The Scintillation Detectors of the Super-TIGER Balloon Experiment

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Abstract: Super-TIGER is a large-area ($5.4m^2$) cosmic-ray balloon experiment designed to measure the abundances of cosmic-ray nuclei heavier than Iron. The instrument has collection power and resolution necessary to measure individual charge abundances between $29 < Z \leq 42$ and exploratory measurements through Z=56. The instrument launched in December 2012 and had a successful 55 day flight. Super-TIGER has three layers of scintillation detectors, two Cherenkov detectors and a scintillating fiber hodoscope. Each scintillation detector (four per layer) employs four wavelength shifter bars surrounding the edges of the scintillator to collect the light from particles traversing the instrument. PMTs are optically coupled at both ends of the bars for light collection. In this paper we discuss the design, construction and performance of the scintillation detectors for the Super-TIGER flight. We also discuss scintillator saturation and how this is approached and addressed in the measurement of the ultra-heavy ($Z > 30$) elements measured by Super-TIGER.

Keywords: Super-TIGER, cosmic rays, OB associations, instrumentation.

1 Introduction

The Super Trans-Iron Galactic Element Recorder (Super-TIGER) is a balloon-borne cosmic ray detector designed to measure the ultra-heavy galactic cosmic-ray abundances for particles with $29 \leq Z \leq 42$ with individual element resolution and to make exploratory measurements up to $Z \leq 56$. It also measures the energy spectra of cosmic rays with $10 \leq Z \leq 28$ at energies between $0.8 < E < 10$ Gev/nucleon with high statistical accuracy. Super-TIGER was launched on a NASA Long Duration Balloon from Williams Field on December 9, 2012 and flew for 55 days. This flight set a duration record for balloons of this type carrying a scientific payload.

Super-TIGER will measure all of the individual elemental abundances for cosmic rays between $34 < Z \leq 42$ for the first time. These measurements provide important clues to understand the origin and acceleration of galactic cosmic rays [1]. In addition the measurement of the energy spectra of lower Z elements provides a test of the hypothesis that the smooth energy spectra of cosmic-rays may be distorted by microquasars [2]

Super-TIGER is based on the highly successful TIGER experiment which had Antarctic LDB flights in 2001 and 2003 [3] but has a geometry factor 6.4 times greater. Super-TIGER consists of three layers of plastic scintillator detectors and two Cherenkov detectors with different radiators (aerogel and acrylic) to determine the energy and charge of an incident particle. The instrument also has a scintillating fiber hodoscope to determine the trajectory of incident particles. In this paper we will focus on the design and performance of the plastic scintillators. An overall discussion of the Super-TIGER instrument is presented elsewhere at this conference [4] as well as detailed discussions on the Cherenkov [5] and hodoscope [6] detectors.

2 Super-TIGER Scintillator Design

The Super-TIGER instrument consists of two identical instrument modules each of which has three layers of scintillator. Each layer of scintillator consists of two counters in their own light-tight aluminum enclosure. Each enclosure has a Rohacell composite sheet bottom attached to an aluminum box frame consisting of aluminum channel pieces along the edges and custom machined corners. The enclosure lid is a 1/8 inch water-jet cut aluminum frame with 0.005" aluminum foil stretched and epoxied across the frame. The detector radiator is a one cm thick piece of Eljen EJ-208B scintillator measuring 116.2 cm x 116.2 cm with the corners notched and held in place by four acrylic corner posts. On the top and bottom of the radiator is a piece of 0.002" mylar to reflect any photons that escape the detector back into the radiator. Four waveshifter bars (WSB) of Eljen EJ-280 surround the scintillator sides. At the ends of each WSB are two Hamamatsu R1924A photomultiplier tubes (PMTs). The R1924A PMTs are epoxied onto the WSB with Eljen EJ-500 optical cement and the PMT-WSB assembly is positioned and glued directly to the aluminum box frame with Momentum 627 RTV An exploded drawing of the detector is shown in Figure 1.

Blue scintillation light is created in the scintillator when

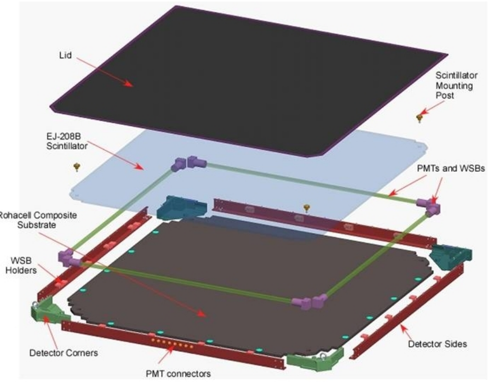

Fig. 1: Exploded Figure of Super-TIGER scintillator counter.

	Colum Density		
Material \ Flight	**TIGER 2001**	**TIGER 2003**	**SuperTIGER**
Light Shield	0.010	0.010	0.033
Upper Structure	0.245	0.195	0.000
Reflector	0.005	0.005	0.007
Scintillator	0.824	0.824	1.046
Reflector	0.005	0.005	0.007
Lower Structure	0.297	0.233	0.114
Light Shield	0.010	0.010	0.000
Total	1.396	1.282	1.207

Fig. 2: Column Density of scintillators for TIGER 2001, 2003 and Super-TIGER in units of g/cm^2. Note that the Gatorfoam upper and lower structure had windows cut into it between TIGER 2001 and 2003 reducing the column density. SuperTIGER was designed to minimize material in the cosmic-ray beam and has a lower column density despite having a thicker scintillator radiator than TIGER 2001 and 2003.

a charged particle traverses the material. This light is internally reflected to the edges of the detector and into the WSBs. There the blue photons are absorbed and then re-emitted isotropically as green photons, some of which are piped down to the PMTs at the end of the bar. This configuration allows us to measure scintillation light from this large area detector with only eight PMTs.

Several improvements have been made in the mechanical design of the SuperTIGER scintillation counters over the scintillation counters flown on previous LDB flights. The detectors were designed to be able to be produced as 12 detectors plus spares are required for the flight instrument. The bottom assembly has been designed to fit together and be epoxied as a single light-tight unit. The lid is attached to the assembly bottom and the seam between the two is sealed by a silicon rubber gasket. The power and signal cables from the scintillator PMTs are routed internally on cables to three bulkhead areas on the sides of the detector rather than coming out at each of the corners as was done for past detectors. This not only makes external cable harnessing neater but eliminates some detector mounting issues experienced in the past because of cables having to be attached at each corners of the detector and routed around the detector. In addition the detector construction and choice of materials has led to a decrease in beam material despite a thicker radiator as shown in Figure 2.

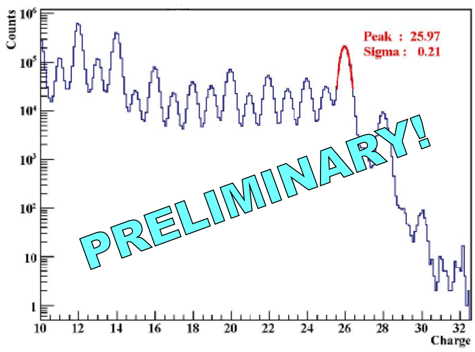

Fig. 3: Charge histogram of select Super-TIGER data. These events have been selected to be above the acrylic Cherenkov threshold (320 MeV/nucleon) but below the aerogel threshold (2.5 GeV/nucleon). Charge for these events is assigned by looking at data from the scintillators and acrylic cherenkov. A further discussion of the Super-TIGER data analysis and results can be found elsewhere at this conference [8].

Another critical part of the scintillator design was the design of the PMT resistor divider chain. In order to measure charged particles with $10 \leq Z \leq 42$ we require our PMTs to be linear up to 90,000 PEs (to reach Z=56 we require linearity to about 150,000 PEs). This is a design challenge due to space-charge effects inside the PMT that cause significant non-linear effects. These effects typically occur when the anode current is the same order of magnitude as the dynode current and usually happens on the last two or three dynodes in the resistor divider chain. Linearity can be improved by increasing the resistance across the last few dynode stages of the PMT to reduce space charge effects. This requires a gradual tapering of the divider. We incorporated such a design into the Super-TIGER scintillator photomultipliers which is discussed in further detail elsewhere [7] and worked extremely well during the flight.

3 Super-TIGER Scintillator Performance

The Super-TIGER scintillators performed very well during flight and preliminary data analysis, shown in Figure 3, indicates a charge resolution of 0.21 at Iron. This is comparable to the final charge resolution at Iron from the TIGER LDB flights in 2001 (0.23 cu) and 2003 (0.21 cu). We expect this resolution will only improve as our analysis continues

Although the in-flight performance of the scintillators was quite good, we did have issues with several of the R1924A PMTs prior to launch. After the Super-TIGER thermal-vacuum test at NASA Glenns Plumbrook station, we found that the glass vacuum envelope on two photomultiplier tubes had been broken. We replaced these tubes and assumed that it was an isolated problem perhaps due to unfortunate high thermal stresses during the test which caused the glass envelopes to break. After shipment to Antarctica these two PMTs as well as twelve others were found to be non-functional. Five of these tubes were replaced prior to launch. These five tubes were later found all to have broken glass vacuum envelop Finally, one tube failed shortly after launch for unknown reasons. Fortunately, even with ten dead PMTs, the performance of Super-TIGER is minimally affected thanks to the significant redundancy and graceful degradation designed into the payload.

We do not know exactly what caused the failure of all these PMTs, however we beleive that it may be related to how the PMTs were mounted to the WLSB and in the scintillator enclosure. For Super-TIGER we used a hard optical epoxy to attach the R1924A PMTs to the WLSB and then an RTV to affix the assembly in the scintillator box. For TIGER and CREAM we have used a more compliant RTV to glue the PMT and WLSB together. The hard epoxy may direct more stress onto the PMT envelope causing it to break during TV testing and shipping.

We also realized after the thermal-vacuum test at Plumbrook that the instrument got significantly cooler than the detector modules from past TIGER LDB flights causing greater thermal stresses. In the Plumbrook chamber the shroud surrounding the instrument achieved a temperature of -20°C and the scintillator detector box reached temperatures around -14°C. For the TIGER LDB flights our temperature data shows the coolest the scintillator detectors got was 11°C.. A simple thermal expansion calculation shows that for the TIGER flights we would expect the WLSB to contract 0.027" but during the Plumbrook test we would expect the WLSB to contract just over three times this at 0.084". Finally there is evidence from the two PMTs that were replaced in Palestine during integration and later found broken in Antarctica that the instrument did not have a gentle transport down to Antarctica which may have led to more damaged tubes, particularly if the tubes were damaged or stressed earlier at Plumbrook.

For the next SuperTIGER flight we plan to look into implementing two design changes that we believe will solve this issue of scintillator PMT damage. First we plan to build up a compliant pad of silicone between the PMT and the WLSB so there is some give which will reduce stresses due to CTE and shock. Second, rather than glue the PMT-WLSB assembly into the detector enclosure we plan to utilize a slide mount system similar to what we have developed for the CREAM Cherenkov detector as pictured in Figure 4. This mounting system would remove much of the shipping vibration and shock problems as well as the thermal stress issues as PMT-WSB assembly can move back and forth in response to these effects.

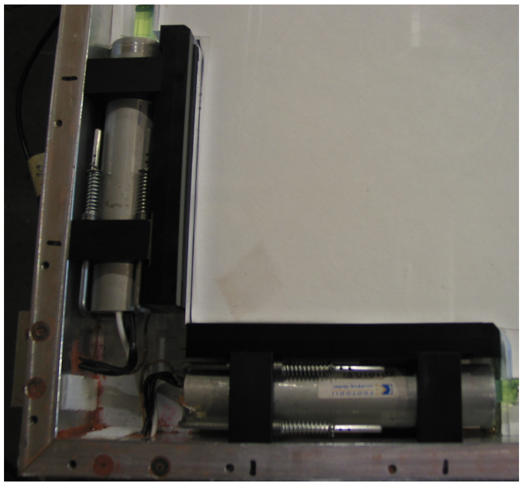

Fig. 4: PMT slide mount. Delrin pieces are mounted directly to the detector enclosure and the PMT-WSB assembly is attached such that it can slide back and forth.

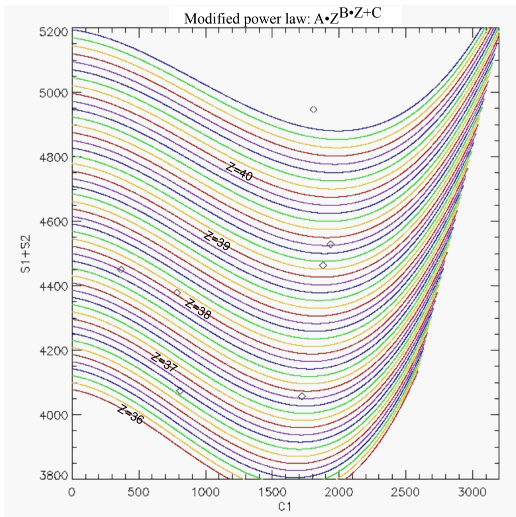

Fig. 5: TIGER 2001 data showing extrapolated charge curves between Z=36 and Z=40 using a modified power law. The Markers represent Z>36 events from the 2001 flight.

4 Scintillator Saturation and Resolving UHGCRs

In an ideal scintillator, the amount of light (dL) produced by a particle of charge Z and velocity v as a function of the pathlength of a particle (dx) is given by:

$$\frac{dL}{dX} \propto \frac{Z^2}{\beta^2} F(\beta)$$

where β^2=(v/c)^2 and F(β) varies weakly with β. This relation holds true for particles with very low charge, however, not for particles with a high charge as they saturate the scintillator. When a charged particle passes through a scintillator it interacts electromagnetically with the plastic molecules exciting them. When the plastic molecules de-excite they emit a UV photon which can then excite dye molecules in the scintillator. When these dye molecules de-excite they produce blue photons which are the photons we refer to when we discuss scintillation light. There are two distinct regions that excitation occurs in: a core region around which a charged particle physically passes through the scintillator and a halo region where knock-on electrons interact. If the excitation density of scintillator and dye molecules in a region is very high, the molecule can de-excite without producing UV or blue photons. This condition has been observed to happen in the core region when a particle of high charge passes through and saturates the scintillator [9]. When a scintillator saturates, the light output does not follow equation above and there is a much more complicated relationship between charge and energy.

There are several mathematical models [10], [11], [12] which have been put forth to describe saturation. We looked at several of these models in 2001 and 2003 in conjunction with our data to account for scintillator saturation in the TIGER detector [13] [14]. We used data from $16 \leq Z \leq 26$ to establish constants for the models and then extrapolated our results to higher charges. The extrapolations for all the models started to diverge the higher in Z one got as is

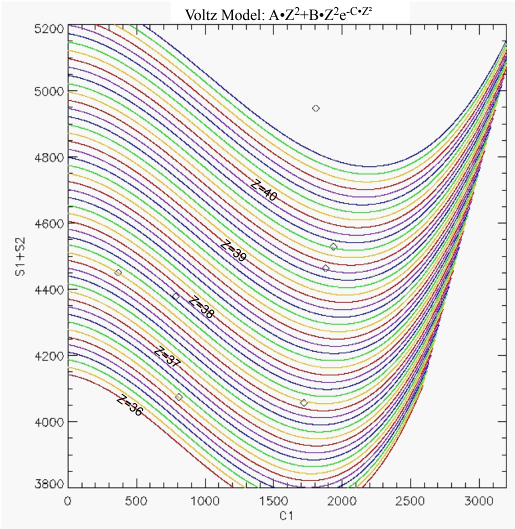

Fig. 6: TIGER 2001 data showing extrapolated charge curves between Z=36 and Z=40 using a Voltz model formulation. The markers represent Z>36 events from the 2001 flight.

expected. This divergence was small enough below Z=34 where we had a statistically significant number of particles that we were confident the ultimate model selection would not significantly affect our analysis; however it was clear that the divergence becomes much more significant at higher charges. This is shown in Figure 5 and 6 where we present extrapolated charge curves from $36 \leq Z \leq 40$ for two models, the Voltz model and a modified power law model. These two models were found to have the best fits to the TIGER LDB data. The modified power law model provides the best fit by a marginal amount between the two, however the Voltz model has a better physical basis for use.

Super-TIGER will have many more events with $Z > 34$ and we expect that the scintillation light model we use in our analysis will be more important. We plan to use a similar approach like we did for the analysis of the 2001 and 2003 TIGER data; however, we have proposed as part of the effort for a second flight of Super-TIGER to calibrate a SuperTIGER scintillator at the heavy-ion accelerator at the NASA Space Radiation Laboratory at Brookhaven National Labs. This calibration will not only prove useful to calibration and understanding our Super-TIGER data but also give us a better understanding of the process of scintillator saturation and how to address it in future instruments.

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References

[1] Meyer, J. P., et al., ApJ, 1997, **487**: 182-196.
[2] Heinz, S., Sunyaev, R., A&A, 2002, **390**: 751-766.
[3] Rauch, B. F., et al., ApJ, 2009, **697**: 2083-2088
[4] Binns, W. R., et al.,“Proceedings of the 33st ICRC”, Rio, 2013.
[5] Murphy, R. P., et al.,“Proceedings of the 33st ICRC”, Rio, 2013.
[6] Ward, J. E., et al.,“Proceedings of the 33st ICRC”, Rio, 2013.
[7] Link, J. T., et al., ICRC 2011: Beijing, 2011, ID 737.
[8] Sasaki.M., et al.,“Proceedings of the 33st ICRC”, Rio, 2013.
[9] Birks, J. B. ”Theory and Practice of Scintillation Counting”, 1964.
[10] Voltz, R. et. al. Journal of chemical Physics, 1966 **45**: 3306-3311.
[11] Tarle, G. et. al. Apj, 1979 **230**: 607-620.
[12] Ahlen, S.P. et. al. NIM, 1977 **147**: 321-328.
[13] Link, J.T. Measurements of Ultra-Heavy Galactic Cosmic Rays with the TIGER Instrument, Ph.D. Thesis, Washington University, St. Louis, 2003.
[14] Rauch, B.F. Measurement of the Relative Abundances of the Ultra-Heavy Galactic Cosmic Rays (30 Z 40) with the Trans-Iron Galactic Element Recorder (TIGER) Instrument, Ph.D. Thesis, Washington University, St. Louis, 2008.