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A mobile neutron monitor to intercalibrate the worldwide network

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Abstract With the commercial availability of high efficiency ^{3}He counters it has become possible to construct a mobile neutron monitor that will count 250 000 particles, i.e. with 0.2% counting statistics, in less than 6 days (at sea level at the highest cutoff rigidities). Such a monitor will have dimensions not exceeding 40x40x90 cm, and its mass will be about 220 kg. It can, therefore, be physically handled and put next to neutron monitors in the world-wide network to intercalibrate them, and to derive intensity spectra (differential response functions) from them. This spectral information will make neutron monitors much more useful cosmic ray detectors. This contribution describes the physical and electronic design of this calibrator, simulations of its counting rate, and the first plans to calibrate it against an NM64 neutron monitor.

1. Introduction

The quality of the 50-year old world-wide neutron monitor (NM) network can be significantly improved in three ways. First, Bieber and Evenson (1995) described the concept of “Spaceship Earth” whereby 11 high latitude neutron monitors are upgraded, redeployed or newly constructed to establish a network with optimal directional sensitivity for the detection of transients such as Ground Level Enhancements and anisotropies. Nine of these neutron monitors have narrow cones of acceptance evenly spaced along the equatorial plane, while the Thule and McMurdo neutron monitors cover the North and South polar directions, respectively. All these neutron monitors have the same (atmospherically determined) low cutoff rigidity, which makes it particularly simple to reconstruct the free space density distribution function of the event.

A second improvement would be to extend the energy range in the calibration of neutron monitors at a particle accelerator laboratory. The recent accelerator measurements on an NM64 at the Osaka University nuclear accelerator facility by Shibata *et al.* (1999) marks the first measurement of the detection efficiency in a controlled environment. This work has provided exciting results that verified Hatton's (1971) work, as well as the simulation used in this work. The internal operation of a neutron monitor is quite complex to model. Therefore, their work is a big achievement in confirming our understanding of how a neutron monitor responds to ground level particles. Since this accelerator calibration was only done with a narrow range of energies, more data from measurements at different energies and particle species would be valuable. Once the detection efficiency of a neutron monitor is determined experimentally and a solid theoretical prediction is established for fitting and interpolation purposes, the particle transport of particles through the atmosphere is the only remaining component needed to determine the neutron monitor yield function.

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A third significant improvement can be realised if individual neutron monitors at different cutoff rigidities can be calibrated against one another. Then the neutron monitor differential response function can be calculated from the difference in counting rate, N, at cutoff rigidity, P_c, of pairs of neutron monitors, using

$$dN/dP \approx [N(P_{c2}) - N(P_{c1})]/[P_{c2} - P_{c1}] \quad (1)$$

This differential response function is a fundamentally important quantity, because it is related to the intensity spectrum, *j(P),* of primary cosmic rays above the atmosphere by,

$$-dN/dP = \sum_{species} S(P,x)\, j(P)\,, \quad (2)$$

where *S(P,x)* is the so-called atmospheric yield function of a particular species of primary particles.

Differential response functions have been measured many times with mobile neutron monitors, as summarised, *e.g.,* by Moraal *et al.* (2000). The intercalibration of stationary neutron monitors has always been an implicit aim of these latitude surveys: when the latitudinal (or cutoff rigidity) and altitude response of neutron monitors is known with sufficient accuracy, the counting rate of a stationary neutron monitor can be calibrated against that response function. The Italian group pursued this intercalibration the furthest, by actually transporting a neutron monitor to several European stations during 1963. From the results, described in Bachelet *et al.* (1972), it seems that the inherent accuracy of individual counting rates could be determined to ≈ ±1%. This is insufficient for useful spectral studies, as will be shown shortly, and the ideal of intercalibration has never been pursued further. The uncertainties in such an intercalibration are mainly due to (a) different responses to primary intensity variations of neutron monitors of different design, (b) different atmospheric (pressure and temperature) responses of the neutron monitors, and (c) environmental differences due to the fact that the calibrator can usually not be transported to the identical environment of the stationary neutron monitor, which literally means inside the same hut. These systematic uncertainties are estimated to be about 0.2%. The statistical uncertainty of the calibration will be smaller than this if the calibrator counts at least 250 000 events per calibration.

2. Spectra Derived From Calibrated Neutron Monitors

The counting rate of a neutron monitor can be parameterized by an expression due to Dorman *et al.* (1970), given by

$$N(P > P_c) = N_0[1 - \exp(-\alpha P_c^{-k})]\exp[\beta(p_s - p)] \qquad (3)$$

From the summary by Stoker and Moraal (1995) of aircraft surveys during solar minimum conditions at 30000 ft pressure altitude, the calculations of Stoker (1994) at other altitudes, the altitude measurements of Raubenheimer and Stoker (1974), and the parameterization of Usoskin *et al.* (1997), it follows that the counting rate of a 6NM64 monitor can be estimated to within 5% from this formula, with N_o = 250 000 counts per hour, α = 10, k = 1.4 - 0.0006p, where pressure p is measured in mm Hg, β = 1%/mm Hg, and p_s = 760 mm Hg.

The accuracy of intercalibration that is required for useful spectral studies can be estimated as follows. From (3) it follows that the (logarithmic) differential response function is given by

$$\frac{1}{N}\frac{dN}{dP} = \frac{\alpha k P^{-k-1}}{1 - \exp(\alpha P^{-k})} \qquad (4)$$

It has a maximum value of ≈ 6 %/GV at P = 4.5 GV at sea level, with values of 0.4 %/GV at P = 1.4 GV (and 0.2 %/GV at P = 1.25 GV). This means that if one wants to have a statistically significant differential response function down to 1.4 GV, two individual neutron monitors must be calibrated against one another with an accuracy of 0.2%. In this case (4) implies that the error on the lowest point of the differential response function is equal to its magnitude. Figure 1 shows what a sea level differential response function would look like when calculated from (1), using 11 neutron monitors, spaced equidistant (logarithmically) between 1.2 and 15 GV, and calibrated against one another to within 0.2%.

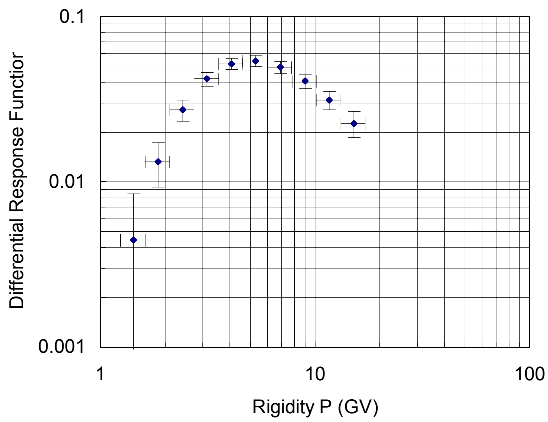

Figure 1. Typical differential response function that can be obtained from 11 intercalibrated neutron monitors that are placed at cutoff rigidity intervals that increase by 30%. The vertical error bars result from 0.2% systematic errors in the counting rate of the individual neutron monitors. The Dorman function as in (3) and (4) was used for this calculation.

If this accuracy can be achieved, cosmic ray spectra can be determined from intercalibrated neutron monitor counting rates down to 1.4 GV, which is equivalent to kinetic energy T = 740 MeV protons, and 230 MeV/nucleon fully stripped cosmic ray nuclei. This lower limit decreases to T = 600 MeV protons if the accuracy of intercalibration is doubled to 0.1%. But this small gain in energy range seems hardly worth the effort, considering that it requires four times the total number of counts. Typical space detectors, such as those on the Pioneer 10 and 11, Voyager 1 and 2, and IMP8 spacecraft have proton channels up to 200 MeV and Helium channels up to 500 MeV per nucleon. This means that spectra deduced from neutron monitors would be entirely complementary to those measured in space. This offers much extended opportunities to study the energy or rigidity dependence of the modulation, without being restricted to (infrequent) latitude surveys. Good examples of such studies are the cross-overs in spectra, described by Reinecke *et al.* (1997), and the analysis of Ground Level Enhancements by, *e.g.,* Lovell *et al.* (1998).

3. The ^{3}He Calibration Neutron Monitor

A calibration neutron monitor has become a realistic possibility with the introduction of high counting rate ^{3}He counters, as described by Clem and Dorman (2000). These counters are filled to a pressure of four atmospheres, instead of the 0.25 atmospheres of the standard $^{10}BF_3$ counters.

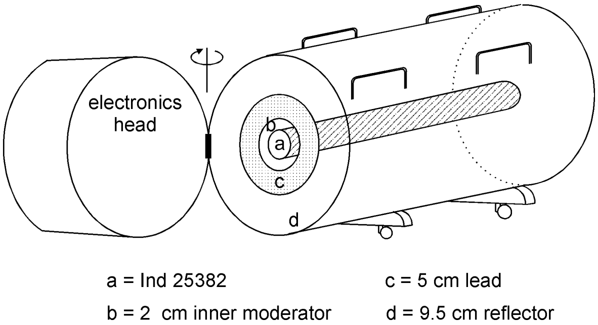

Figure 2. Schematic diagram of the LND25382 ^{3}He calibration neutron monitor. It consists of a ^{3}He counter surrounded by a 2 cm thick inner moderator, a 5 cm thick lead producer, and a 9.5 cm outer reflector, inside an Aluminium box 0.5 cm thick.

Figure 2 shows a schematic diagram of such a neutron monitor. Its outer dimensions are ≈ 80 cm long with a radius of ≈ 20 cm. The LND25382 counter has a length of 63 cm (one third of the standard length of the LND25373 and NM64 counters) and a radius of 2.5 cm. It is surrounded by a 2 cm thick moderator, made of paraffin wax. The moderator, in turn, is surrounded by a 5 cm lead ring, which acts as a producer of neutrons, while around that there is an outer paraffin wax reflector with a thickness of 9.5 cm, so that the total radius of the detector is 19 cm. In this configuration, the lead has a mass of 170 kg, the paraffin wax 25 kg, while the mass of the whole unit is estimated to be 220 kg. Four people can carry such a box if it has conveniently placed handles. With these dimensions and mass it can be placed inside a neutron monitor hut. Experiments will be done to determine interference effects between the calibrator and the stationary neutron monitor due to insufficient shielding. Counting rates can also be measured outside the hut, and the calibrator can even be hoisted into the air to test for all kinds of environmental effects.

Preliminary simulations were done on such a neutron monitor using the FLUKA particle transport package described by Clem and Dorman (2000). So far, only the response to the most important contributors, neutrons and protons, has been calculated. This is regarded as sufficient to determine the general characteristics of the monitor. Figure 3 shows that this simulation predicts that the calibrator will count at approximately 1.5% of the rate of a 6NM64. This is equivalent to ≈ 1 Hz at sea level at high latitudes, and 0.5 Hz near the equator. To achieve statistical accuracy of 0.2%, it will have to count for ≈ 60 hours against a stationary neutron monitor at high latitudes, and for ≈ 135 hours at 17 GV. This is quite practical.

The counting ratio in Figure 3 has a slope of –0.18%/GV, or -2.7% from 1 to 15 GV. This is much too large for calibrations that must be accurate to within 0.2%. The reason for this different cutoff rigidity dependence lies in the different geometry, mainly in the lighter lead ring than for the NM64. Simulations have also been done with gas mixtures containing carbon, which reduces the rigidity dependence, but at the expense of counting rate. It will probably be impossible to eliminate the effect entirely. It can, however, be incorporated into the calibration procedure, as long as it is accurately known.

4. Mechanical and Electronic Design

Two LND25382 counters were delivered in March 2001. At present the calibrator is being constructed along the lines of Figure 2. The electronics "head" will swivel onto the body of the detector, and will be replaceable as a unit. This "head" will function as follows: (a) Because of the low counting rate of ≈ 1 Hz, the arrival times of individual counts will be registered. These arrival times are recorded by a microprocessor. When a pulse arrives, the time, in minutes:seconds:milliseconds, as well as the pressure are recorded. Diagnostics such as counter temperature, high voltage (1300 V), and GPS time in cc:yy:mm:dd:mm:ss are only recorded once per minute. Pressure is, however, recorded for each individual pulse with the hope that the difficult problem of roll and pitch with neutron monitors on open seas can be studied further. (b) Data is recorded at a rate of 1.5 MB per day onto a 20 GB hard disk. The communication with the disk has not been finalised, but we do plan to include a 120 MB diskette drive from which the last 80 days' of recordings can be downloaded. Diagnostics will also be displayed on an LCD display. (c) A Paroscientific digiquartz solid state barometer with an accuracy of 0.02 mm Hg, will record atmospheric pressure. This is about 10 times more accurate than required for pressure corrections of the counting rates to within 0.2%. Strictly speaking, separate pressure corrections are not necessary for calibration of stationary neutron monitors that have their own pressure standards, but the barometer is included to make the calibrator so much more versatile. (d) The power supply input will have a dynamic range of 80 to 260V AC. When DC battery operation is needed, the user must supply a UPS.

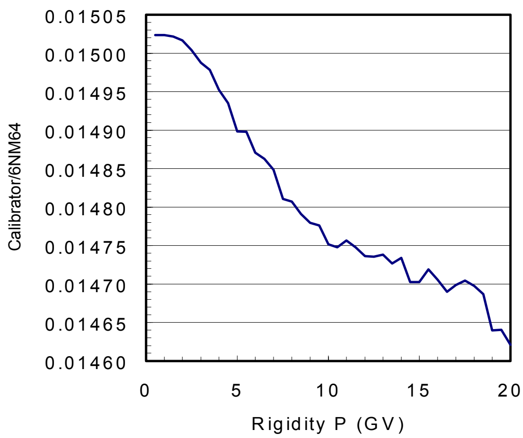

Figure 3. Preliminary estimate of the ratio of the counting rate of the calibrator neutron monitor relative to that of a 6NM64. This calculation is based on the response to neutrons and protons only.

The required 0.2% counting accuracy implies that computer time may drift with up to 3 minutes per day before it becomes significant. Current computers easily meet this requirement, and, therefore, GPS time is only passively stored as a check and to correct *post hoc* for unexpected eventualities.

5. Calibration Procedure and Initial Plans

Two calibration monitors are presently being built, with the target date for testing 1 September 2001. One of the calibrators will remain stationary at the same site, probably at the Potchefstroom neutron monitor, with the other one travelling to neutron monitors in the network. Occasionally, the travelling calibrator will be brought back to the stationary one to verify their long-term stability.

The first step will be to put the calibrator inside the container of the Australian/US mobile 3NM64 neutron monitor on its voyage from Seattle to Antarctica in the Austral summer of 2001/2002 (see Bieber *et al.*, 1997). The main purpose is to measure the latitudinal dependence of the counting ratio predicted in Figure 3. When this is confirmed, or the differences between the predictions and the measurements understood, the calibration of stationary neutron monitors can begin. This calibration procedure should consist of two parts. First, the calibrator should be put as near to the neutron monitor as possible, preferably inside the same hut, but such that cross-interference is kept to a minimum. Additional calibrations should then be done at the same site, but in an environment that is as open as possible, removed from buildings or other structures. The difference between the first and secondary calibrations then gives an indication of the local environmental effects on the neutron monitor at that particular site.

Acknowledgements

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