29th International Cosmic Ray Conference Pune (2005) **2**, 485-488

Neutron Monitor Temperature Coefficients: Measurements for BF_3 and ^3He Counter Tubes

P. Evenson, J. W. Bieber, J. Clem and R. Pyle
Bartol Research Institute, University of Delaware, Newark, DE 19716, USA
Presenter: R. Pyle (pyle@bartol.udel.edu), usa-pyle-R-abs2-sh36-poster

The Bartol neutron monitor network, part of the Spaceship Earth (SSE) project, utilizes a combination of BF_3 and ^3He neutron counter tubes. In order to make the datasets from these near-identical stations as comparable as possible, we have found it necessary to apply temperature corrections to the data. By analysis of several years of data we have measured the absolute temperature coefficients for both BF_3 and ^3He neutron counter tubes. Counter tubes at the end of a linear array exhibit a higher coefficient than the other tubes. We will compare these results with Monte-Carlo simulations of the temperature response, which include the effects of monitor structure and temperature-dependent cross-sections. The measured temperature coefficients are now being used to correct all of the Bartol network data for which we have adequate temperature measurements. Supported by NSF grant ATM-0000315.

1. Introduction

Spaceship Earth (SSE) is a multi-national project utilizing a network of neutron monitors strategically located so that they provide precise real-time measurements of the cosmic ray flux in three-dimensions. This network consists of nine stations whose asymptotic acceptance directions lie near the Earth's equatorial plane, at approximately 40-degree intervals. Two other stations have acceptance directions towards the North and the South, providing the network's three-dimensional capability. Since all of these stations are near-identical standard NM-64 design, and lie near sea-level in regions of near-zero geomagnetic cutoff, they have a uniform spectral response of approximately >300 MeV, set by the atmospheric cutoff.

The six SSE stations which are operated by the University of Delaware (Inuvik, Fort Smith, Peawanuck, Nain, Thule and McMurdo) consist of 18 ^3He or BF_3 counter tubes and associated electronics. The Fort Smith, Peawanuck and Nain stations were new (built in 2000), and each consisted of six ^3He counters in each of three 20-foot shipping containers, arranged as two 3NM-64 monitors back-to-back. Each container is equipped with thermostatically-controlled electrical baseboard heaters. Since there is no provision for cooling of these containers, it was recognized during the design phase that we could not guarantee good temperature stability over the course of a year and we attached temperature sensors at the center and at the back of each counter, plus several in-air sensors, each read out once an hour.

Over the first two years of operation, we experienced several thermostat failures in individual shipping containers, with the result that the ratio of count rates between containers changed appreciably; a higher-temperature van showing a relatively higher count rate. These uncontrolled 'tests' only indicated the approximate temperature dependence of the monitors; the rate of temperature change was too high to allow the monitors to come to equilibrium and we could see that the counting rate rise lagged significantly behind the air temperature because of the insulating effect of the monitor structure.

In addition to the three new Canadian stations, we augmented the Thule 9-counter BF_3 monitor with the addition of nine ^3He counters. The Thule monitor is housed in a large building with poor temperature control, and over the course of a year we observed a significant change in the counting rate ratio between the BF_3 and the ^3He counters. The monitor consists of three separated 3NM-64 sections (BF_3 counters) and one 9NM-64 section (^3He counters). The Inuvik station (three 6NM-64 sections, all BF_3) was updated with new electronics and also equipped with temperature sensors.

In the following sections we will discuss a) preliminary Monte-Carlo simulations of these counter structures as a function of temperature, and b) the methods we used to determine the temperature coefficients (fractional change per degree C) for the two varieties of counters and the effect of location of the counters.

The neutron capture cross-section varies inversely proportional to its velocity while the average capture energy is 3/2kT based on Maxwellian statistics. It then follows that the cross-sections should vary inversely as the square root of T since the kinetic energy = $0.5 \cdot mv^2 = 3/2$ kT. Most of the captures or counts observed in the tubes are evaporation neutrons thermalized after passing through the moderator. Upon reaching thermal equilibrium the neutron's motion becomes random and a significant fraction of captures occur outside the counter tube. Only those captures occurring in the tubes are detected while captures elsewhere could be considered an attenuation effect. As the temperature varies these two effects are compensating in terms of the total counts observed. For example as the temperature rises, the detection efficiency of the tubes decreases, however the attenuation length increases. If we consider only these two effects, the temperature dependence of the counting rate is roughly of the form $R(T) \sim \exp(- K_1 (T_0/T)^{1/2}) (1.0 - \mathrm{Exp}(- K_2 (T_0/T)^{1/2}))$, where K_1 and K_2 represent the average number of capture pathlengths *outside* and *inside* the counter, relative to a given reference temperature (T_0). Over a narrow range of temperatures, the relationship can be approximated by a linear function.

2. Monte-Carlo simulations of 3NM-64 monitors

The temperature effect on a Neutron Monitor's detection efficiency was determined using a particle transport code called FLUKA (Fasso et al. 1993). Briefly, the simulation generates primary particles (protons) pulled from the moderate solar modulated spectrum which are then propagated through the atmosphere using FLUKA particle transport packages. Sea-level particles are collected and are used as input to another simulation which propagates particles through a typical NM-64 structure again using FLUKA and software developed by one of the authors (Clem and Dorman 2000). In this part of the code, the temperature ratio is used to scale the low energy (E<20MeV) neutron velocities as well as the absorption, gamma ray emission, fission cross-sections and resulting ionization from an interaction in the different material used in a typical 3-tube monitor. Both the traditional BF_3 and ^3He detectors were considered. The fit to the ^3He monitor results produces an intercept of $1.0020 \pm 0.0022\ ^oC^{-1}$ and slope of $7.30 \cdot 10^{-4} \pm 0.71 \cdot 10^{-4}\ ^oC^{-1}$ while BF_3 monitor results produces an intercept of $0.9993 \pm 0.0019\ ^oC^{-1}$ and slope of $1.76 \cdot 10^{-4} \pm 0.60 \cdot 10^{-4}\ ^oC^{-1.}$

It is clear from this data that the simulation suggests a ^3He monitor is more sensitive to temperature changes than that of a BF_3 monitor. The reason becomes obvious when individual components in NM are heated separately. The temperature effect of the BF_3 proportional tube is compensated by the temperature effects of the other BF_3 monitor components (producer, reflector and moderator) whereas the ^3He counter detection efficiency is less sensitive to temperature changes so that the overall temperature effect of a ^3He counter is dominated by the moderator with some contribution from the producer and reflector.

Preliminary simulations have also been performed to examine the effect of counter position on the temperature coefficient (^3He 3NM-64 only). Approximate values obtained were $8 \times 10^{-4}\ ^oC^{-1}$ for end counters, $7 \times 10^{-4}\ ^oC^{-1}$ for middle counters.

3. Measuring temperature coefficients using ratio variations

Let R_0 be a counting rate at temperature T_0. Then assume $R(T) = R_0 \cdot [1 + \alpha \cdot (T-T_0)]$. We will allow α to be different for ^3He and BF_3 tubes, and also for 'end' and 'middle' tubes. If α_1 and α_2 are <<1 (our Monte-Carlo simulations give values of α less than order 10^{-3}), the ratio of two count rates is then

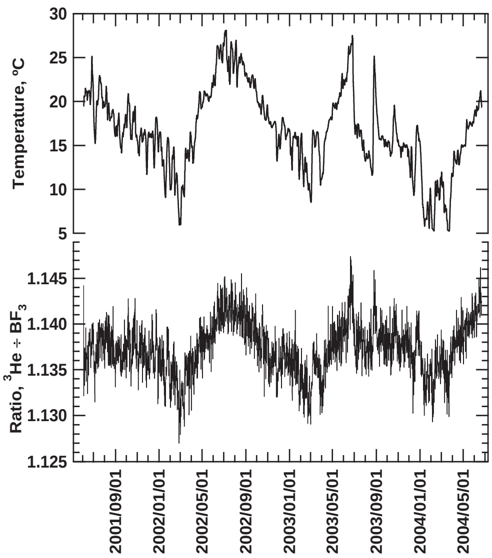
$R_1/R_2 = (R_{10}/R_{20}) \cdot [1 + \alpha_1 \cdot (T_1-T_0) - \alpha_2 \cdot (T_2-T_0)] + [\mathrm{order}(\alpha_2 \cdot (T-T_0)^2]$ [Eqn 1]

To first order: $R_1/R_2 = A + BT$, where $A = R_{10}/R_{20}$ and $B = R_{10}/R_{20} \cdot [\alpha_1 \cdot (T_1-T_0) - \alpha_2 \cdot (T_2 - T_0)]$

We define two simplified cases:

a) *isothermal*, $T_1 = T_2$: $A = R_{10}/R_{20}$, $B = (R_{10}/R_{20}) \cdot (\alpha_1 - \alpha_2)$ [Eqn 2]

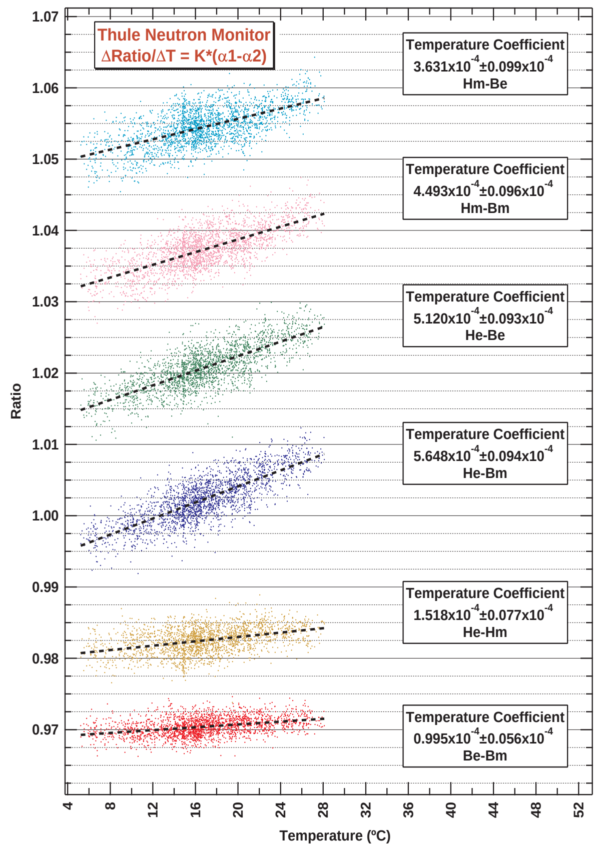
b) *same tube-type*, $\alpha_1 = \alpha_2$: $A = R_{10}/R_{20}$, $B = (R_{10}/R_{20}) \cdot \alpha$ [Eqn 3]



For the Thule data, where there is a large seasonal temperature variation, the entire monitor is nearly isothermal and the temperature is varying relatively slowly, so that we can use Eqn 2. This method will give us only the *difference* between αs for the four tube types: BF_3 ends (Be), BF_3 middles, (Bm), ^{3}He ends (He) and ^{3}He middles (Hm).

For the Nain data, where each of the three containers could be held at a different temperature for an extended period, we can use Eqn 3, where ratios of the same tube types (i.e. ^{3}He ends or middles) are compared as a function of temperature difference. This method will yield a direct measurement of the ^{3}He temperature coefficients. When combined with the Thule differential measurements, the BF_3 coefficients can be derived.

Equation 1 (the general case), with two αs and two Ts, has not been attempted.

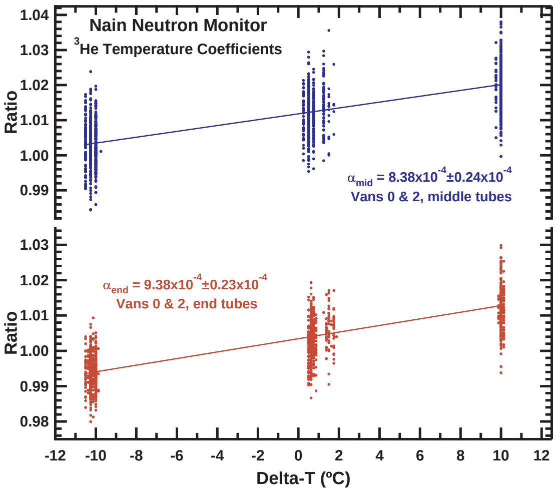


4. Thule Neutron Monitor (~isothermal case, Equation 2)

In Figure 1 we display the average counter temperature (upper panel) and the ratio of the total rate from the nine ^{3}He counters to that of the nine BF_3 counters (lower panel). There is an obvious correlation between the two. In the following, we will use these Thule measurements to examine the relative ^{3}He and BF_3 coefficients with the separate consideration of end counters and middle counters.

As described earlier, the Thule neutron monitor consists of nine BF_3 counters, arranged in three separated 3-counter sections (i.e. six end and 3 middle counters) as well as nine ^{3}He counters in one structure (section) (*i.e.* two end counters and seven 'middle' counters, The monitor is supported by 4x4 in. wood beams on a concrete floor in a large room at Thule Air Base.

An overall 12-hr average temperature database was constructed by averaging the 36 temperature sensors (one at the center, one at the end, of each counter). Similarly, 12-hour averages were made of the combined rates of the similar counter types: 6 BF_3 ends (Be); 3 BF_3 middles (Bm); 2 ^{3}He ends (He); 7 ^{3}He middles (Hm).



We display the data in Figure 2 as a set of six correlations (three independent) and superimposed fits. From Eqn 2, the difference in α between the various tube types (α_1 - α_2) is the value of B/A from each fit. The measured differences in the temperature coefficients are shown in the boxes.

5. Nain Neutron Monitor (two-temperature case, direct ^{3}He measurement)

containing six ^{3}He counters in two standard 3-NM64 sections, placed back to back. Thus there are four end counters and two middle counters in each van. Each section is supported by a ~3-foot platform, and the vans rest on 6 x 6 in. wooden supports on a crushed rock base. There are separate thermostats and heaters in each van.

Using the thermostats in the three containers, we artificially held the container temperatures constant for about two weeks, with a ~10 °C separation. The results of this test are summarized in Figure 3. Twelve-hour averages of temperatures and count rates, averaged over like counter-types (^{3}He end and middle) were constructed and linear fits done, this time to Ratio vs. Delta-T, using Eqn 3. This will give the absolute α's for ^{3}He ends and middles. In the Figure, the (upper) red plot is for the end counters, the (lower) blue for the middle counters. The resulting values of the ^{3}He temperature coefficients are shown in the Figure.

6. Summary and Conclusions

Finally, we have combined the Thule and Nain measurements to obtain temperature coefficients for the four counter types/positions: ^{3}He-end and middle, BF_3-end and middle (all values are in units of 10^{-4} °C^{-1}.

α (BF_3-end) = 4.74 ± 0.25 α (BF_3-middle) = 3.63 ± 0.25

α (^{3}He-end) = 9.38 ± 0.23 α (^{3}He-middle) = 8.38 ± 0.24

Combining these measurements to obtain temperature coefficients for 3NM-64 monitors:

α (BF_3 3NM-64) = 4.37 ± 0.18 α (^{3}He 3NM-64) = 9.05 ± 0.17

To summarize the simulations which have been carried out:

α (^{3}He 3NM-64) = 7.30 ± 0.71 α (BF_3 3NM-64) = 1.76 ± 0.60

α (^{3}He Middle) = 6.7 ± 1.6 α (^{3}He End) = 7.9 ± 1.4

In the future, we plan to conduct more simulations, especially for the BF_3 3NM-64 configuration, in order to see why the simulation is significantly lower than the measured coefficient.

We are now routinely using the measured coefficients to correct the counting rates from each counter to a temperature of 20 °C (-10 °C at South Pole), before pressure-correcting the data.

7. References

[1] J.W. Bieber, P. Evenson, "Spaceship Earth – An Optimized Network of Neutron Monitors", *Proc. 24th Internat. Cosmic Ray Conf.* (Rome), **4**, 1316 (1995).

[2] A. Fasso, A. Ferrari, A. Ranft, P.R. Sala, G.R. Stevenson, J.M. Zazula, "A Comparison of FLUKA Simulations with Measurements of Fluence and Dose in Calorimeter Structures", *Nucl. Instr. Meth.*, **A332**, 459 (1993).

[3] J.M. Clem, L.I. Dorman, "Neutron Monitor Response Functions", *Sp. Sci. Rev.*, **93**, 335 (2000).