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New Boron Trifluoride proportional tube for the NM64 Neutron Monitor

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Abstract: The BP28 BF_3 proportional tube was specifically designed for the NM64 neutron monitor introduced to the cosmic ray community in 1964. This neutron monitor design has remained the standard to date. In 1999, during the construction phase of the Space-Ship Earth NM64 monitors, it was realized the cost of a highly efficient ^{3}He filled proportional tube, manufactured by the LND company, was less than a BP28, and provided nearly the same sensitivity as a BP28 in a NM64 structure. Consequently, the LND ^{3}He tubes were chosen for the new SSE NM64 stations, and to upgrade stations Thule, South Pole and Newark. Unfortunately, since then, the price of the ^{3}He tubes has significantly increased, due to the rising cost of He^3, and the original BP28 tubes are no longer manufactured. Consequently, we have embarked on an investigation to evaluate a suitable BF_3 proportional tube to replace the original BP28. The investigation includes characterization of key performance parameters of two slightly different proportional tubes, with different anode wire and cathode tube thicknesses, while maintaining the same tube geometry, gas volume, pressure and purity. In this paper we present measurements and discuss the results.

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1. Introduction

Primary cosmic rays enter the atmosphere and undergo multiple interactions producing a shower of secondary particles which may reach ground level and be detected by a neutron monitor, which consist of neutron sensitive proportional tubes, surrounded by moderator material and a lead target. The proportional tubes detect evaporation (fission) neutrons produced locally from incident particles interacting in the lead. The evaporation neutrons are thermalized by the moderator to detectable energies. Even though neutrons do not leave an ion trail in the proportional tube, the absorption of a neutron by a nucleus is usually followed by the emission of charged particles which can be detected. A proportional tube filled with either $^{10}BF_3$ or ^{3}He gas responds to thermal neutrons by the exothermic reaction $^{10}B(n,\alpha)^{7}Li$ or $^{3}He(n,P)^{3}H$. The reaction cross-sections for both nuclei are roughly inversely proportional to the square root of kinetic energy (having a thermal endpoint 0.025eV) of 3840 barns and 5330 barns respectively. Surrounding the lead is a thick outer moderator, usually referred to as to the reflector, which serves to reject unwanted low energy neutrons produced in the local surroundings from entering the detector.

The original proportional tube developed for NM64, was based on the investigation by Fowler [1], which involved the characterization of BF_3 counters, each 190cm length and 15cm diameter, for different gas pressure, gas mixtures and cathode materials. The conclusion of this work emerged as the BP28 $^{10}BF_3$ proportional tube, the standard NM64 proportional counter. The BP28 has a gas pressure of 20mm-Hg of pure BF_3, enriched to 96% ^{10}B and corrugated stainless steel cathode tube with an average thickness of 2mm. The anode wire diameter is 0.2mm resulting in a gas gain of roughly 35 for an operating voltage of 2800V.

This counter design has remained the standard to date. However, in 1999, during the construction phase of the Space-Ship Earth (SSE) NM64 monitor network, it was realized the cost of a highly efficient ^{3}He (with 3% CO_2 quencher) gas filled proportional tubes, manufactured by the LND, Inc. company, was less than a BP28, and provided nearly the same sensitivity as a BP28 in a NM64 structure. The LND ^{3}He tubes are same length as the BP28, but 5cm in diameter filled to 4 atm of gas pressure. Consequently, the LND ^{3}He tubes were chosen for the new SSE NM64 stations and to upgrade stations Thule, South Pole and Newark. Unfortunately, since then, the price of the ^{3}He counters has significantly increased, due to the rising cost of ^{3}He gas, and the original BP28 tubes are no longer available.

2. Methology and Observations

We have begun an investigation to evaluate a suitable BF_3 proportional tube to replace the original BP28. The LND company has recently designed a BF_3 proportional tube with similar specifications to the BP28 including geometry, gas volume, pressure, purity and isotopic enrichment, with the exception the tube is not corrugated. The consequence of smooth tube is that it must be constructed with a thicker shell to mechanically withstand the negative differential gas pressure (200mm-Hg), and the thicker shell will result in a higher thermal neutron absorption and therefore lower sensitivity. The LND tube model number is SK02895, although we will call this model LND-BP28-1 in this report.

Figure 1. Photos of the LND-BP28-2 located in Sharp Lab, University of Delaware. The right photo shows the location of the measurements alongside an original BP28.

Two detectors were ordered from LND with different configurations to evaluate the effects of differing anode wire diameter and cathode tube thicknesses, while maintaining the same tube geometry, gas volume, pressure and purity. One tube was ordered with standard configuration, which we designate as “LND-BP28-1” while the other was ordered with a larger another wire and thinner cathode wall, designated “LND-BP28-2”. One of the tubes, ordered by the Thailand Neutron Monitor group, is located at the Princess Sirindhorn Neutron Monitor in Thailand. The other was ordered by the University of Delaware Neutron Monitor group is located near the Newark Neutron Monitor (see photo in Figure 1). Both tubes were tested using the same procedures.

Tube Identifier	Cathode Tube Thickness(mm)	Anode Wire Diameter (mm)	Operating Voltage (Volts)
LND-BP28-1	2.1	0.05	1150-1450
LND-BP28-2	1.5	0.2	2100-2400
BP28	0.8	0.2	-2800

Table 1. Comparison of the different configuration of the LND BF3 tubes being evaluated with the original BP28.

Table 1 specifies the different configurations of the tubes being evaluated. The operating voltage must be set at a level such that the collected charge is proportional to the ionization, but high enough for maintaining an adequate avalanche volume for gas gain. The BP28 is operated with a higher gas gain and lower preamplifier gain compared to LND-BP28-2. The preamplifier gain is the same for the two LND tubes, but different voltages and anode diameter result in similar gas gain as recommended by manufacturer.

Both LND-BP28 tubes were tested inside a moderator alongside an original BP28 also inside a separate moderator. Below is a list of the tests that were performed on both counters.

1) Waveforms recorded over a range of voltages to evaluate rise time.
2) Pulse height analysis for a range of voltages recommended by the LND company.
3) Extended run to determine relative sensitivity.

Figure 2 shows a calculation of the electric field variation in a cylindrical geometry using the specifications for the LND tubes. In the presence of an electric field the ionization electrons, generated in the gas from a $^{10}B(n,\alpha)^{7}Li$ reaction accelerate inward toward the anode. The strength of the electric field inside of the tube is linearly proportional to the potential difference V between anode wire and cathode tube. The field in the LND-BP28-1 is calculated using 1450V while 2400V was used to calculate the field in LND-BP28-2. With the exception of locations very near LND-BP28-1 anode wire, the electric field is higher in the LND-BP28-2. Nevertheless, depending on the dielectric breakdown of BF_3 at 200mm-Hg, which is expected to be roughly E~10^6 V/m, the gas gain is greater for LND-BP28-1 being that avalanche region could have a larger diameter.

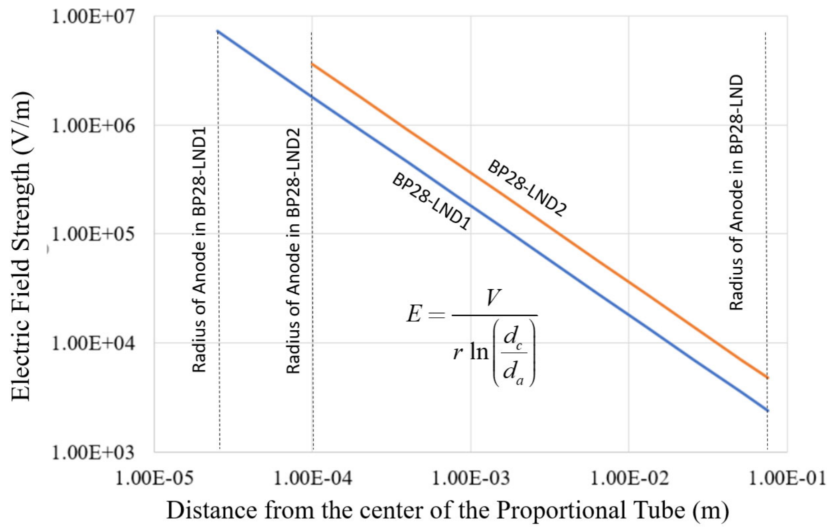

Figure 2. The expected electric field strength inside the proportional tubes for different configuration. The lower blue line represents the E-field inside BP28-LND1 at 1450V and the upper red curve represents the field inside BP28-LND2 at 2400V. Also shown are the radii of the anodes for the two configurations. In the equation, V is the operating voltage, d_a is the diameter of the anode wire, d_c is the proportional tube diameter.

In the region of the tube near the wire, the electric field is strong enough to accelerate the ionization electrons to energies capable of ionizing additional atoms. These secondary electrons are then accelerated, which further releases another generation of electrons, and the process continues resulting in an avalanche cascade. This cascade effect amplifies the amount of charge deposited onto the wire and is proportional to the original number of charges entering the avalanche region. This is referred to as the gas multiplication of the detector which is typically about 35 for the BP28 at 2800V. The potential difference between the anode wire and cathode tube will move the location of the avalanche boundary and consequently control the gas multiplication.

Waveform data of the counters were recorded for both LND-BP28s and an original BP28 as shown in Figure 3, Pulses from each counter have similar shapes, however the variation in size and rise-time is more significant for the LND-BP28-1 than that from LND-BP28-2. The rise-time, which is the measure of the time required for the leading edge of the signal to increase from 10% to 90% of the peak, was extracted from the waveforms, and the average and RMS were calculated. These are summarized in Figure 4 and show no dependence on voltage, consequently the different rise-time variation of the two LND tubes is not likely related to a change in the electric field strength in each counter within the range of the investigation. Neutron absorption reaction can occur anywhere in the counter resulting in spatial isotropic distribution of ionized tracks, a spread of pulse rise-times is expected.

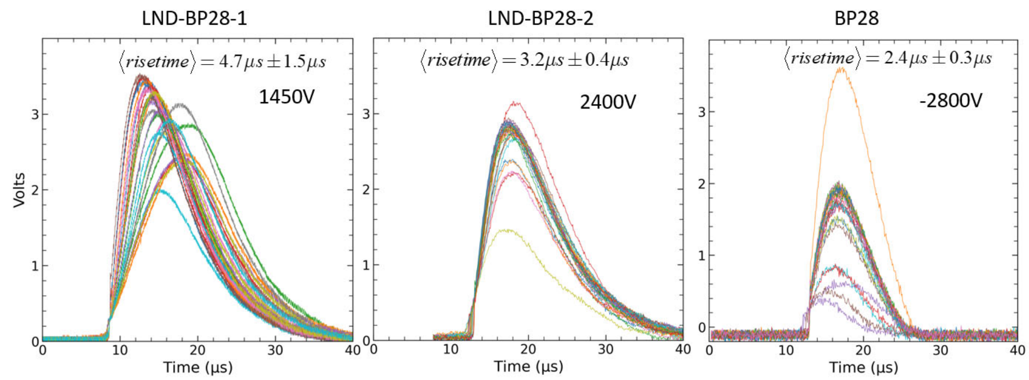

Figure 3. Waveforms from proportional tube pulses with the different configurations including an original BP28. Also shown in the average rise-time and the rms of the rise-time.

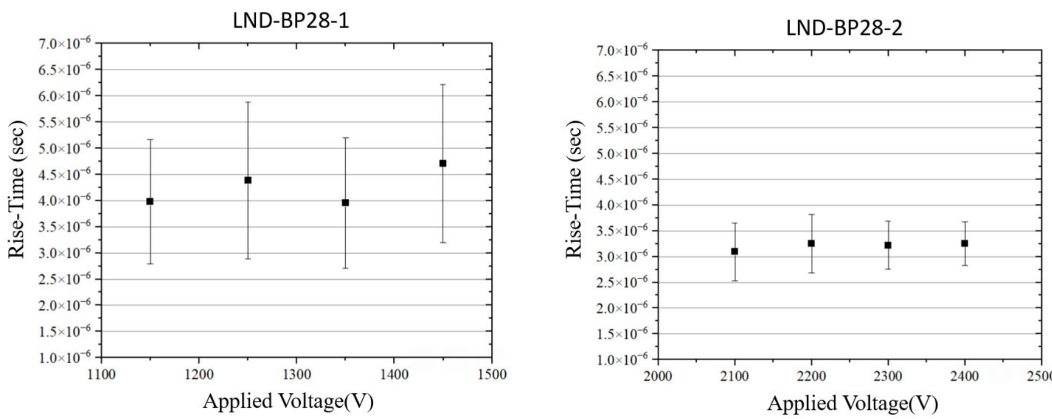

Figure 4. Average rise-time and RMS (error bars) derived the sample of waveforms for different voltages.

Roughly 6% of the $^{10}B(n,\alpha)^7Li$ reactions the α particle and ^7Li products are in their ground states, and 2.78MeV is available as kinetic energy for ionization tracks while 94% of the reactions the ^7Li product is left in an excited state of 480 KeV and 2.3 MeV is available as kinetic energy. It is important to note that if the α-particle and ^7Li products from the neutron absorption deposits all of their energy in the gas, and all the associated ionization electrons are collected at the same time, then we would observe only two different pulses from the counter with one corresponding to the 2.3 MeV and 2.78 MeV channels. Although this is nearly accomplished, there are factors that prevent this, such as the wall effect, the isotopic direction of the reaction products and electron capture by BF_3.

In Figure 5 is a comparison of the pulse height distributions of the BP28 and the two LND-BP28 configurations. The pulse height is proportional to the amount of ionization that enters the avalanche region which is in turn correlated to the amount of energy depoited in the gas outside of this region. However, electron capture of BF_3 will reduce the number of ionization electrons, produced in an neutron absorption reaction, that enter the avalanche region and the amount of electrons lost from this process depends on the number of collisions with BF_3 molecules as the electrons drift toward the anode. Longer drift distance from the anode wire will increase the probability of a BF_3 electron capture. Also neutron absorptions that occur near the wall of cathode tube can potentially suffer another loss of ionization. If either the α-particle and ^{7}Li products hitting the cathode tube wall, a smaller signal is observed. A thermal neutron has very little momentum before the absorption reaction, therefore the velocity of the two products must be in opposite direction to each other. This effect is referred to as the wall effect and forms a tail in the pulse-height distribution on the low side of the 2.3 MeV and 2.78 MeV peaks.

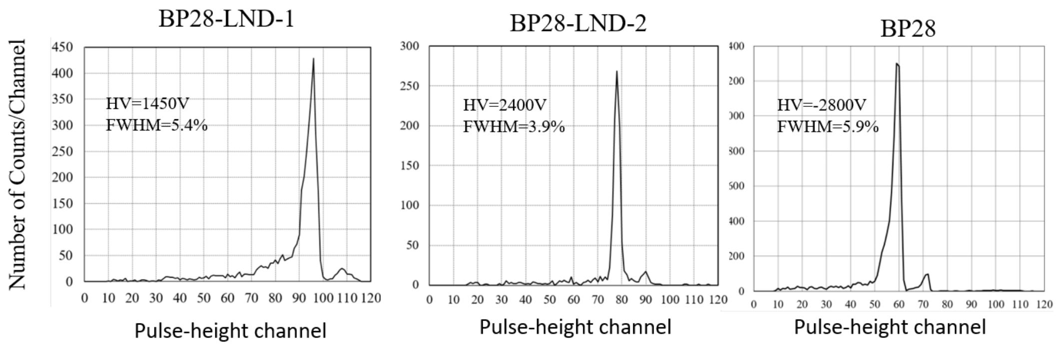

Figure 5. Pulse-height Distributions of the two different LND configurations and the BP28

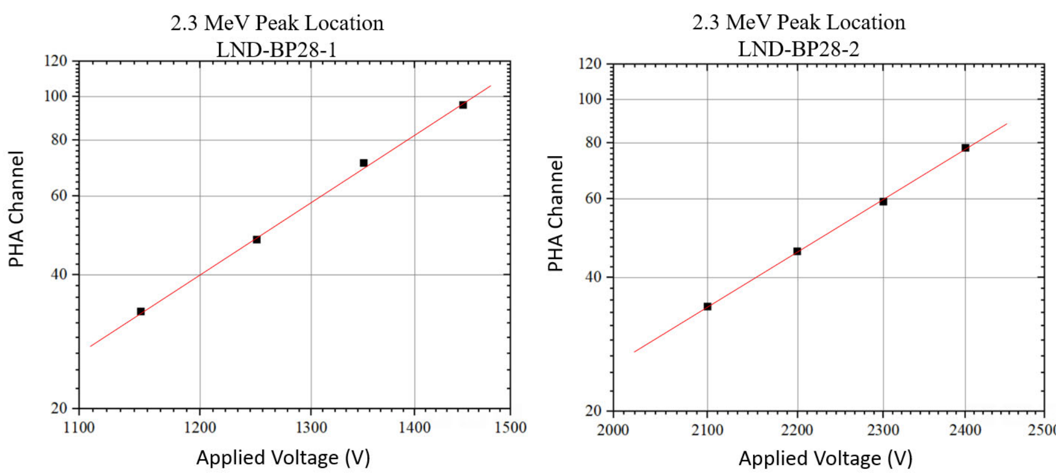

Figure 6. The location of the 2.3MeV peak in the pulse height distribution for different applied voltages plotted in log-log space. Both tubes reveal a power law gain curve.

Shown in Figure 6 is the variation of the 2.3 MeV peak location for different applied voltages. Increasing the voltage expands the avalanche volume centered about the anode wire allowing a larger cascade of electrons to develop before collected and consequently producing a larger pulse. The compounding growth of the electron population in a cascade can be represented by power law.

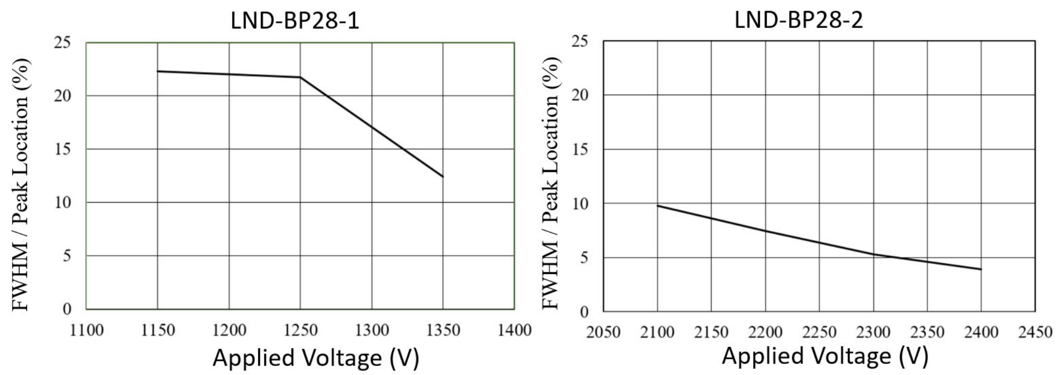

Figure 7. Full Width Half Maximum of the 2.3MeV peak in the Pulse-height distributions of the two LND-BP28 tube configurations for different voltages.

The ratio of the full width half maximum (FWHM) of the dominate 2.3 MeV peak to the peak location is given in Figure 7, and provides a proxy of the energy resolution of the detectors. As a consequence of Poisson statistics, the number of ionization electrons should be proportional to the inverse square of this ratio. Although the same number of ionization electrons is expected for 2.3 MeV energy deposit in both tubes, we observe a strong variation with applied voltage, which is possibly caused by a greater number of electron captures of BF_3 in the lower E-field regions.

As mentioned earlier in this report the LND company was unable to fabricate a corrugated counter tube nor willing to use an old BP28 tube to make a new one. The thinnest tube wall thickness from LND tube thickness is 0.15 cm of 321 stainless steel while the BP28 is has an average thickness of 0.08cm. The relative sensitivity of LND tubes with respect to a BP28 was measured and results are shown in table 2. This was performed by recording data from both BP28 and LND-BP28 for an extended period of time (Figure 1). The observed relative sensitivity for LND-BP28-1 was determined to be 0.9 respect to a BP28 while 0.95 was observed for LND-BP28-2. Using the weighted average cross-section for absorbing thermal neutrons in Iron, Chromium and Nickel based on the composition of 321 SS, which is roughly 3.6 barns [3], the thermal neutron losses through the tube wall can be calculated. Given the uncertainties the calculation is consistent with observations. This is summarized in table 2.

Tube Identifier	Cathode Tube Thickness(mm)	Calculated Relative Sensitivity to BP28	Observed Relative Sensitivity to BP28
LND-BP28-1	2.1	0.94	0.9
LND-BP28-2	1.5	0.96	0.95
BP28	0.8	1.	1

Table 2. Relative sensitivity of each counter with respect to a BP28 that was being recorded simultaneously alongside with the new counters. Also shown is an estimate of thermal neutron absorption losses in the cathode stainless steel tube.

3. Conclusions

We performed of a series of measurements to evaluate a potential replacement for the BP28 proportional tube. The gain curves for both LND-BP28 configurations produce a well-defined power law relationship. The ratio of the FWHM of the 2.3MeV peak to the peak location is significantly different for each configuration. Poisson statistics imply the number of ionization electrons should be proportional to the inverse square of this ratio, consequently this implies the ratio should be constant for the same amount of energy deposit in both tubes. However, we observed a correlation with applied voltage. One possible explanation is the probability of BF_3 electron capture is higher in the lower E-field regions.

Although the average rise-time and associated RMS is significantly different for each tube, neither tube shows a dependence with the applied voltages. A higher electric field reduces the drift time from the point of the neutron absorption inside the gas to the ionization-charge collection on the anode wire, consequently one might expect a higher acceleration from a stronger field would reduce the rise time variations in the pulses, however observations imply this is not a dominate effect. Another potential source to explain the difference in the timing of the two tubes, is that the same amplifier design is used on both tubes which have different capacitance as a result of the different wire sizes.

The pulse-height distribution of the LDB-BP28-1 at 1450V implies it is an adequate replacement for the BP28. The lower voltage will allow operation in a higher humidity environment than that not allowed for higher voltages. Observations of the sensitivity suggest the thinner wall tube improves the response by 5%.

4. Acknowledgements

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