Abstract: We discuss the design and construction of the scintillation detectors for the Super-TIGER experiment. Super-TIGER is a large-area (5.4m²) balloon-borne experiment designed to measure the abundances of cosmic-ray nuclei between Z=10 and Z=56. It is based on the successful TIGER experiment that flew in Antarctica in 2001 and 2003. Super-TIGER has three layers of scintillation detectors, two Cherenkov detectors and a scintillating fiber hodoscope. The scintillation detector employs four wavelength shifter bars surrounding the edges of the scintillator to collect the light from particles traversing the detector. PMTs are optically coupled at both ends of the bars for light collection. We report on laboratory performance of the scintillation counters using muons. In addition we discuss the design challenges and detector response over this broad charge range including the effect of scintillator saturation.

Keywords: Galactic Cosmic Rays, Scintillator, Instrumentation

1 Introduction

1.1 The Super-TIGER Experiment

Super-TIGER (Super Trans-Iron Galactic Element Recorder) is a new balloon borne-cosmic-ray detector under construction for a 2012 flight from McMurdo Base, Antarctica. It will measure ultra-heavy (UH) galactic cosmic-ray (GCR) abundances (Z>29) with individual element resolution in order to test the model of cosmic-ray origins in OB associations and explore the mechanism for the selection of nuclei for acceleration. Super-TIGER is based on the successful TIGER experiment, which flew in 2001 and 2003 but has a geometry factor ~6.4 times larger than TIGER [1].

The Super-TIGER instrument consists of 3 layers of plastic scintillator detectors along with acrylic and aerogel Cherenkov counters to measure the charge and energy of incident particles. The instrument also utilizes a scintillating fiber hodoscope to track particle trajectories. The Super-TIGER instrument is described in more detail elsewhere in this conference [2], as are the Cherenkov counters [3] and scintillating fiber hodoscope [4]. In this paper we will focus on the design and performance of the plastic scintillation detectors for Super-TIGER.

1.2 Super-TIGER Scintillator Detector

The Super-TIGER scintillation detectors consist of a 1 cm thick piece of Eljen EJ-208B scintillator measuring 116.2 cm x 116.2 cm with the corners notched. Surrounding the scintillator plastic are four wavelength shifter bars (WSB) of Eljen EJ-280 which absorb the blue photons from the scintillator and re-emit them isotropically as green photons. Optically coupled to the ends of each WSB are two Hamamatsu R1924 photomultiplier tubes (PMTs) which detect the green photons light piped down...
2 Scintillator Behavior and Design for the Detection of UH GCRs.

2.1 Scintillator Saturation

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

$$\frac{dL}{dx} \propto \frac{Z^2}{\beta^2} F(\beta)$$  \hspace{1cm} (1)

where $\beta^2=(v/c)^2$ and $F(\beta)$ varies weakly with $\beta$. 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 [6]. When a scintillator saturates, the light output does not follow equation (1) and there is a much more complicated relationship between charge and energy.

There are several mathematical models [7,8,9] which have been put forth to describe saturation. We looked at several of these models in 2001 in conjunction with our data to account for scintillator saturation in the TIGER detector. We used data from $Z=16$ to $Z=26$ to establish the constants for these models and then extrapolated our results to higher charges. Our data set only had good statistics up to $Z=34$. All the models for saturation yielded essentially the same results in charge assignment [10].

2.2 Dynamic range required for UH Cosmic-ray Measurements

One of the challenges in building a cosmic-ray detector like Super-TIGER with sensitivity from $Z=10$ to $Z=56$ is ensuring that the detector electronics has adequate dynamic range. The analog-to-digital (A/D) converter in the digitization electronics needs to have sufficient bits to cover the signal variation from the smallest particle signal to the largest particle signal. Care must also be taken in the selection of the PMT and design of its base so that there is a linear PMT response for the signals of interest as well. In order to verify that the detector electronics have sufficient dynamic range, we need to calculate the number of PEs we expect to see for the brightest and dimmest events we expect in our scintillator.

The number of photons seen by a PMT from a particle traversing the scintillator depends on the charge ($Z$) and energy ($E$) of that particle as well as its pathlength and location relative to the PMT in that detector. Energy dependence can be calculated using the Bethe-Bloch relation. For Super-TIGER the energy range of interest for events in the scintillation detectors is about 300 MeV/nucleon to 2.5 GeV/nucleon. Over this energy range, the number of photons varies by a factor of about 1.6. The pathlength of the particle through the detector depends on its angle of incidence. Particles with a high angle of incidence travel through more material than particles with a low angle of incidence. The correction factor for pathlength is sec($\theta$). For the Super-TIGER instrument we chose our maximum incident angle as 45°. It is possible to have particles with larger incident angles pass through the instrument, but these particles will most likely interact, especially if they have a high charge. The correction factor due to pathlength is then sec(45°)=1.4. Finally the location of the particle in the detector affects the number of photons collected by a PMT. We can use area correction maps for the scintillators from the 2003 TIGER flight to derive this factor [11]. These factors were used to correct PMT signals based on where a par-
particle traversed the detector. A histogram of correction factors for one PMT is presented in Figure 2. We find that most of these factors occur between 0.5 and 1.5, which suggests over the detector our signal can vary by a factor of 3.

![Figure 2: Histogram of the area correction factor for a PMT in the S1 scintillator for the TIGER 2003 flight.](image)

Combining the factors together for energy, pathlength and location together gives us a correction factor of 6.72. The product of this factor and the effect of charge allows us to calculate the number of photons seen in a scintillation detector.

In this paper we consider two simple cases of charge dependence in the scintillator. In the first case, we assume saturation does not occur and so the charge dependence is \( Z^2 \). This scenario can be taken as a worse case since the PMT saturating. We calculate using equation (2) that this saturation appears to be occurring at about 10,000 PEs.

\[
N, P, E = \left( \frac{\text{Mean} - \text{Pedestal}}{\text{Sigma}} \right)^2 \tag{2}
\]

To test for linearity we look at the ratio of the peak of the PMT signal distribution for a LED driver voltage between -2 and -8V in height and 50 ns in width. The pulse was quenched by offsetting the baseline to 2V to reduce afterpulse effects. The LED was placed 4 cm from the PMT in a light tight box. The PMT was run at 700V. We made a set of filters consisting of different layers of Tekwipes to attenuate the light and then collected data while varying the LED drive voltages along with the number of Tekwipe filter layers between the LED and PMT. We then found the mean and sigma of the signal distribution and from this the number of photoelectrons seen by the tube using the relationship:

\[
N, P, E = \left( \frac{\text{Mean} - \text{Pedestal}}{\text{Sigma}} \right)^2 \tag{2}
\]

The Super-TIGER PMTs must be linear to at least 40,000 PEs and possibly up to 150,000 PEs which is a design challenge due to space-charge effects inside the PMT. These effects typically occur when the anode current is the same order of magnitude as the divider current. This usually happens on the last two or three dynodes in the resistor divider chain of the base. One way to improve PMT linearity is to increase the resistance and hence the potential difference across the last few dynode stages of the PMT which reduces space charge effects. This requires a tapering of the divider to increase the potential difference across the last stage but it must be done gradually to maintain a good electrostatic focus between PMT gain stages.

In order to test the linearity of our PMTs, we used a red LED driven by a square pulse that was -2 to -8V in height and 50 ns in width. The pulse was quenched by offsetting the baseline to 2V to reduce afterpulse effects. The LED was placed 4 cm from the PMT in a light tight box. The PMT was run at 700V. We made a set of filters consisting of different layers of Tekwipes to attenuate the light and then collected data while varying the LED drive voltages along with the number of Tekwipe filter layers between the LED and PMT. We then found the mean and sigma of the signal distribution and from this the number of photoelectrons seen by the tube using the relationship:

\[
N, P, E = \left( \frac{\text{Mean} - \text{Pedestal}}{\text{Sigma}} \right)^2 \tag{2}
\]

In Figure 3 we show the peak ratio results of a linearity test done for a standard base design. Resistor ratios for this taper are given in Table 2. We see that as the light level increases our peak will not increase linearly and points at different voltages will not remain parallel.

<table>
<thead>
<tr>
<th>Charge Scale = ( Z^2 )</th>
<th>Charge Scale = ( Z^{1.67} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( #) PE for 2 GeV/nuc, Center Vertical event</td>
<td>( #) PE for 300 MeV/nuc, Edge 45 degree event</td>
</tr>
<tr>
<td>( #) PE for 2 GeV/nuc, Center Vertical event</td>
<td>( #) PE for 300 MeV/nuc, Edge 45 degree event</td>
</tr>
<tr>
<td>56</td>
<td>21092</td>
</tr>
<tr>
<td>40</td>
<td>11200</td>
</tr>
<tr>
<td>28</td>
<td>4732</td>
</tr>
<tr>
<td>18</td>
<td>1792</td>
</tr>
<tr>
<td>10</td>
<td>700</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 1: Calculation of the number of PEs seen for a scintillation light box for \( Z^2 \) and \( Z^{1.67} \) scaling.

2.3 Super-TIGER Electronics and PMT Design

From the discussion in section 2.2, we see that there is a factor of 211 between the PEs produced by the dimmest Z=10 event and the brightest Z=56 event when scaled as \( Z^2 \) and a factor of 120 when scaled as \( Z^{1.67} \). The Super-TIGER scintillator readout electronics use a 16-bit A/D with a pedestal of 160 channels. If we put our dimmest Z=10 event in channel 400 this puts our brightest Z=56 event in either channel 28,800 or channel 50,640 depending on our charge scaling. Either of these is well within the channel range of the A/D.

In Figure 3 we show the peak ratio results of a linearity test done for a standard base design. Resistor ratios for this taper are given in Table 2. We see that as the light level increases our peak will not increase linearly and points at different voltages will not remain parallel.

<table>
<thead>
<tr>
<th>K-D1</th>
<th>D1-D2</th>
<th>D2-D3</th>
<th>D3-D4</th>
<th>D4-D5</th>
<th>D5-D6</th>
<th>D6-D7</th>
<th>D7-D8</th>
<th>D8-D9</th>
<th>D9-P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Base</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Tapered Base</td>
<td>6</td>
<td>1</td>
<td>1.5</td>
<td>1.5</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 2: Base resistor ratios for tested designs.
To increase the linear range of our PMT we have developed and designed a tapered base design whose resistor ratios are given in Table 2. The peak ratios for this PMT base design is plotted in Figure 4. The lines are nearly parallel for all of the LED driver voltages and filters which suggests the PMT was fairly linear for all light levels used in this test. We calculate that the brightest light levels for this test were in excess of 150,000 PEs (for -8V drive voltage and no filters the light level was calculated to be 210,000 PEs). Based on our earlier calculation, this linearity should be sufficient for the Super-TIGER scintillators.

3 Summary

We have described the scintillation detectors for the Super-TIGER experiment and discussed the detector performance and dynamic range requirements to measure cosmic-ray nuclei between Z=10 and Z=56. We have reported on how the detector readout electronics has been designed with sufficient dynamic range to accomplish this measurement. In particular we have looked at the design of our PMT base and how the use of a tapered design allows us to obtain a linear response from the PMT up to ~200,000 PEs.

References: