Direct Determination of a Bare Neutron Counter Yield Function

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Abstract

Ground based neutron counters are a standard tool for detecting atmospheric showers from GeV-range primary cosmic rays of either solar or galactic origin. Bare neutron counters, a type of lead-free neutron monitor, function much like standard neutron monitors but have different yield functions primarily because they are more sensitive to neutrons of lower energy. When operated together with standard monitors the different yield functions allow estimates to be made of the energy spectrum of galactic or solar particles. In 2010 a new array of twelve bare neutron detectors was installed at the South Pole to operate together with the neutron monitor there. Prior to installation, two of the detectors were operated on a ship that traveled from Sweden to Antarctica and back from November 2009 to April 2010. The purpose of this latitude survey was to use Earth's magnetic field as a spectrometer, blocking cosmic rays below the local cutoff rigidity (momentum per unit charge), from which we determined the response function vs. rigidity of these bare counters. By comparing that measured response function to direct measurements of the cosmic ray spectrum taken by the PAMELA spacecraft, we were able to make a direct determination of the yield function for these detectors.

Observation

Instrumentation

The bare neutron detector design used in the latitude survey is shown in Figure 1. It consists of an LND25373 ^{3}He neutron counter [1] surrounded by a paraffin wax moderator inside a wooden box. Two such detectors were strapped on top of an ice Cherenkov detector of cosmic ray showers for the IceTop surface component of the IceCube Neutrino Observatory at the South Pole [2]. The detectors were housed in a temperature-controlled freezer container.

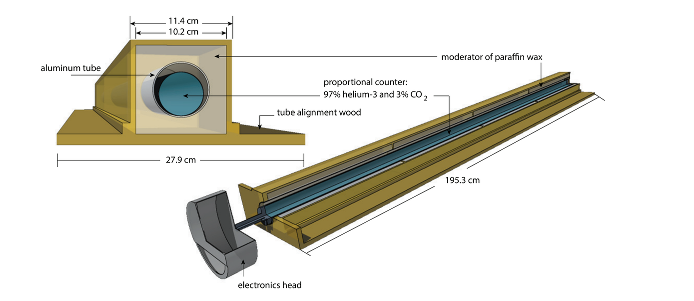

Figure 1: Rendering of an end view and cutaway oblique view of a paraffin bare neutron counter to detect cosmic ray showers.

The 2009 – 2010 Latitude Survey

This survey began on 11 Nov of 2009 from Helsingborg, Sweden at a cutoff rigidity of 1.88 GV. There was an extensive port call in Uruguay at about 8.2 GV, after which the survey continued to McMurdo Station, Antarctica. The return trip was via Punta Arenas at 5 GV, and Uruguay at 8.2 GV, and back to Sweden on 26 Apr 2010.

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Data

The counting rate of each detector was recorded once per second together with the attitude of the ship (pitch and roll). Once per minute the barometric pressure was recorded, as was the position of the ship derived from GPS data, which also provided absolute timing. Apparent geomagnetic cutoffs [3, 4, 5] were calculated at half hour intervals.

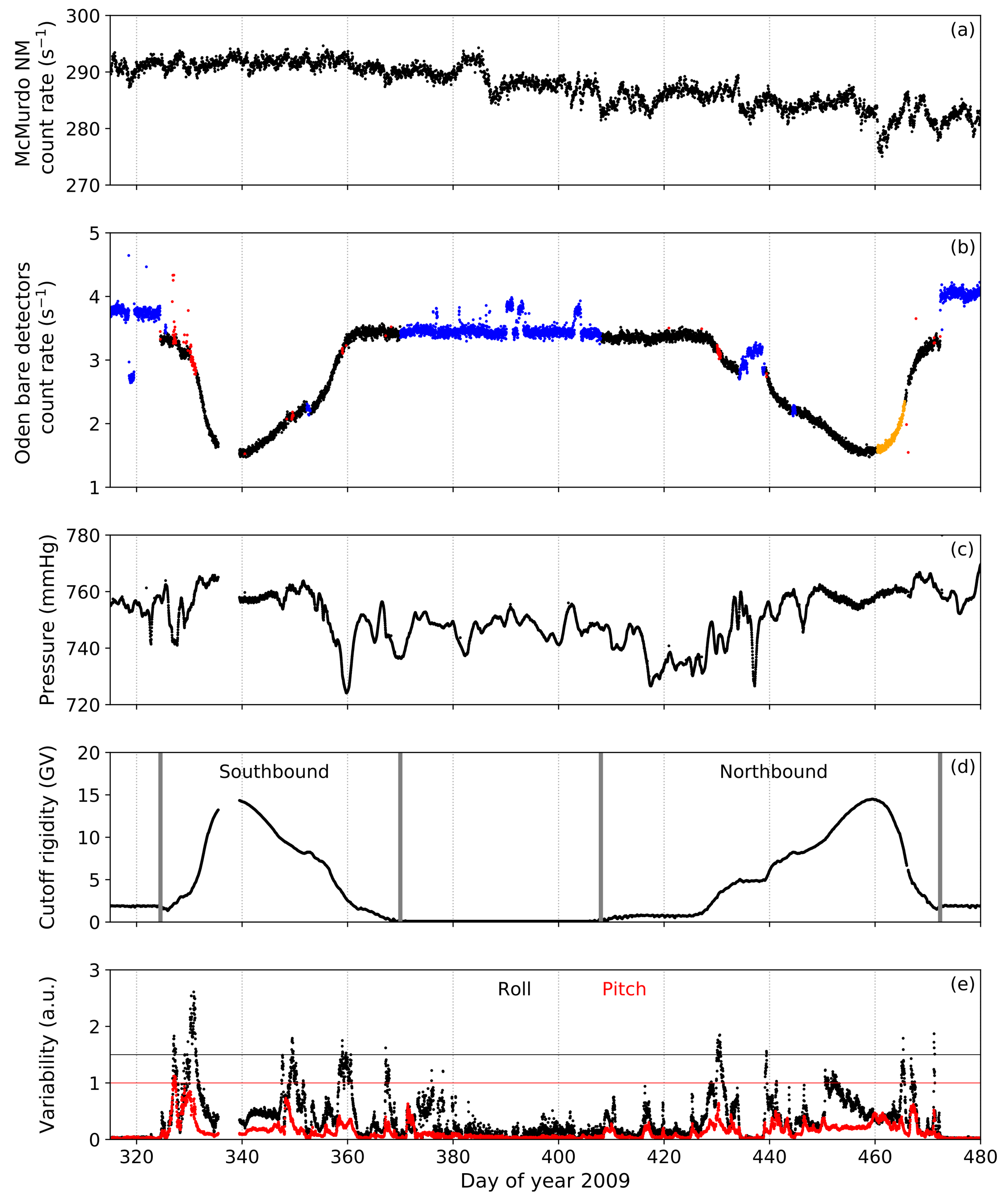

Figure 2: Data set used in this analysis. (a) Pressure corrected count rate of the 18NM64 McMurdo neutron monitor. (b) Pressure corrected average count rate of the two bare neutron counters on board the Oden. Black points were accepted as valid data while points of other colors were excluded. (c) Pressure in mmHg. (d) Apparent cutoff rigidity at the Oden in GV; vertical lines define the Southbound and Northbound intervals. (e) Standard deviation of Oden roll (black) and pitch (red) angles (arbitrary units). Horizontal lines show the applied cuts for rejecting time periods of strong pitch or roll.

Data Exclusions

- **Forbush decrease:** Data excluded for a major Forbush decrease due to a CME occured during the north bound period are shown in orange in Figure 2(b).
- **Barometric Pressure Correction:** A strong anti-correlation is observed between a neutron monitor count rate and barometric pressure. Pressure-corrected data has been used in our analysis by using 13 surveys [6] to establish (for an NM64) the pressure coefficient, β.
- **Short Term Modulation:** The McMurdo monitor count rate in Figure 2(a) indicates time variations in the galactic cosmic ray flux due to solar activity, known as solar modulation. Even a cursory examination reveals that the overall level of solar modulation is quite different near the early "southbound" and the late "northbound" portions of the survey. We consider this difference quite an important one to preserve in the analysis, and indeed think that a self consistent handling of this difference strengthens our determination of the yield function. Our correction for short-term variations in modulation level is based on variations in the McMurdo count rate. There are two steps to this analysis. First, following the methods of [6], we determined regression coefficients (S) between the bare neutron detector count rate corrected for pressure for each rigidity bin, i.e., 0–1 GV, 1–2 GV, …, and 13–14 GV and the McMurdo count rate corrected for pressure, C_P. Second, we found that the function suggested by Eqs (3) and (4) in [7], with the parameters S_i given in Table 1 in [7], provides a reasonably good fit to the data.

Latitude Survey Response Functions

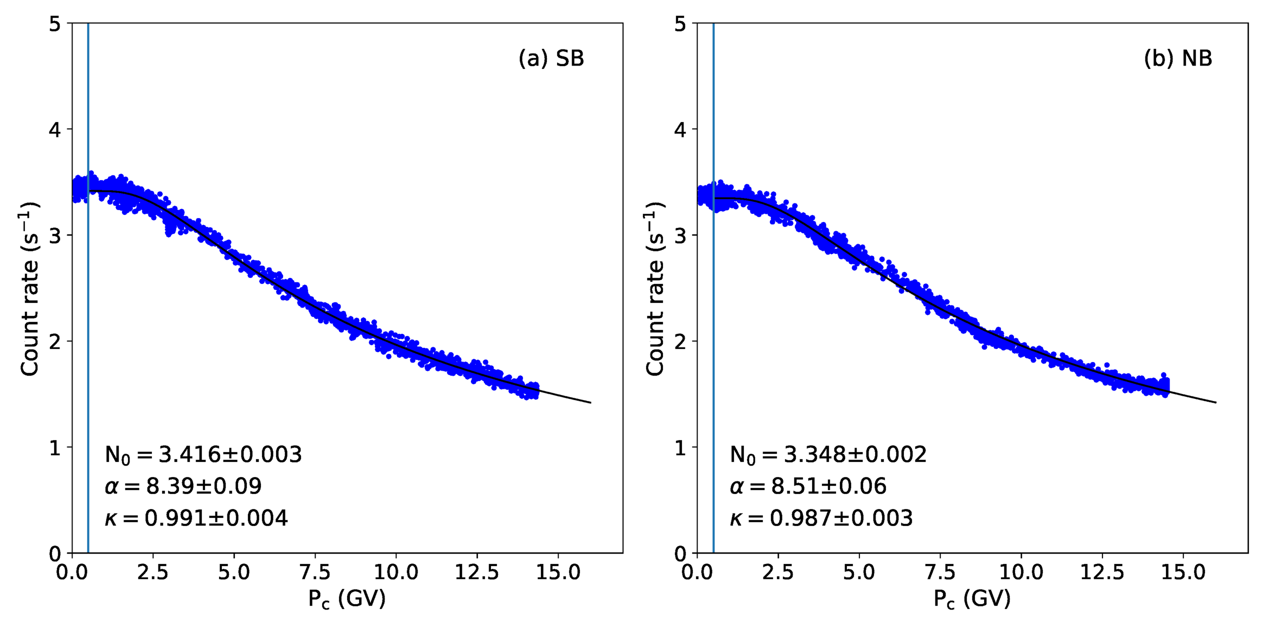

Figure 3: Separate Dorman function fits to (a) southbound (SB) and (b) northbound (NB) bare neutron detector count rates. The vertical line shows the lower cutoff limit used during the fitting procedure.

Solar modulation conditions were different for the southbound and northbound intervals of the latitude survey. Figure 3 shows the Dorman function fit to the southbound and northbound intervals separately. In performing these fits we excluded all data from geomagnetic cutoffs below 0.5 GV.

Direct Determination of Yield Functions

We derived the yield function using an approach similar to that of [8] for a standard NM64. Conceptually the yield function of the neutron detectors is simply the ratio of the DRF to the particle spectrum at the top of the atmosphere. A complication is that each particle species has its own yield function and spectra of different elements have different rigidity dependence. We approximate the multiple ion species actually present by assuming that there are only protons and ^{4}He nuclei (alpha particles), since the spectra of the heavier elements tend to resemble the alpha spectrum but at significantly lower intensity, and multiply the alpha spectrum by a scale factor F_{hn} to account for heavier elements.

To evaluate the yield function several assumptions are made. First, we use the Local Interstellar Spectrum (LIS) derived from spacecraft and balloon data [9, 10]. A force-field approximation [11] of the solar modulation was applied to the LIS using the solar modulation parameter Φ determined by [12] for the time of interest. Then, we assume a ratio between the yield functions of protons and alphas, $F_Y(R)$, using an approach similar to that for a standard NM64 as proposed by [8]. Finally, we include the contribution of heavy nuclei by a multiplicative scale factor, F_{hn}, to the alpha particle yield function. We consider two published estimates of this scale factor. One is $F_{hn,C} = 1.584$ from [8], to be consistent with their calculation of F_Y, and the second is $F_{hn,G} = 1.445$ from [12] to be consistent with their calculation of Φ. The yield function of the bare counters to protons is calculated as:

$$Y_p(P) = \frac{DRF(P)}{J_p(P,\Phi) + F_{hn}F_Y(P)J_\alpha(P,\Phi)}, \qquad (1)$$

where $J_p(P,\Phi)$ and $J_\alpha(P,\Phi)$ are the spectra of protons and alphas at the top of the atmosphere, respectively. The yield function to the alphas is then determined as:

$$Y_\alpha(P) = F_Y(P)Y_p(P) \qquad (2)$$

The two legs of the latitude survey of 2009 present distinguishable solar modulation conditions and provide two estimates of the yield functions. For the southbound interval, we use the solar modulation parameter determined using the time dependent PAMELA spectrum [12] and references therein]. The average modulation parameter estimated from the PAMELA monthly spectra from November and December 2009 is $\Phi_{PAM,SB} = 414 \pm 30$ MV (private communication with authors of [9, 10, 12]. To the best of the authors' knowledge, time dependent spectra from PAMELA have not been published for the northbound interval. Therefore we use the time dependent solar modulation parameter calculated from the McMurdo neutron monitor counting rate [12, 13]. During the northbound interval the average value was $\Phi_{McM,NB} = 484$ MV with a standard deviation of 19 MV. (Data were extracted from the database located at http://lpsc.in2p3.fr/crdb/). As a consistency check, during the Southbound interval, the average hourly solar modulation parameter was $\Phi_{McM,SB} = 422$ MV with a standard deviation of 8 MV, in agreement with $\Phi_{PAM,SB} = 414 \pm 30$ MV.

With this set of assumptions, and using $F_{hn,G}$, the yield functions were calculated numerically and are presented in Figure 4(a). There is a very good agreement between the yield functions calculated for the two periods, with a ratio compatible with 1 within the uncertainty (bands in Figure 4(b) represent 1σ statistical uncertainty). Changing F_{hn} to $F_{hn,C}$ would induce a systematic change of about 3% to the yield functions above 3 GV. Below 3 GV, the statistical uncertainties dominate and the results are not sensitive to the choice between the two factors.

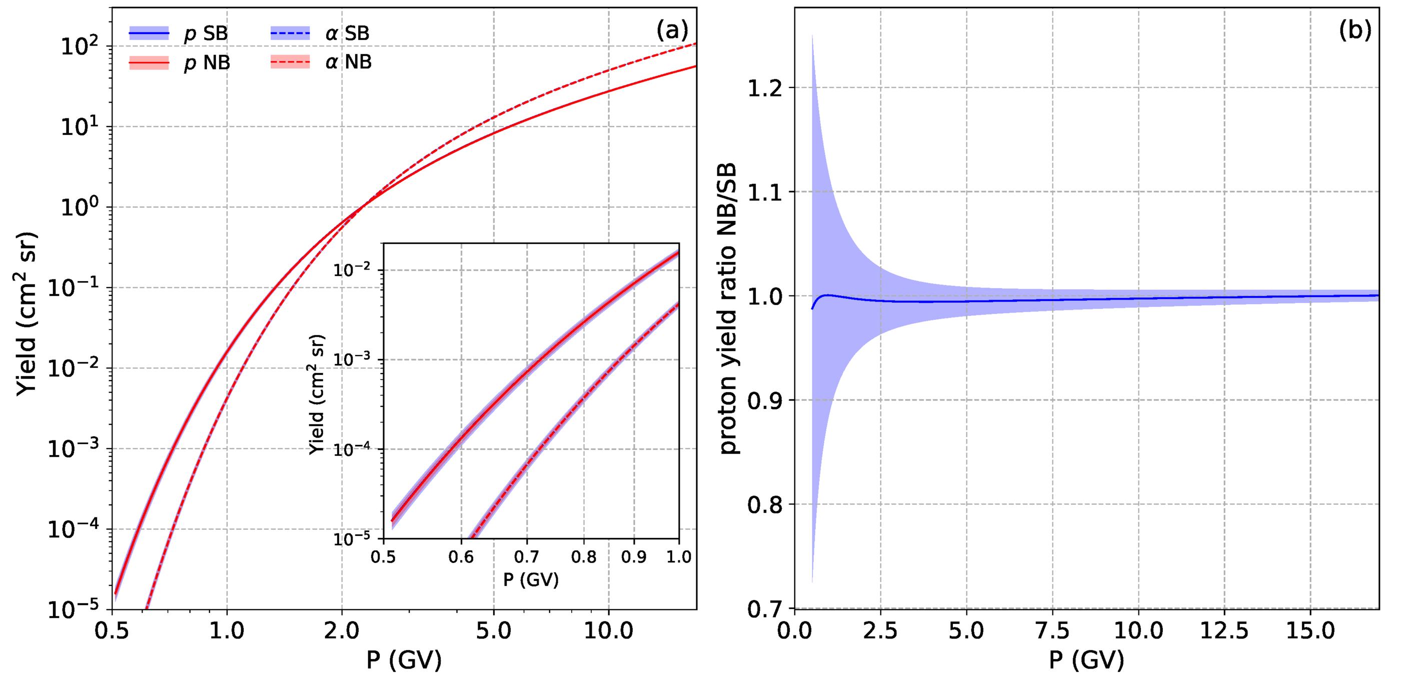

Figure 4: (a) Yield functions of the two bare neutron counters for protons and alphas derived from the 2009 – 2010 latitude survey and particle spectra at the top of the atmosphere as described in the text. (b) Ratio of the southbound to the northbound proton yield functions. We use $F_{hn,G}$ as the scaling factor from [12].

Conclusion

We performed a latitude survey of two bare neutron counters with compact paraffin moderators that detected atmospheric showers from galactic cosmic rays on board the Swedish icebreaker Oden during 2009–2010. By taking such measurements as the ship traversed a wide range of magnetic latitudes, we were able to measure the response function of the bare detectors for the distinct conditions of solar modulation (i.e., effects of solar activity on the galactic cosmic ray flux) during the southbound interval (mostly late 2009) and the northbound interval (early 2010). Combining these measurements with cosmic ray spectra inferred from the PAMELA spacecraft, we derived two estimates of the yield function that are in very good agreement, marking the first direct determination of the yield function of a specific configuration of bare neutron detectors.

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