Preliminary FLUKA simulations of the Changvan Neutron Monitor

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Abstract. A neutron monitor (NM) is a ground- (or sea-) based detector of the flux of cosmic ray particles in space. The high-energy cosmic rays in the GeV primary range interact in the upper atmosphere, producing a cascade of subatomic particles, some of which reach Earth’s surface. A neutron monitor is mostly sensitive to the neutron component of the atmospheric cascade. The standard-design neutron monitor (NM64) contains lead, the nuclei of which fragment when struck by a high-energy particle. Some of the fragments are neutrons which are moderated and trapped by polyethylene acting as a reflector and moderator. These neutrons can then be detected by induced nuclear fission of $^{10}$B in a $^{10}$BF$_3$ gas proportional counter. The Changvan neutron monitor is a portable neutron monitor assembled in Thailand and housed in a standard insulated shipping container to conduct long-term research in polar regions. There are three proportional counters in the Changvan, but the central counter lacks the lead producer. Since the detector has a non-standard semi-leaded design, we examine the detection efficiency of the Changvan for neutrons and other atmospheric secondary particles. We are also developing an electronic board and a highly sensitive control module to reduce dead time to a minimum, for monitoring neutrons in the GeV energy range. Simulation results accounting for the dead time will also be reported.
1. Introduction
Cosmic rays are high-energy charged particles from astrophysical sources. Cosmic rays can mostly be classified into two types according to their origin, i.e., solar energetic particles due to solar storms and Galactic cosmic rays (GCRs) from sources in our Galaxy outside the solar system. When primary cosmic rays collide with an atom in the Earth’s atmosphere, they can produce a shower of lighter particles. This so-called air shower produces secondary cosmic rays including muons, protons, pions, electrons, positrons, photons, and neutrons. In this work, we are interested in simulating the detection of these secondary particles that propagate through a neutron monitor.

Neutron monitors (NMs) are ground-based detectors of cosmic ray showers that are broadly used for monitoring changes in the GCR flux due to variations of the solar wind or solar storms. Hatton and Carmichael designed the standard neutron monitor (NM64) containing boron trifluoride ($^{10}\text{BF}_3$)-gas proportional counters made at Chalk River Laboratories in Canada [1]. The outer component of the NM64 is a reflector, which is made of polyethylene. When lower energy particles from the environment collide with the reflector, they will be blocked. The more energetic particles from cosmic ray showers penetrate to lead rings. These lead rings are typically called the producer, since they produce multiple lower-energy neutrons. We call the production of several lower-energy neutrons from a single incident particle the “multiplicity”. The next component inside the lead producer is a moderator made from high-density polyethylene to slow the neutrons. The innermost component is a proportional counter filled with $^{10}\text{BF}_3$ gas, enriched to 96% of the $^{10}\text{B}$ isotope. The neutrons are detected by induced nuclear fission [$^{10}\text{B} (n, \alpha)^7\text{Li}$]. The resulting bursts of energy ionize the gas and eventually produce electrical pulses on a wire maintained at a potential of about -2,800 V. An electronic module counts and times these electric pulses transmits the information to the data-acquisition system.

2. Changvan neutron monitor
We constructed a transportable neutron monitor housed in an insulated container, which we call the “Changvan”. We mounted the Changvan on the Chinese icebreaker Xue Long for two voyages between Shanghai, China and Zhongshan station in Antarctica during 2019 and 2020 to study short-term variations in the GCR flux due to solar modulation and determine the Galactic cosmic ray response function (product of the cosmic ray spectrum and the NM yield function) as a function of the geomagnetic cutoff, i.e., the minimum energy requires for charged particles to penetrate Earth’s magnetic field, which primarily depends on magnetic latitude.

The Changvan neutron monitor contains three $^{10}\text{BF}_3$ proportional counters as shown in figure 1. The center counter lacks its own lead producer, so this is a semi-leaded 3NM64. Three square segments of plywood with holes in the middle are used to hold the middle detector at the correct spacing. The thickness of each plywood segment is 1.5 cm. The two outer counters include the ring-shaped lead producer, as in the standard design for the NM64 neutron monitor.

![Figure 1. The geometry of the Changvan neutron monitor implemented in the FLUKA program. The dimensions and materials of some the main components are provided.](image-url)
3. Monte Carlo simulation

This work describes the results of simulations performed using FLUKA (FLUktuierende KAskade), a program that utilizes a semi-integrated Monte Carlo method to simulate the interaction and transport of particles and nuclei in matter [2,3].

To study the changes in the detection efficiency of the Changvan neutron monitor due to different surroundings, two different instances of FLUKA geometry were created. In both cases, a rectangular neutron beam was projected down vertically from 16 meters above the detectors. The beam energy ranged from 1 meV to 100 GeV [4]. The abbreviation “CVM” representing the Chang Van Monitor was used to denote the FLUKA geometry of an isolated Changvan neutron monitor and shipping container with a small beam that fully covers just the size of the shipping container (244.24×605.48 cm²).

Abbreviation “SCM”, denoting Ship and Changvan Monitor was used for the simulation of the Changvan neutron monitor mounted on the icebreaker Xue Long, as shown in figure 1. A beam size of 2,400×15,565.48 cm² was applied for this case to completely cover nearby areas on the ship. We also performed simulation to determine a suitable beam size with acceptable uncertainty. A dead time of 20 microseconds (µs) was included in the simulations. We defined the count per beam luminosity (CBL) as a measure of the detection efficiency as a function of the energy of secondary particles. The CBL is the ratio of the number of counts to the number of beam particles per beam area (in units of cm²). Note that the CBL has units of area and can be interpreted as an effective detector area. The CBL from simulations of the CVM and SCM is shown in figure 2.

To study the energy response of the Changvan neutron monitor to atmospheric particles besides neutrons, we used the SCM model to simulate eight particle species with energies varied from 1 MeV to 100 GeV [4], with a 20 µs dead time. The results are shown in figure 3.

To see the impact on count rates, we performed simulations with the following dead times: 0 µs, 20 µs, 100 µs, 1.2 milliseconds (ms), and 4 ms [4]. The detection efficiency for different counter tubes, three discrete energy values, and dead times is shown in figure 4.

4. Results

4.1. Effects of surrounding

Referring to figure 2, at energies lower than 100 MeV, the geometry of the Changvan mounted on the ship enhances the neutron counts per unit area (higher count rate per beam luminosity: CBL) due to the surrounding materials. We saw a major difference in the detection efficiency of the two cases (SCM and CVM) at energies below 10 MeV. There are almost no visible differences between the two cases at high energies on a logarithmic scale. For non-vertical incidence, as in actual operation, surrounding materials could have a greater effect. The abbreviations T1, T2, and T3, refer to the tube numbers as shown in figure 1. The response of T2 in the case of SCM is lower than those of T1 and T3 by 39% at 100 MeV (the peak of the response of a neutron monitor [5]). For the CVM case, the differences were reduced to 36%. In each case, we show the energy responses of each tube separately. We also simulated a standard 3NM64, and found the overall response similar to that of the fully leaded detectors in the Changvan. Due to the lack of lead, the response of T2 at 100 MeV is 60% lower than of a fully leaded T2.

The CBL is about the same for the two cases for energies above about 10 MeV. For the lead-free neutron counter (T2) in the CVM model, the CBL is higher than for the other tubes at 10 MeV and switches to be the lower at higher energy. Tube 2 lacks lead rings; therefore, it has less chance for high energy particles to produce counts compared with the other two tubes with the lead producers, but is presumably more sensitive to lower energy environmental neutrons. In the following subsections we will only discuss the results from the SCM model which more closely reproduces the structure of the Changvan neutron monitor on the ship in the real experiment.

4.2. Energy response of atmospheric particles

Figure 3 displays the resulting detection efficiency (count rate per beam luminosity) vs. energy of the Changvan neutron monitor for each tube for nine different vertically incident secondary particle species.
For the nucleons, i.e., protons and neutrons, the CBL consistently increases when the energy increases. Proton and neutron CBL at energies above 100 MeV were similar as expected. Below 100 MeV, the proton CBL diminishes significantly. This is due to the ionization energy loss of protons.

For photons with energy considerably more than 10 MeV, the Changvan neutron monitor response was similar to those for both electrons and positrons. The response from muons above 1 GeV is roughly 3.5 orders of magnitude below the hadron response. Negative muons with energies higher than 1 GeV produced neutrons through photo-nuclear interactions and electromagnetic showers resulting in multiple ionization tracks which are then counted by the proportional counter. At energies below 1 GeV, the negatively-charged muons are captured to form muonic atoms and are absorbed by lead nuclei. The de-excitation occurs with the emission of neutrons which can then interact with \(^{10}\)BF\(_3\) gas in a proportional counter. This nuclear reaction produces increased detection efficiency relative to positively charged muons. Positive and negative charged pions give rise to a nearly identical response to positively charged muons. While negative pions can undergo nuclear capture like negative muons at lower energies.

![Figure 2](image1.png)

**Figure 2.** Comparison of simulated detection efficiency (count rate per beam luminosity) of each counter tube of the Changvan neutron monitor to vertical secondary neutrons for two configurations, CVM and SCM.

![Figure 3](image2.png)

**Figure 3.** Count rate per beam luminosity as a function of energy for different particle types vertically incident on the Changvan neutron monitor (SCM model). The general trend in these graphs is consistent with the results shown in [6]. (a) Example results for an end counter (T3) and (b) for the middle counter (T2).

### 4.3. Energy responses to vertical neutron beam for different dead times

The relationship between count rate per beam luminosity and different electronics dead time for each tube as shown in figure 4 indicates the response changes depending on the energy of neutrons and the dead time. The Changvan neutron monitor can count more neutrons at the lower dead times, i.e., 0 µs, 20 µs, and 100 µs. Here, we consider only three discrete energy values: 100 MeV, 1 GeV, and 100 GeV, which are representative of the energy response of the Changvan neutron monitor. We hardly see
dependence on dead time for 1.2 ms and 4 ms, but for shorter dead time the effect is very significant. The current electronic dead time for the Changvan neutron monitor is approximately 100 µs for the full timing analysis. If we continue to use the conventional electronics that are currently installed, we will miss important information on the energy spectrum of the incoming particles. The simulation confirms the value of our efforts to develop remote board electronics for the Changvan neutron monitor to minimize the dead time.

5. Conclusions
In this work, the relationship between count rate per beam luminosity and energy was used to indicate the “detection efficiency” or the “response” of the neutron monitor. The effect on the Changvan neutron monitor from various things located on board the icebreaker Xue Long such as other shipping containers and radar has a significant impact on count rates for neutron energies below 10 MeV. On the other hand, we can see only a slight difference in the detection efficiency in the logarithmic scale for neutron energies higher than 10 MeV. The responses to various atmospheric secondary particles are consistent with prior simulations [6]. Minimizing the remote-board electronics dead time is important for enhancing the energy resolution of neutron monitors. This is the motivation to develop new electronics with advanced technology to reduce dead time to near zero.

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