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New method of observing neutron monitor multiplicities

J. W. Bieber[1], J. M. Clem[1], P. Evenson[1], M. L. Duldig[2], J. E. Humble[3], and R. Pyle[1]

[1]Bartol Research Institute, University of Delaware, Newark, DE 19716, U.S.A.

[1]Bartol Research Institute, University of Delaware, Newark, DE 19716, U.S.A.

[2]Australian Antarctic Division, Kingston, Tasmania 7050, Australia
[3]School of Mathematics and Physics, University of Tasmania, GPO Box 252-21, Hobart, Tasmania 7001, Australia.

Abstract. We have recently augmented the electronics in our neutron monitor (NM) latitude survey station to record the elapsed time (δT) between counts from each proportional tube. These data are used to study the different characteristics of the δT distribution as a function of rigidity cutoff and primary spectrum. These observations also provide the opportunity to quantify the count rate reduction from using a longer dead-time (as used by the Russian NM stations). Preliminary analysis of our data suggests the NM response to primary cosmic rays is a strong function of dead-time. The results of Monte Carlo calculations are also shown and are compared to these observations.

1 Introduction

Multiplicity measurements made on neutron monitor latitude surveys provide additional information on the shape of the primary spectrum. The earliest known measurements of the latitude dependence of multiplicity were performed by Dyring and Sporre(1966) using a 2-tube IGY monitor. Traditionally the multiplicity of an event is determined by opening a time-gate initiated by a single count and adding the additional counts that occurred during the gate length. The total number of counts in each event determines the multiplicity level. Each level has an associated response function corresponding to a different median rigidity of primary particles. Due to the complicated nature of the neutron monitor detection process and the broad energy fluctuations of ground level secondaries for the same primary energy, extracting the resulting primary spectrum from a multiplicity distribution is very difficult. Our method provides a new approach of measuring multiplicity which records the δT distribution between counts. By preserving the time structure, the observations provide additional constraints on the primary spectrum. In this work, we present a preliminary analysis of data measured during the 2000-2001 Bartol/Tasmania survey.

Correspondence to: J.M. Clem (clem@bartol.udel.edu)

Multiple counts in a neutron monitor occurring within a period of a few milli-seconds (msec) can be produced by two independent phenomena: (1) incident particle showers containing a hadron density of roughly >2 m^{-2} and (2) multiple secondaries generated from a single particle interaction in the Pb (lead) producer. Due to the short interaction length (~100g/cm^2) a hadron observed at sea-level is a product of roughly 10 inelastic interactions since the parent primary entered the atmosphere. If the last atmospheric interaction occurred 1/2 of an interaction length above the monitor, the detection of multiple incident particles requires that the angular separation between the resulting secondaries produced in the interaction must remain within 2x10^{-3} radians (not considering scattering effects). Even though such events provide a relatively small contribution to the total count rate, it is not clear as to how significant a role they play in the multiplicity events. This will be investigated in the near future. However, for our present analysis, we consider only uncorrelated single events.

Roughly 60% of the energetic hadrons that enter the Pb producer of a neutron monitor produce an inelastic interaction. The n-Pb interaction process can generally be separated into two stages. During the first stage, knock-on nucleons, heavy fragments and mesons are generated with a wide range of energies and a scattering distribution strongly biased in the direction of the incident particle's momentum. Generally, these secondary particles escape detection or produce further interactions within the Pb. The next stage of the process is the de-excitation phase in which additional particles are emitted from the unstable, wounded Pb nucleus. Most of these emissions are evaporated neutrons that are characterized by a spectrum peaked near 2.5 MeV and an isotropic angular distribution. The average number of evaporated neutrons generated in an interaction is energy dependent and can be roughly described as a power law

$$\nu_n = 25E^{0.4}$$

where ν_n is the average number of evaporated neutrons and E is the energy (GeV) of the incident particle (Hughes et al.

1964, Shen 1968, Hatton 1971). Therefore, a Pb interaction involving a 100 MeV incident neutron produces an average of 10 evaporation neutrons.

The probability of detecting an evaporation neutron depends on its initial energy and the location of the n-Pb interaction within the producer. An average detection energy dependence has been calculated (Hatton 1971) by integrating over the producer volume of an NM-64. This calculation yielded average values ranging from 2% at 20 MeV to 10% at 0.2 MeV. Applying these results, the probability of detecting one or more evaporation neutrons from a 100 MeV neutron-Pb interaction was determined to be roughly 40%, 8% for 2 or more and 1% for 3 or more and so forth, resulting in a multiplicity distribution which is dependent on the energy of the incident particle. Multiple detections of evaporation neutrons from the same interaction do not occur instantaneously, but exhibit a characteristic time distribution defined by the energy spectrum of the incident hadrons, and by the diffusion properties and geometry of the materials used in a neutron monitor. To provide better understanding of this internal instrument process and additional checks of our simulations, we have augmented the electronics in our 3-tube NM-64 latitude survey station to measure the elapsed time (δT) between counts from each proportional tube. This is a unique method of measuring multiplicity in latitude surveys; however Hatton and Tomlinson (1968) made very similar measurements with IGY and NM64 monitors at one location. These observations also provide a means to determine the response of a neutron monitor as a function of deadtime and rigidity cutoff. This relationship will allow the ability to quantify the response differences between our stations and the Russian stations which have a much longer deadtime (Eroshenko 2001).

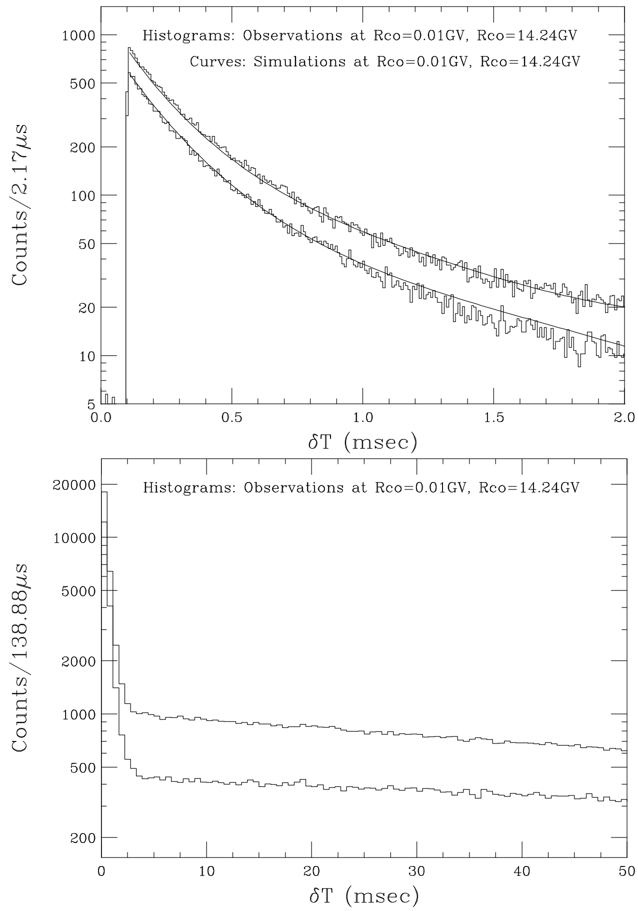

Fig. 1. Top: Distribution of the elapsed time (δT) between measured single tube counts for 14.2 GV rigidity cutoff and 0.0 GV cutoff locations. The histogram represents the observed data and the curve represents simulated data scaled by 0.7. Bottom: The condensed distribution of the elapsed time (δT) data.

2 Method

Each detector is read out by custom electronics and the elapsed time between counts is derived from a sixteen bit scaler internal to a microcontroller. This scaler advances uniformly at a frequency derived from an external oscillator (3.6864 MHz divided by eight), thus each tick of the clock is 2.17 μsec.

When the appropriate logic in the microcontroller is armed, a firing of the detector counting discriminator latches the internal scaler in a register and generates an interrupt to the microcontroller. Processing this interrupt takes approximately 95 μsec to the point where the circuit may be re-armed. This determines the minimum time separation that can be measured (deadtime). Keeping track of scaler overflows would increase this latency dramatically, so we simply allow the scaler to cycle with the result that times are recorded modulo approximately 142 mses.

Primary readout of the detector electronics takes place once per second. A count of the total number of discriminator firings (from a hardware scaler) is transmitted, together with various housekeeping information. Part of this housekeeping information is the timing scaler reading and pulseheight for the first 12 sequential discriminator firings.

For the present analysis, we ignore the first scaler reading (since the actual latency of that is unknown due to the time occupied by the readout cycle) and compute the delay times first-to-second, second-to-third, and so forth. Histograms of these times (1024 channels) are accumulated and recorded for each hour.

Figure 1 displays the time distribution of the center tube for two different locations on the 2000-2001 Bartol-Tasmania latitude survey. The truncation at the low end (95μsec) of the distribution is the result of the deadtime in the multiplicity circuit. It should noted that the corresponding deadtime in the counting circuit is 20 μsec (NM64 standard value). The effective vertical rigidity cutoffs of these two locations were 14.24 GV (bottom) and 0.01 GV(top) and the elapsed exposure time at each location is 24hrs. These particular locations were chosen such that the McMurdo neutron monitor count rate was fairly constant for these periods of the survey.

Data in the top panel are compared to simulations. The shape of the simulations are fairly consistent with the observations, however there some systematic differences. A

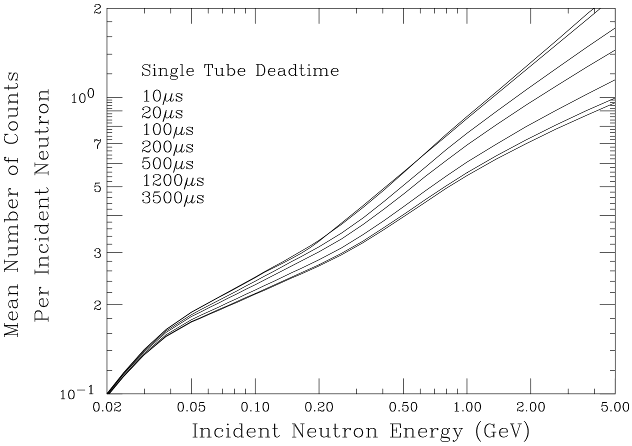

Fig. 2. The average number of counts in a 6 tube NM-64 calculated for different deadtimes.

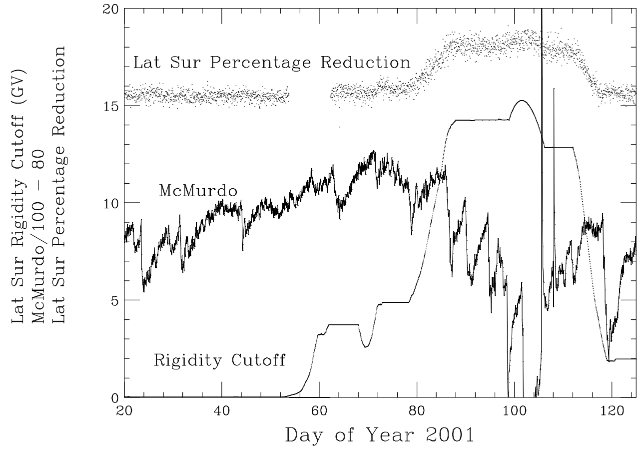

Fig. 3. Time profile plot of the 2000-2001 latitude survey north bound voyage. The data at the top of the plot shows the percentage of counts with a δT between $95\mu sec < \delta$T$< 1200\mu sec$ compared to δT$> 95\mu sec$. The McMurdo count rate shown (scaled by 0.01 and offset by 80) provides an indicator of solar activity during the survey. The effective vertical rigidity cutoff is shown as a curve.

scaling factor of 0.7 was needed to adjust for the difference in normalization, which is very likely the result of unknown detection inefficiencies in the neutron counters. Previously, comparison of accelerator data of neutron monitors have shown normalization differences from 10% to 30% (Shibata et al. 1999 and Birattari et al. 1998). Briefly, the simulation generates primary particles (protons and alpha particles) pulled from the typical solar maximum spectrum which are then propagated through the atmosphere using FLUKA and HEAVY particle transport packages (Fasso et al. 1993, Engel et al., 1992). Sea-level particles are collected and are used as input to another simulation which propagates particles through a typical NM-64 structure using FLUKA and software developed by one of the authors (Clem 1999, Clem and Dorman 2000). The elapsed time between the starting position of the primary particles at the top of the atmosphere and thermal neutron detection is accumulated accordingly throughout the full calculation and is recorded along with other relevant parameters for primary and secondary particles. Further details of this simulation can be found Clem and Dorman (2000) and references therein.

The bottom panel in Figure 1 gives the condensed distribution of the same data shown in the top panel. This figure clearly reveals a break in the pure exponential distribution near 4msec. Single cosmic ray events are randomly distributed in time, hence the resulting δT data should follow an exponential distribution of a fixed time constant. This would suggest the break in distribution separates single uncorrelated events from multiplicity events. These measurements show that most multiplicity events have δT values of less than 3.5msec.

3 Deadtime Effects

Our data also allow us to study changes in count rates for different deadtimes by summing events in the δT distributions with different lower limits. Figure 2 displays calculated average number of counts per incident neutron as a function energy and deadtime. In order to isolate deadtime effects of multiple detections from single incident particles, losses from multiple incident particle events occurring within the deadtime period are ignored. This calculation was performed through simulating particle transport and detection in a NM64 standard structure as described in the previous section. As shown, these results suggest that the NM64 ability to detect multiple evaporation neutrons from a single incident particle is nearly maximized for a deadtime set at 20μsec and nearly minimized for 1200μsec. However, the data shown in the bottom panel of Figure 1 suggest that a longer deadtime ($\sim 3500\mu$sec) is needed to remove most of multiplicity events assuming all incident particles are uncorrelated in time. Unfortunately, the short deadtime calculation can not be verified by the data. Interesting enough, the original amplifier-discriminator attached to the BP-28 counters have an average deadtime of 20μsec while the Russian run stations have introduced a 1200μsec deadtime to avoid multiplicity events. According to the calculation these two deadtimes were properly chosen to achieve the desired effect, however the δT data suggest 3500μsec would have been more appropriate for rejecting multiplicity events. The difference between this calculation and observations could be the result of ignoring the contribution of multiple incident particles produced from the same high energy primary.

As one would expect, the NM-64 response to primary cosmic rays is different for these two deadtimes as used by the Russian stations and the Standard NM-64 value. This effect can be shown through summing the events in the δT distribution with different lower limits which represents the deadtime. Since the multiplicity circuit has an intrinsic 95μsec deadtime, we are unable to make a direct comparison between these two exact deadtimes, but a lower limit on the effect can be determined. Figure 3 displays δT data in a per-

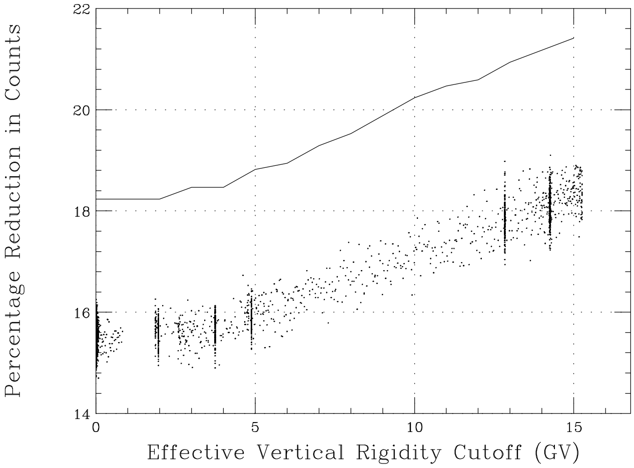

Fig. 4. The observed percentage of counts with a δT between $95\mu sec < \delta$T$<$ $1200\mu sec$ compared to δT$<$ $95\mu sec$ as shown in the previous figure as a function of effective vertical rigidity cutoff. The curve represents the expected reduction as derived by a simulation.

centage reduction of counts if the δT circuit deadtime were changed from 95μsec to 1200μsec. This "Russian reduction" is shown as function of time measured during the 2000-2001 latitude survey along with the local effective vertical cutoff (GV) and the McMurdo neutron monitor station count rates. The sun was very active during this period with little effect on the "Russian reduction", however there is a fairly strong dependence in cutoff rigidity. The reduction increases with increasing rigidity which implies the Russian stations are less sensitive to high rigidity primaries. This also implies that a Forbush decrease changes the normalization of sea-level hadrons spectra, but has very little effect on the spectral shape. As previously discussed, the evaporation neutron multiplicity in the producer is strongly dependent on the incident spectra. The rigidity cutoff, however has a significant effect on both normalization and spectral shape.

Figure 4 displays the direct correlation of percentage reduction and rigidity cutoff as shown in Figure 3. The percentage reduction varies from 15.5% to 18.5% over a rigidity cutoff range from 0-15 GV. This dependence is quite significant, because some research projects require neutron monitor accuracies better than a few percent. The rigidity dependence of the "Russian reduction" would actually be stronger if the standard deadtime of 20 μsec was compared. The same calculation that generated the results in Figure 1 is also shown in this plot for comparison. The shape represents the observations fairly well, however the normalization is off. A scaling factor of 0.85 is roughly the difference in normalization. This difference is probably symptomatic of the minor difference in the shape of the calculation and observations as compared in Figure 1. These anomalies in the calculation provide interesting clues in our on-going investigation to understanding the internal processes of neutron monitor.

4 Conclusion

This method of recording multiplicities provides a powerful tool to study various characteristics of a neutron monitor and the ability to sample different rigidity regions of the primary spectrum at a fixed location. It will allow us to better understand the statistics of count rates with and without multiplicity events. The Monte Carlo simulations seem to reproduce the parameter correlation of our observations fairly well, however the normalization differences will be investigated.

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