29th International Cosmic Ray Conference Pune (2005) **00**, 101–104

Atmospheric Neutron Measurements in the 10–170 MeV Range

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We present revised results from atmospheric neutron measurements in the energy range 10–170 MeV performed during the solar minimum in 1987 at four different sea level and mountain altitude locations in the United States. The measurements were conducted by a neutron double-scatter telescope developed at the University of New Hampshire. For the reconstruction of the incident neutron flux we used an improved detector response matrix derived from recent Monte Carlo simulations. For the four locations we determined the energy spectrum and angular distribution of the secondary cosmic ray neutrons. From these results we derived the atmospheric neutron attenuation length as well as the the flux change due to different geomagnetic cut-off rigidities at the four locations.

1. Introduction

Initiated by primary galactic cosmic rays neutrons are produced as secondary particles in hadronic cascades in the Earth's atmosphere. The flux of these neutrons depends on the atmospheric depth, the geomagnetic cut-off rigidity at the site of measurement, and the solar activity. Furthermore, local peculiarities may also affect the neutron flux. Although the flux at ground level is small, for high-density microelectronics cosmic ray neutrons are a source of soft upsets. Higher in the atmosphere neutrons play a significant role in the assessment of radiation risks in aviation. Therefore, new interest in the knowledge of atmospheric neutron flux has emerged.

The study of atmospheric neutrons was first performed by Hess et al. [1]. Later measurements were conducted by Preszler et al. [2], Ait-Ouamer et al. [3], and more recently by Gordon et al. [4]. We report the reanalyzed results of a campaign to measure cosmic ray neutrons at ground level in the energy range 10–170 MeV during the solar minimum in 1987. We first describe the instrument used to make the measurements and how it was calibrated and modeled. We then describe the campaign and the results.

2. Instrumentation

The University of New Hampshire designed and built a double-scatter neutron telescope to measure the energy spectrum and the zenith angle dependence of the secondary cosmic ray neutron flux at ground level. A detailed description of the instrument was given by Saxena [5]. The detector determines the energy and zenith angle of individual neutrons using the double scatter technique. A neutron entering the telescope scatters first in a liquid-scintillator-based detector module, D1. The scattered neutron is then detected by a similar detector module, D2, placed vertically below D1. Both modules are viewed by four photomultiplier tubes (PMT) each. The pulse height in D1 provides a measure of the energy of the recoil proton. The energy of the scattered neutron is then determined by a time-of-flight (TOF) measurement using the signals from D1 and D2. The sum of both energies is then a measure of the incident neutron energy. If the scatter in D1 is an elastic neutron–proton scatter, then the kinematics of the process, together with the measured energies provide an estimate of the neutron scatter angle. Since the detector modules are aligned vertically, the scatter angle corresponds to the local zenith angle. The azimuth angle of the incident neutrons cannot be determined, but the azimuthal asymmetry of the neutron flux is expected to be small. In order to reject signals caused by charged particles entering the telescope or produced in inelastic neutron scatters, the modules D1 and D2 are surrounded by plastic scintillator detectors. Pulse-shape discrimination (PSD) and TOF is used to reject signals due to γ-rays.

The neutron telescope was calibrated at the Indiana University Cyclotron Facility [5]. The calibration was necessary because the scintillator has a non-linear pulse-height response to protons below a few MeV due to ionization saturation. Primary neutrons may also undergo scattering in the passive material of the detector. Calibration measurements provide insight into the angular resolution of the telescope. Reaction channels other than elastic neutron-proton scattering become more important with increasing neutron energy, and reduce the efficiency. The measured efficiency for detecting neutrons at 20° off the zenith ranges from $\sim 10^{-4}$ at 20 MeV to $\sim 10^{-5}$ at 100 MeV. Off-diagonal response matrix elements are generally smaller than the diagonal ones.

Because the instrument was exposed to discrete neutron beam energies and incident directions, the calibration measurements are of limited value in measuring a continuous neutron spectrum in energy and angle. The detector response matrix can also be computed by Monte Carlo simulations. The code originally used is described by Ryan et al. [6]. Below 50 MeV the agreement of the results of this calculation with the calibration measurements was $\sim 30\%$, but at higher energies the simulated efficiencies were a factor of ~ 2 higher than measured. Although several years have elapsed since the measurements, we developed a Monte Carlo code based on the state-of-the-art GEANT4 libraries [7] to reanalyze the data. All the active material, i.e., the liquid and plastic scintillators, is modeled in the code. We do not consider passive materials such as the aluminum housing for the scintillators or the support structure of the photomultiplier tubes.

3. Measurements

The measurements were performed in 1987 in a campaign at Leadville and Boulder in Colorado and Mt. Washington and Durham in New Hampshire. For the four locations the relevant data are compiled in Table 1. In Leadville, Boulder, and Durham the detector was located in buildings with relatively thin roofs. At Mt. Washington the telescope was housed in an air conditioned truck with a thin aluminum roof. At each location gain calibrations were periodically performed with muons and radioactive sources, and the data were corrected for TOF and PSD walk. The durations of the measurements varied according to the local neutron flux from 5 days at Leadville to 26 days at Durham.

Table 1. Data relating to the measurement locations.

Site	Altitude [m]	Atmospheric depth [$\mathrm{g\,cm^{-2}}$]	Geographic longitude	Geographic latitude	Geomagnetic cut-off [GV]
Leadville, CO	3109	705	106.30°W	39.25°N	2.97
Boulder, CO	1655	846	105.21°W	40.05°N	2.90
Mt. Washington, NH	1850	826	71.30°W	44.43°N	1.43
Durham, NH	24	1030	70.94°W	43.13°N	1.61

All the PMT signals were gain corrected. In order to accept only signals from neutrons that underwent elastic neutron–proton scatters and that travelled from D1 to D2, TOF and PSD selections were applied. The PMT signal in D1 was converted into recoil proton energy, and the TOF into kinetic energy of the scattered neutron. The data were then binned into 5 intervals of total energy (10–170 MeV) and 3 intervals of zenith angle (15°–45°).

4. Results

For each site the differential flux values of each energy/angle bin was computed from the count rates using the simulated response matrix. Due to limited statistics we integrated over the entire period of measurement. In order to extrapolate the integral flux in the zenith angle range 15°–45° to the entire upper hemisphere we derived the zenith angle dependence from the data. We integrated the fluxes of the four sites over the energy range 20–170 MeV and normalized the obtained zenith angle distributions. Assuming a zenith angle dependence $\propto \cos^n \theta$, we obtained from the best fit a power-law index $n = 2.9 \pm 0.3$. A comparison to the values derived by Preszler et al. [2] ($n = 3$) and Heidbreder et al. [8] ($n = 3.5 \pm 1.2$) shows that our measured flux is less peaked towards the zenith. However, all the three values agree within their uncertainty. Figure 1 shows the extrapolated fluxes for the upper hemisphere.

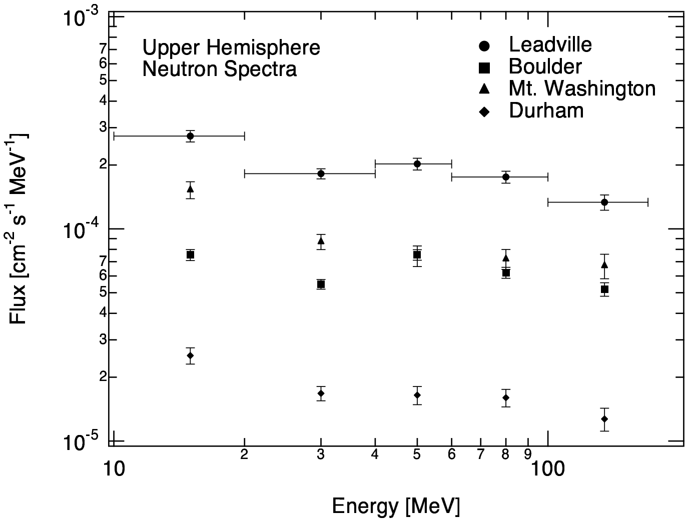

Figure 1. Upper hemisphere neutron spectrum at four sites during in 1987.

We integrated the differential fluxes over the energy range 20–170 MeV and the zenith angle range 25°–45° to investigate the dependence of the total fluence on altitude and latitude. For an exponential attenuation of the neutron flux in the atmosphere we determined the e-folding attenuation length for both pairs of locations with similar geomagnetic cut-off rigidities, R_c. For the New Hampshire measurements we obtained $126 \pm 9\,\mathrm{g\,cm^{-2}}$ ($R_c \simeq 1.5\,\mathrm{GV}$), and for the Colorado measurements $143 \pm 10\,\mathrm{g\ cm^{-2}}$ ($R_c \simeq 2.9\,\mathrm{GV}$). The combination of both values yields $134 \pm 7\,\mathrm{g\,cm^{-2}}$. This value is in reasonable agreement with the computed value by Flückiger et al. [9] and measurements by Ashton et al. [10]. However, Hess et al. [1] reported a greater attenuation length of $155\,\mathrm{g\,cm^{-2}}$ as did Tajima et al. [11] of $159\,\mathrm{g\,cm^{-2}}$. We used the derived attenuation length to normalize the spectra to sea level. Due to the difference in the geomagnetic cut-off rigidities between the New Hampshire and the Colorado sites, $\Delta R_c \simeq 1.5\,\mathrm{GV}$, we measured a difference in flux of $(6 \pm 7)\%$. Although the detector response matrix suffers from unspecified systematic uncertainties, this should not significantly affect the estimates of the neutron attenuation depth or the rigidity dependence. We could then use these coefficients to compile a global energy spectrum and zenith angle distribution.

The summed normalized spectrum for Durham is shown in Figure 2 where the omnidirectional fluxes at all sites are corrected to sea level. Our measurements include the upper hemisphere only, therefore the values are expected to adjust upwards if the lower hemisphere is also considered. From the four fluxes normalized to

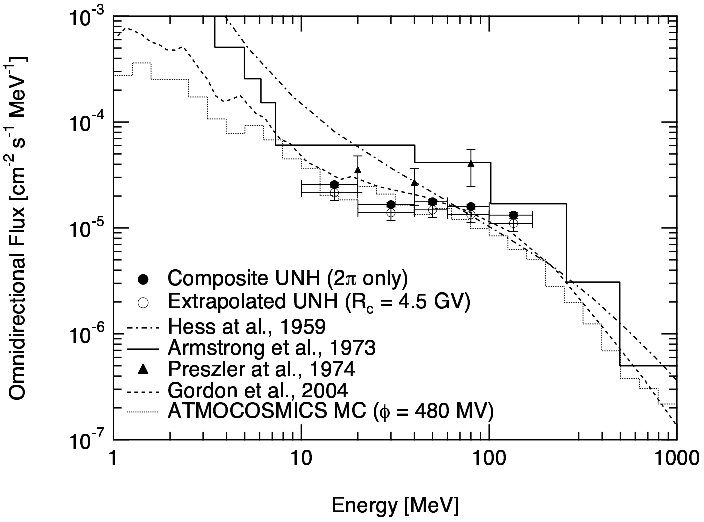

Figure 2. The cumulative midlatitude sea level neutron energy spectrum. For details see text.

sea level we derived a cut-off rigidity gradient of $(10 \pm 8)\%/\mathrm{GV}$. To better compare with other spectra we extrapolated our flux to a cut-off rigidity of 4.5 GV. The spectrum of [1] is significantly softer than other measurements [2] and calculations [12]. We also show the calculated neutron flux for the same location and solar activity and for the upper hemisphere using the GEANT4 based ATMOCOSMICS code [13]. Above 10 MeV these values are in a good agreement with other recent measurements [4]. Our measurements show little variation above 20 MeV, similar to those of Preszler et al. [2]. Fitting a single power-law dependence E^{α} to our spectrum we derived a spectral index $\alpha = -0.25 \pm 0.10$. This corresponds to an even harder spectrum than that by Preszler et AP. [2] and obtained from ATMOCOSMICS. Our flux values extrapolated to 4.5 GV are the lowest in Figure 2. However, applying a correction to obtain an omnidirectional flux might raise and soften the spectrum. The computed instrument efficiency will also be adjusted downward by including passive material in the simulations. This will raise the corresponding flux values. Further analysis of the data is in progress.

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