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Neutron Bursts from Air Showers in Ice: Implications for Neutron Detection with the South Pole Neutron Monitors

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Observations of apparent neutron bursts from air shower cores interacting in soil have been recently reported. The primary mechanism for neutron bursts, which show up as anomalous long-duration counts in a detector, is the production of evaporation neutrons from air shower cores that enter the ground in the vicinity of a detector. Neutron monitors are ground-based detectors that observe the primary cosmic ray flux in the GeV range, allowing them to be sensitive to neutron bursts. Neutron bursts would produce an unwanted background that should be taken into account in spectral studies using neutron multiplicity. We report on a simulation study of neutron bursts from air shower cores interacting in ice and discuss the implications for spectral studies done with the South Pole Neutron Monitor. We use FLUKA, including a detailed simulation of the atmosphere, snow, and neutron detectors at the South Pole.

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1. Introduction

Cosmic rays are highly energetic particles that arrive at earth from outside our solar system [1]. They span a vast range of energies, from 10^7 eV to 10^{20} eV, with a flux that decreases roughly as a power law, and falls even faster at around 10^{15} eV, the so-called "knee" of the spectrum, where it is thought that the galactic to extra-galactic components separate. Beyond 10^{18} eV, the "ankle" of the spectrum, the flux becomes harder. Above 10^{14} eV the flux is too low for any useful observation of primary particles. However, as these primary particles enter the upper atmosphere, they collide with nuclei already existing in the atmosphere, producing showers of secondary particles [2]. Some of these secondary particles then reach the ground where they can be observed using ground-based detectors. At the lower energy range of ground based observations, detectors of a few tens of square meters are sufficient for measurement of cosmic ray rates and for spectral studies.

Neutron monitors are ground level detectors that indirectly observe secondary particles produced from galactic cosmic ray air showers[3] [4]. Neutron monitors can also record solar energetic particles through the ground level enhancement of radiation caused by coronal mass ejections[5]. The detector element of a neutron monitor consists of a proportional counter containing either ^{3}He or BF_3 gas. In a standard neutron monitor, Figure 1, the central counter is surrounded by layers of paraffin wax or polyethylene, which serve to reflect environmental neutrons and moderate higher energy neutrons. A lead producer enables nuclear reactions between the target lead nuclei and neutrons, which result in the production of evaporation neutrons, some of which are observed in the proportional counter. [6].

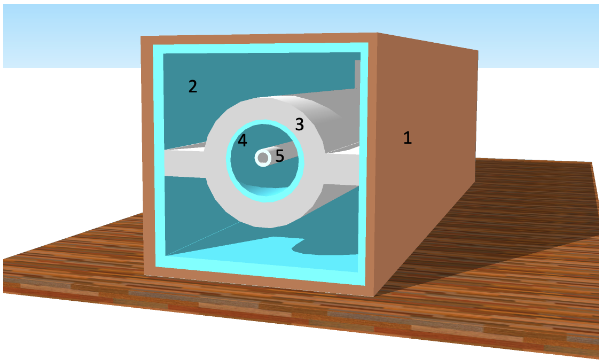

Figure 1: Schematic of a neutron monitor, similar to the configuration at the South Pole.1) Outer crate housing, 2) polyethylene reflector, 3) lead target producer, 4) polyethylene moderator, 5) ^{3}He proportional counter. The South Pole neutron monitor is also equipped with insulation and heaters.

One specific construction of a neutron monitor is referred to as the NM64 model[4]. Here the primary cosmic ray of interest in is in the 1-10 GeV range and it's estimated that only a single neutron per shower reaches the detector. Neutron detection rates need to be corrected for pressure, temperature, and humidity in relevant environments. In the NM64, the reflector is a thick-walled polyethylene structure, which acts as a filter for the monitor. It's purpose is to reject low energy neutrons that are prevalent in the atmosphere while allowing higher energy neutrons that may be secondaries from cosmic ray showers. Particles that traverse the reflector will reach the "producer", a target mass of lead surrounding the other internal components. Inelastic collision with the heavy nucleus produces evaporation neutrons at a rate of A^{γ} where $A = 208$ for lead and $\gamma \sim 0.7$ for incoming neutrons of a few hundred MeV energy[6]. It is due to this phenomenon that the lead is the main source of neutrons that are detected. Next, particles reach the inner moderator, another layer of polyethylene (or paraffin wax) that will slow down neutrons to near-thermal energies to facilitate their capture in the proportional counter. The counter is the central component of the monitors, composed of a steel tube filled with Helium-3 gas. Neutrons are captured in the Helium-3 through the reaction, n+^{3}He $\rightarrow$ p+ ^{3}H + $Q, Q = 764$ keV. The full 764 keV is not always available for ionizing the gas as either the proton or triton can collide with the wall of the tube before depositing all of their energy. This leads to the characteristic pulse height distribution of a Helium-3 neutron monitor with a distinct peak and preceded by two plateaus due to the wall effects.

Worldwide, neutron monitors have been in operation for more than seven decades [7] with a large number of them providing data to the public. On its own, a single neutron monitor station gives the integral cosmic ray rate above the local geomagnetic cutoff. By exploiting the array of neutron monitors distributed across latitudes with different geomagnetic cutoffs, spectral and anisotropy studies can be carried out. Neutron monitors provide continuous, real-time data on galactic cosmic ray rates, have observed during the past seven solar cycles, and are sensitive to transient events such as ground level enhancements and Forbush Decreases[8][9]. Neutron monitors can provide calibration information for space borne cosmic ray detectors and for bench marking simulations of the production, acceleration, and transport of solar energetic particles.

The South Pole station Neutron Monitors [10] is composed of three insulated and heated NM64 model neutron monitors on an elevated outdoor platform, Figure 2 as well as twelve "bare" monitors that are housed inside the South Pole Station. Neutron Monitors have operated at the South Pole since 1964 with a two year interruption between late 1974 and the end of 1976, and a four-year interruption between 2006 to 2010. Prior to the first interruption the neutron monitor was of the IGY type. The location at the Amundsen-Scott South Pole Station puts it at an elevation of 2800 m, at 90° South latitude. The vertical, essentially atmospheric, cutoff is 0.1 GV. As a standalone station, the combination of the 3NM64 and bares as well as the nearby IceTop Cosmic Ray Detector can be used for spectral and composition studies of solar energetic particles. Because of the extreme environment, the 3NM64 are installed in individual, insulated housing and are heated to approximately 10°C.

Previously reported observations of apparent neutron bursts from air shower cores impacting the soil near cosmic ray detectors[11][12] opens the question on whether such bursts might be observable for air shower cores impacting the snow and ice near the exterior South Pole neutron monitor platform. In this work, the FLUKA Monte Carlo simulation package is used to investigate a possible background in ground based observations of neutrons caused by air shower cores penetrating the ice and snow below the three exterior NM64 model neutron monitors.

2. Simulation

FLUKA[13][14] is a multipurpose Monte Carlo transport code used to simulate particle transport and particle interactions. It can simulate the interaction and propagation of about sixty different particles in complex user-defined geometries with high accuracy. In some cases particles can be simulated up to thousands of TeV in energy and, in the particular case of neutrons, down to thermal

Figure 2: The South Pole Neutron Monitor during Auroral activity. The South Pole Station is on the right. Photo Credit NSF/R. Streeter

energies. FLUKA modeling is optimized at the single particle level through comparison with real data. FLAIR[15] is an advanced user-friendly graphical interface for FLUKA, which provides a accessible route to constructing FLUKA projects. Flair also provides tools for preliminary analysis of data, including graphical analysis.

For this project all relevant processes are activated in FLUKA, including low energy neutron transport, which is key in neutron monitor physics. A simulation of the 3NM64 neutron monitor system, Figure 2, including the proportional counter, moderator, lead, reflector, outer housing and platform was constructed. Additionally, a model of the South Pole atmospheric density profile composed of eighty-five layers reaching an altitude of 20km was simulated alongside a model of the Antarctic ice firn, composed of twelve layers of increasing ice density reaching down 180m.

The main purpose of this simulation is to deduce if there is an observable difference in neutron counts detected in the 3NM64's due to products of neutron bursts that occur from air shower cores in the snow and ice below the NM platform. To do this, a three step simulation process was executed. Initially, eight energy bins of primary protons extending up to 300 GeV were injected at the top of the simulated atmosphere. The distribution of primary protons was normalized to the shape of the galactic cosmic ray spectrum for subsequent steps of the simulation. At the equivalent atmospheric height of the 3NM64 platform, called observation level, the position and energy distributions of secondary protons and neutrons was recorded. This information was then used to determine the initial conditions for the rest of the study. The distribution of neutrons and protons at the end of this step is shown in Figure 3

The second and third simulation steps are identical, expect for the simulated environment around the 3NM64 platform. Both begin with protons and neutrons, reaching up to 300 GeV, being re-injected into the atmosphere at observation level according to the energy distributions recorded in the initial step. In the second step the ice is simulated below the platform as usual, Figure 4. This allows particles to enter the ice and produce more secondaries, some of which may scatter upward and out of the ice. However, for the third step the ice underlying the 3NM64 is excluded

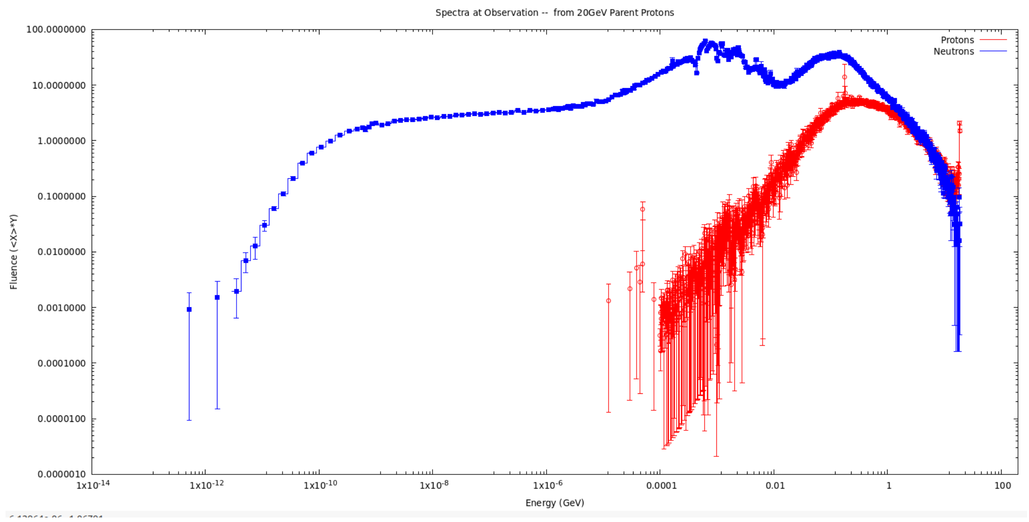

Figure 3: Blue squares represent observed fluence vs. energy of secondary neutrons. Red circles represent observed fluence vs. energy of secondary protons. Both are produced from 20 GeV protons injected at the top of the atmosphere and data was collected at observation level. Fluence is initially measured in cm^{-2} GeV^{-1} per incident primary unit weight, but presented here as Energy× Fluence to better resolve features of secondaries spectra.

so only neutrons that originate directly from air showers cascading through the atmosphere can be observed. In both scenarios, neutrons are recorded as they enter the central proportional ^{3}He counter in each of the 3NM64 modules.

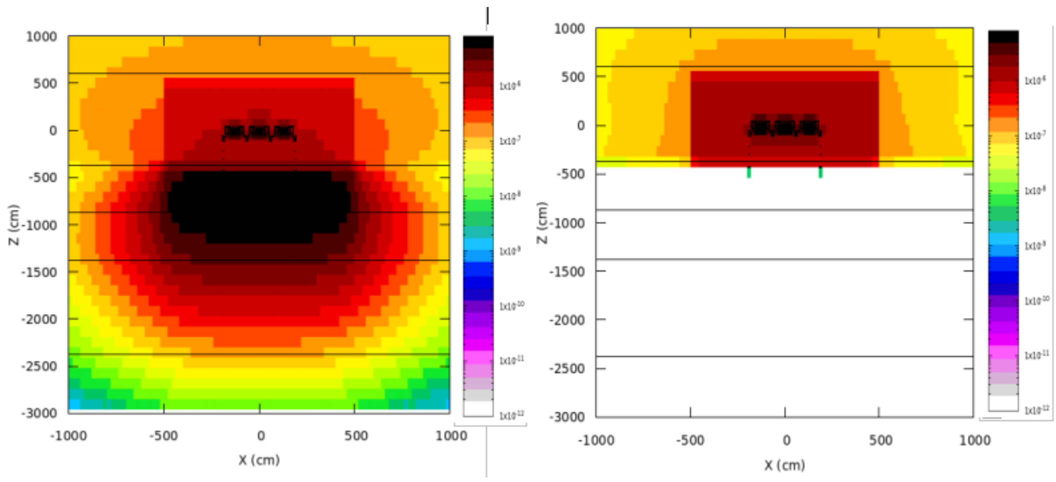

Figure 4: Fluence of neutrons produced by air showers (left) and ice and by air showers only (right).

Any additional neutrons observed in the second step, above those recorded in the third step, could be deemed to originate in the ice. There are two likely sources of neutrons that come from the ice back up to the 3NM64; neutrons from the air shower that scatter upward after reaching the ice and neutrons that are produced in the ice from the proton core of the air shower.

3. Results and Discussion

When creating the timing distributions of secondary neutrons, it was assumed that the curvature of the shower front can be ignored at the length scale of the neutron monitors since they extend only a few meters in each horizontal direction and primaries were injected vertically above the monitors. Secondary particles re-injected in the 3NM64 simulation were deemed to be injected at time $t = 0$ and the times of all particles are recorded with respect to this time.

All neutrons that entered any of the three He-3 tubes were recorded and a distribution of times of those neutrons are shown in Figure 6. The top panel shows the time distribution of neutrons that reach the He-3 and the bottom panel shows the ratio of the two distributions. The result shows that up to a few ms the number of neutrons produced in the ice and then enter the central counters is negligible. At longer times the ratio fluctuates but this is also a region of limited statistics.

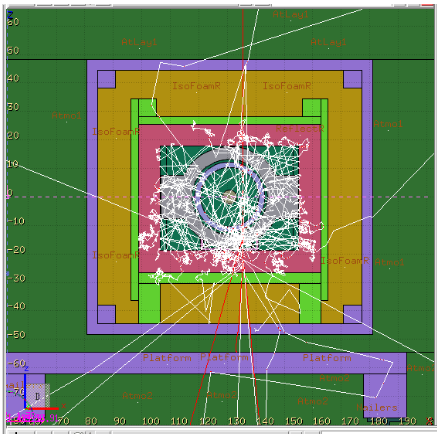

Figure 5: The tracks indicate neutron interactions and transport inside the neutron monitor.

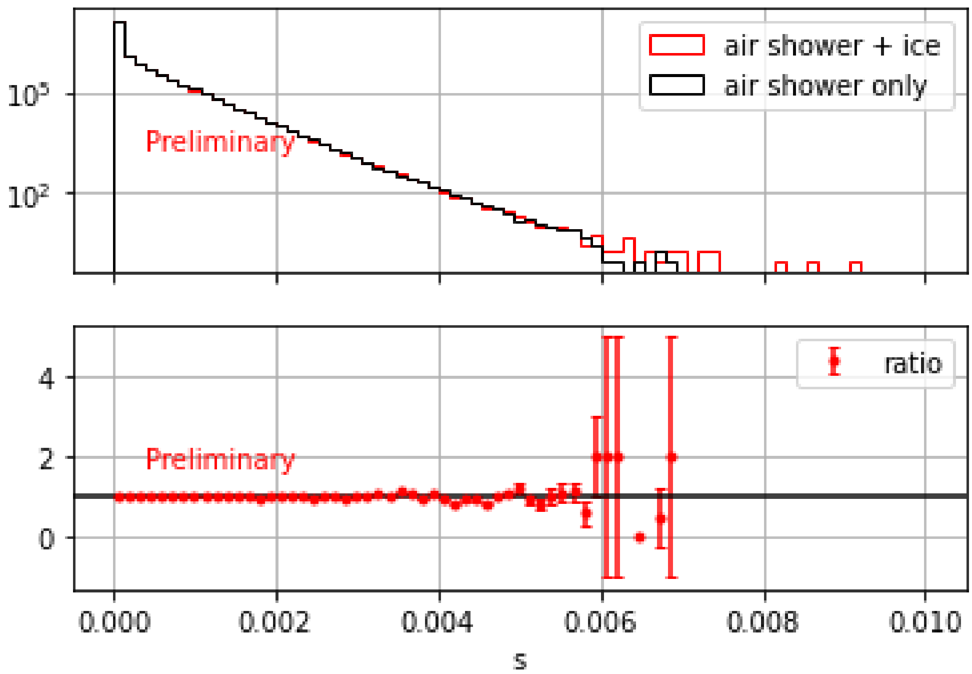

Figure 6: The top panel shows the distribution of arrival times of neutrons in any of the three He-3 counters. The red distribution shows neutrons arriving from the air shower and any that would arrive from the ice after secondary particles enter the ice. The black curve shows the neutrons arriving only from the air shower. The bottom panel shows the ratio of these two distributions.

A neutron monitor is designed to capture thermal neutrons, ∼ 0.025 eV, that enter the He-3.

Figure 7 shows the result for thermal neutrons only. While there are thermal neutrons that arrive in the monitors after 8 ms, again it is a statistics limited region.

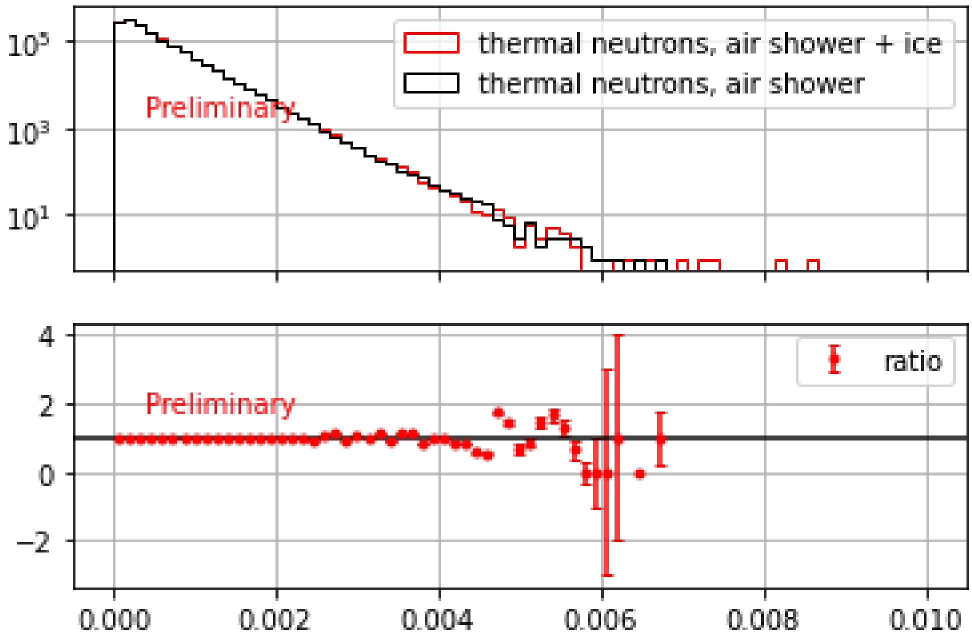

Figure 7: Same as Figure 6 but with only thermal neutrons included.

There may be several reasons why the so-called neutron bursts are not seen in this study. Given that the ice below the neutron monitors act as a moderator, neutrons produced in the ice may undergo more than enough scatterings, ~ 200 or so, and be moderated down to thermal energies before they escape the ice, if at all. The highest energy primaries used in this study is 300 GeV, perhaps too low to observe neutron bursts. In follow up work neutrons from higher energy shower cores will be explored. For now, it appears that long time pulses from neutron bursts may not be a background for time-delay analyses with the South Pole neutron monitor.

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