporation neutrons from nuclear decays for each initial neutron that is captured by the lead. Each of these neutrons has lower energy than the original neutrons from which they were created. Following the lead-producer component is the high-density polyethylene moderator, which reduces the speed of the evaporation neutrons to make them more easily detectable. These slow (thermal) neutrons then enter the proportional counter where nuclear fission reactions allow them to be detected.

In this work, we will discuss results from two different gas-filled proportional counters. If the proportional counter contains the boron trifluoride (\(^{10}\)BF\(_3\)) enriched to 96% of boron-10, the reaction
produces Lithium-7 and Helium-4 ions. If the proportional counter is filled with Helium-3, the reaction produces tritium (or hydrogen-3) and a proton. These ions generate free electrons in either reaction. A high voltage between the outer cylinder, and central wire accelerates the free electrons to create an electron cascade resulting in a pulse of charge, the so-called electron avalanche process. The electrical pulses are digitized using custom electronics enabling the data processing. Just like a standard neutron monitor (NM64), a lead-free neutron detector (or “bare”) can provide a ground-based measurement of the flux of cosmic rays. In this work, we report on Monte Carlo simulations to find the energy response comparing three-different types of bares (figure 1(b), 1(c), and 1(d)) with a standard NM64 (figure 1(a)).

Princess Sirindhorn Neutron Monitor station at the summit of Doi Inthanon, Thailand’s highest mountain at altitude ~2560 meters from the ground level uses 18 NM64, and three polyethylene bares. For both detector types, the proportional counters contain boron trifluoride. The two models are shown in figure 1(a) and 1(b).

Figure 1(c) shows a polyethylene bare, in which the proportional counter uses Helium-3. It is located in the basement electronics shop in Sharp Laboratory, the University of Delaware. This detector is similar to the bare indicated in figure 1(b), but the gas in the proportional counters is different.

The paraffin bare refered in figure 1(d) has a paraffin-and wood moderator to moderate high-energy neutrons. This detector was placed inside a temperature-controlled shipping container aboard the Swedish icebreaker Oden, which went from Helsingborg, Sweden to Uruguay to McMurdo, Antarctica and back, stopping at Punta Arenas and Uruguay, during a 6-month voyage in 2009-2010. It is now installed at the primary science staging area inside the Amundsen Scott station at the South Pole.

Figure 1. Rendered sketch of neutron detectors. (a) Standard neutron monitor (NM64). (b) Polyethylene bare containing boron-trifluoride in the proportional counter. (c) Polyethylene bare containing helium-3 in the proportional counter. (d) Paraffin bare. The renderings are created by Flair, which is an advanced user friendly interface for FLUKA [3].

3. Monte Carlo simulation
Monte Carlo simulation is a mathematical technique of computational algorithms that count on repeated random sampling for minimizing uncertainty to achieve numerical results. FLUKA (FLUktuierende KAskade) [3-5] can simulate with high accuracy the interaction and propagation of about 60 different particle species. In this project, the FLUKA Monte Carlo simulation program is used for finding the count per beam luminosity (CBL) of the detectors versus energy. The CBL is the ratio between the number of counts from the simulation and the beam luminosity. The beam luminosity is defined as the
number of beam particles per beam area (in units of square centimeters). In this work, we input several-
million particles with many running cycles to reduce the uncertainty. We therefore have almost no
visible statistical error bars from the results of this work.

The objective of the simulations is to understand the energy response of the Bares to sub-GeV
neutrons. We will further simulate the paraffin bare used for the latitude survey or “Oden” survey in
2009-2010. We applied the dead time of 20 micro-seconds throughout this work. We set a neutron beam
of 496.22 cm above the detector for all studies. The simulation procedures follow the basic techniques
indicated in [6]. We find the response for 17 discrete energies varying from 1 meV to 100 GeV through
this work.

4. Results

4.1. Comparison of four different-type neutron detectors

This study compares the energy response among four different types of neutron detectors. We model
the geometry of the detectors in the air with the FLUKA program, with four sets of input parameters for
different detector types. No structure surrounding them is included in the model. In the simulation, we project
a rectangular-shaped neutron beam down onto the monitors. From figure 2, we can see that the responses
of the three bare counters (black, red, and green) have the same shape, but different in detail. The black
squares and red triangles react very similarly (same order of magnitude) because both of the detectors
are moderated the same by polyethylene (PE); only the gas contained in the proportional counters is
different. The paraffin bare response (green inverted triangles) at 100 MeV is roughly a half order of
magnitude below the PE bares and about three orders of magnitude below the NM64 (blue circles). The
neutron detectors are most sensitive to 100 MeV cosmic rays after taking the atmospheric profile into
account [7]. We can see that the energy response of three different types of bare neutron detectors is
inversely proportional compared to the standard model NM64. This because the NM64 has a lead ring
that produces lower energy neutrons at high energies, while the other three detectors are lead-free
detectors. Additionally, the NM64 has a reflector that does not allow low-energy particles to enter, while
the lead-free neutron detectors do not have a reflector.

![Figure 2](image_url)

**Figure 2.** Energy response of four different types of neutron monitors to secondary neutrons. The blue
circles show the response of the standard-model NM64 ($^{10}$BF$_3$ proportional counter). The black squares
show the response of the polyethylene bare ($^{10}$BF$_3$ proportional counter) and the red triangles show the
same model but with a $^3$He proportional counter. The inverted triangles show the response of the paraffin
(Oden) bare.
4.2. Effects of surrounding structure

We studied three different surrounding structures with the same detector, the paraffin bare. The first case simulated a shipping container housing two paraffin bares plus an Ice Cherenkov detector. The second case modeled the geometry of the portable detectors in the shipping container onboard a ship. The model geometry for this is shown in figure 3. We compared these results with the third case, an isolated paraffin bare (the geometry is shown in figure 1(d)) obtained from the previous study to see the effects of the surrounding structure.

The responses for the three cases are shown in figure 4. The results are shown separately for each tube, indicated by different colors, blue for T1 and red for T2. We infer that low-energy neutrons are not able to penetrate the container’s walls (0.2 cm outer aluminum, 7.5 cm central foam, and 0.1 cm inner stainless steel) or may be blocked from the stainless steel that makes up the ship, resulting in the CBL of the isolated paraffin bare being higher than the other two cases which include the container or the container and the ship. For isolated paraffin bare without surrounding structure, we found that it is difficult to measure high energy neutrons that have energy more significant than 100 MeV because such neutrons move too fast to be caught by the detector. On the other hand, the responses of the two cases in which have the surrounding structures around are more likely to be higher at neutrons with higher energy than 100 MeV. The neutron response of the insulated paraffin bare at 100 MeV is roughly 2.5 orders of magnitude below the other two cases.

Figure 3. Rendering of side view the icebreaker “Oden” and a cutaway oblique view of the insulated shipping container that contains two paraffin moderated bare neutron counters. The two bares were fastened on top of an ice Cherenkov detector of cosmic ray showers for the IceTop surface component at the South Pole [8]. This work does not include the results from the ice Cherenkov detector.

Figure 4. Response functions of three cases in the energy range from 1 meV to 100 GeV. The open squares of “Only Container” show the energy response of the container that contains two paraffin bares inside. The solid squares of “Ship+Container” show the energy response of the same previous configuration housed on the icebreaker Oden. Different colors indicated different tubes. The inverted triangles of “Paraffin Bare” show the energy response of an isolated paraffin bare.
4.3. Energy responses of the paraffin bare to atmospheric particles

There are three major components (electromagnetic component, hadronic component, and mesonic component) of a cosmic ray extensive air shower that produce secondary atmospheric particles, i.e., muons ($\mu^+$, $\mu^-$), pions ($\pi^+$, $\pi^-$), photons ($\gamma$), electrons ($e^-$), positrons ($e^+$), and hadrons (protons and neutrons) in the atmosphere when primary cosmic rays enter the atmosphere and hit the air nuclei. We herein used the model geometry of the container mounted on the ship. From [6], the simulations have been performed for nine types of secondary particles, considering 17 energy values of neutrons varied from 1 meV to 100 GeV and only eight energy values of other particles varied from 1 MeV to 100 GeV. The energy responses for nine types of atmospheric particles are shown in figure 5. As expected, there is an excellent agreement in the response between neutrons and protons at energy higher than 1 GeV. At lower energies excitation and ionization for a beam consisting initially of protons become significant, greatly reduces the probability of interaction, which reflects in the decreasing response.

The response of the bare from muons above 1 GeV is about 3.5 orders of magnitude below the hadrons. In this energy region, the primary mechanisms for muon induced counts are neutron production in photo-nuclear interactions and electromagnetic showers. Below 1 GeV, the negative charge muons are captured by heavy nuclei into a mesic orbit and absorbed by then. The de-excitation process occurs and releases neutrons. That is the main reason for increasing the response at lower energies. Positive and negative charged pions produce similar responses of hadrons at high energies while at lower energies negative pions undergo nuclear capture like negative muons. Photon, electrons, and positrons have the same physics processes such as pair production or annihilation, therefore the energy response is almost identical.

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Example of CBL as a function of energy for different secondary particles incident on the paraffin bare T2. The basic results in these graphs are consistent with the energy response shown in [9].

5. Conclusion

There are three aims for this work. The first aim is to study the response of different types of neutron detectors used in the real experiment. We found that the type of gas-filled in the proportional counter does not change the response to secondary neutrons, but seems to be significantly affected the detection
efficiency. Helium-3 provides greater response throughout all energy ranges. Bare counters generally are more sensitive to low energies of neutrons.

Installation of the two paraffin bare detectors in the shipping container and mounted it on board the ship has made the bare detectors more responsive to high energy particles. In the case of having a ship and without a ship, the response of both tubes gives the results very similar at higher energies, starting from 1 MeV, indicating that interactions with the shipping container walls must be the dominant factor for the increase in response.

In section 4.3, the results are reasonable, as explained in the text, and consistent with the results described in [9]. In future work, we will vary zenith and azimuth angles secondary particles and take atmospheric profiles from Global Data Assimilation System (GDAS) and NRLMSISE-00 empirical model of the atmosphere into account. Complete simulations will allow us to calculate counting rates to further compare with the counting rates from the actual data. The ultimate goal is to determine the yield function from the simulations to compare it with [2].

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