

Updated Analysis of SuperTIGER Flight Data for Galactic Cosmic-Ray Elemental Spectra

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SuperTIGER (Trans-Iron Galactic Element Recorder) is a large-area, balloon-borne cosmic-ray experiment designed to measure the galactic cosmic-ray abundances of elements from $Z=10$ (Ne) to $Z=56$ (Ba) at energies from ~ 0.8 GeV/nuc to ~ 10 GeV/nuc, with the primary goal of measuring relative abundances of ultra-heavy elements above $Z=30$. SuperTIGER flew for a record 55 days over Antarctica in 2012-2013 and for a second flight of over 32 days in 2019-2020. Although the primary goal is measuring ultra-heavy cosmic-ray relative abundances, the SuperTIGER data analysis uses measurements of abundant elements at $Z<30$ for precise charge calibration extended to the ultra-heavy elements. In this technical presentation, we will report ongoing progress on analysis to obtain energy spectra for these $Z<30$ elements, from Ne to Cu. We will present new details of the aerogel and acrylic Cherenkov calibrations necessary for calculating energies for generating absolute spectra, including effective photoelectron resolution, knock-on electron contributions, and other background signals in the Cherenkov detectors.

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1. Introduction

SuperTIGER (the Trans-Iron Galactic Element Recorder) is a large area, balloon-borne experiment designed and flown to measure the galactic cosmic-ray abundances of elements from Ne ($Z=10$) to Ba ($Z=56$) at $\sim 0.8\text{--}10$ GeV/nuc. SuperTIGER had a record-breaking flight of 55 days around Antarctica, from December 8, 2012 to February 1, 2013 [1] and another, shorter flight from December 16, 2019 to January 16, 2020.

Previously reported relative abundances of ultraheavy elements ($30 \leq Z \leq 40$) in SuperTIGER 2012-2013 data are consistent with galactic cosmic ray origins in OB associations with preferential acceleration of refractory elements over volatile elements [2]. Additionally, relative abundances of iron secondaries measured by SuperTIGER, e.g. $(\text{Sc}+\text{Ti}+\text{V})/\text{Fe}$, are consistent with HEAO measurements as well as Standard Leaky Box Model calculations [3,4].

While these results make use of measured element ratios in SuperTIGER data, we have abundant data at $Z=11\text{--}29$ to attempt absolute spectral intensities. Previous work included attempts to detect microquasar signatures in Fe spectra, but those spectra were scaled to match ACE/CRIS spectra at lower energies [3]. In order to obtain absolute intensities, corrections for energy losses and interactions in both the instrument and atmosphere must be undertaken with the help of detailed Geant4 simulations of the instrument. This work was initiated in 2019 [5], and this paper describes significant extension of that work.

2. The SuperTIGER Geant4 Model

The SuperTIGER instrument is described in detail by Binns et al. [1]. The payload is divided into two nearly identical modules. Each module is composed of a stack of several detectors. The detectors in each module are a plastic scintillator (S1) for charge measurement, a scintillating optical fiber hodoscope (H1) to measure (with H2) particle trajectories, an aerogel Cherenkov (refractive index $n=1.025$ or $n=1.043$) detector (C0) to measure charge and velocity, an acrylic Cherenkov ($n=1.49$) detector (C1) also for charge and velocity, another plastic scintillator (S2), a bottom hodoscope (H2), and a third plastic scintillator (S3). In one module, the aerogel blocks in the C0 detector are entirely $n=1.043$ refractive index aerogels (threshold energy of ~ 2.5 GeV/nuc), while in the other module, half of the C0 aerogels have a refractive index $n=1.043$ while the other half have $n=1.025$ (threshold energy ~ 3.3 GeV/nuc). Particle data are stored in onboard solid state drives as well as transmitted via line-of-sight (LOS) telemetry or TDRSS satellite.

We use the Geant4 library [6] to construct models of the the SuperTIGER instrument and to simulate its responses to incident energetic charged particles. The simulations include physical description of the payload, including the bulk materials in the particle beam. Support structures outside of the particle beam as well as materials with negligible mass are not included (e.g the thin film wrapping the aerogels). Test particles (e.g. Fe) are simulated with normal or isotropic incidence, depending on application, and varying kinetic energies from 200 MeV/nuc to >10 GeV/nuc. Using the default physics models, the Geant4 code simulates ionization energy losses

and energy deposited in all materials, scattering, and production of secondary particles. Figure 2 shows a sample Fe event going through a SuperTIGER model and creating secondary particles.

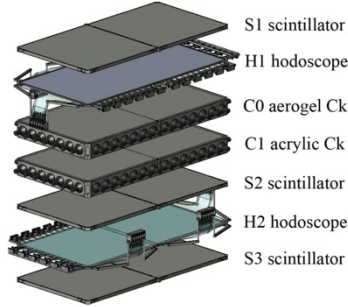


Figure 1: Expanded view of one SuperTIGER module, from Binns et al. [1].

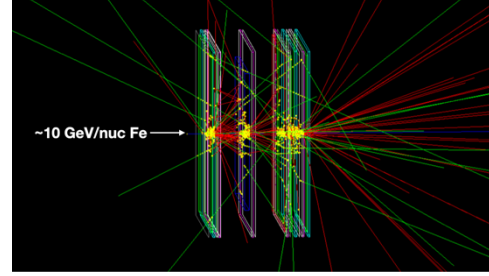


Figure 2: A simulated 10 GeV/nuc Fe particle passing through SuperTIGER material.

3. Interaction Losses

When particles pass through the SuperTIGER detectors, they lose or deposit energy as well as produce secondary particles, and some of those particles are a result of nucleons breaking off the incident nuclei. Since energies deposited in matter are proportional to $\sim Z^2$ for each incident particle, the energies deposited will change significantly in layers after such charge changing interactions. Particles undergoing interaction losses are eliminated by charge consistency selection criteria, usually imposed between the S1 and S2 scintillators; the addition of S3 has been found to make only a small contribution the overall charge consistency cut [1]. Regardless, the loss of incident particles due to charge consistency cuts must be corrected in order to obtain elemental abundances at the top of the instrument and the top of the atmosphere.

Figure 3 show Geant4 calculations of inelastic interaction losses through the instrument. Each figure shows the fraction of particles incident at the top of the instrument that survive without changing charge to S1, S2, and S3 vs. energy (MeV/nuc). Thus, for ~ 500 MeV/nuc Fe ($Z=26$), about 80% of the particles survive through S1, but only $\sim 50\%$ survive through S2 and $\sim 45\%$ survive through S3. For each of these curves, 200k particles with energies from 200 MeV/nuc to 40 GeV/nuc were simulated, in a power law spectrum with an index of -2. Simulations were run for $Z=10$ through $Z=29$, and a matrices were constructed to tabulate interaction losses through each layer.

4. Energy Losses

Since velocities are calculated from the aerogel and acrylic Cherenkov signals (C1 and C2), the energies derived by those Cherenkov signals have to be corrected to the top of the instrument and top of the atmosphere for losses in the atmosphere and instrument above each Cherenkov detector. Figure 4 shows Geant4 calculations of relative energies at TOI and at the top of C1, compared to the top of C0, for ~ 200 MeV/nuc to 10 GeV/nuc Fe. For ~ 500 MeV/nuc Fe at C0, the same particle would lose almost 5% of its energy before the top of C1 (i.e. hitting ~ 475

MeV/nuc), while that same particle would have had about 15% more energy at the top of the instrument, or a total energy of 575 MeV/nuc. As shown in Figure 4, at higher energies, the relative differences shrink to negligible.

5. Knock-on Electron Corrections

Just above Cherenkov threshold, signals from knock-on electrons (delta-rays) can be comparable in magnitude to the primary particle signal, so corrections to the Cherenkov signals must be obtained and applied to the energy calibrations. Figure 6 shows the result of Geant4 simulations, showing Z-26 (Fe) Cherenkov signals for primary particles in red (two bands, for $n=1.043$ and $n=1.025$ aerogel blocks), knock-on electron signals (blue) due to knock-on electrons induced by the primary particles above Cherenkov threshold, and knock-on electron signals (green) due to knock-on electrons produced by primaries below Cherenkov threshold.

The low knock-on signals are due to knock-on electrons produced primarily within the aerogel Cherenkov radiator, but the higher knock-on signals are due to electrons produced in the overlying material in the detector stack.

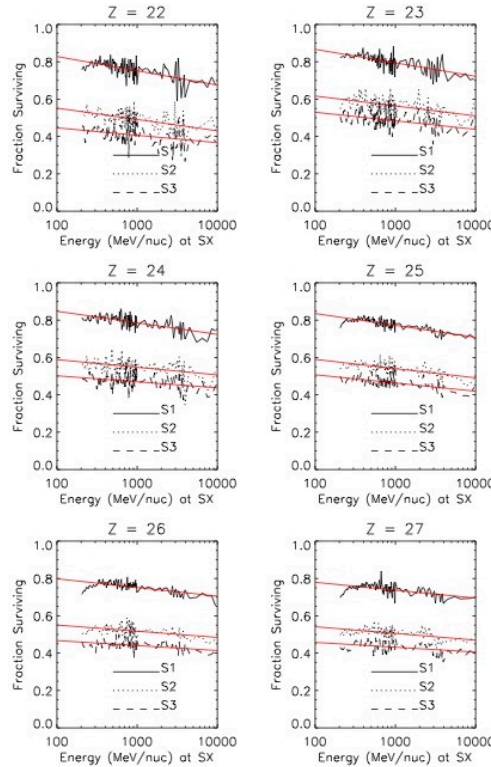


Figure 3: Particle survival fractions vs. energy for $Z=22$ – $Z=27$ from the top of the instrument through each of the scintillators, calculated by the SuperTIGER Geant4 simulation.

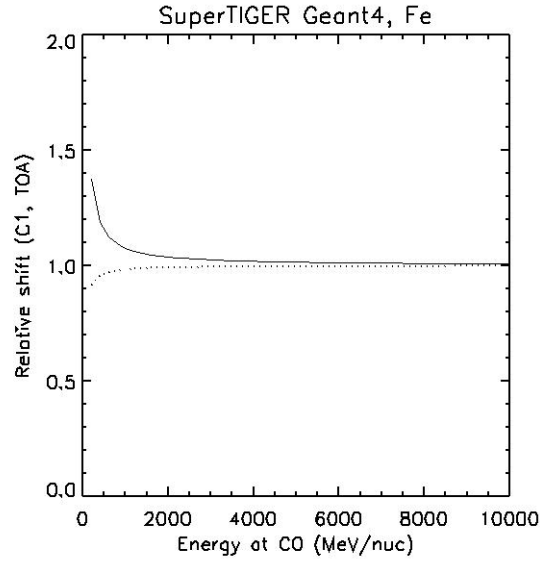


Figure 4: Geant4 calculations of Fe energies measured at TOI [the label TOA is incorrect] and C1 relative to energies measured at C0.

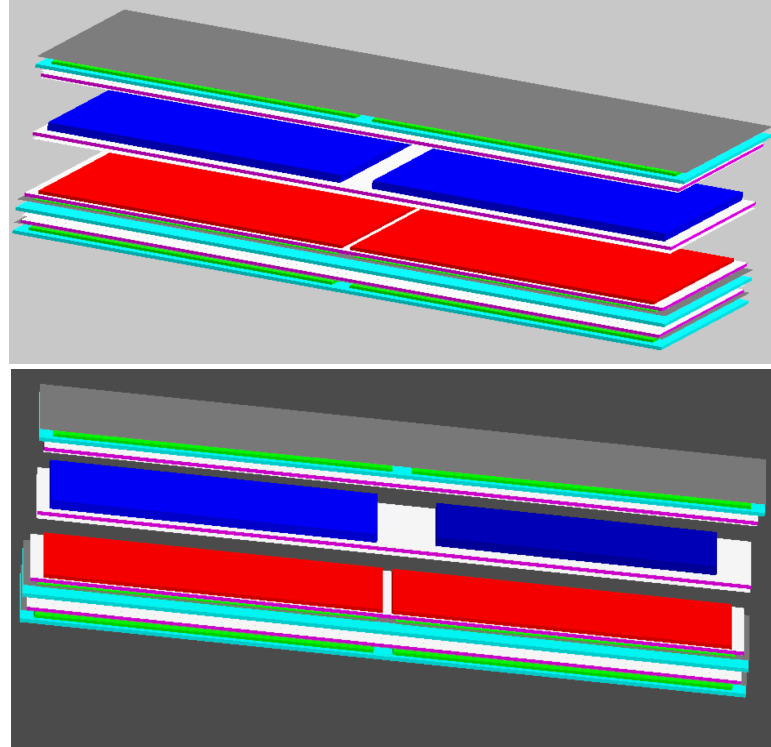


Figure 5: Geant4 models of the SuperTIGER Module with two $n=1.043$ aerogel sections (top; aerogels in dark blue), and the module with one $n=1.043$ and one $n=1.025$ aerogel sections (bottom). These models may be used both for the interaction loss and energy shift corrections but also to calculate geometry factor.

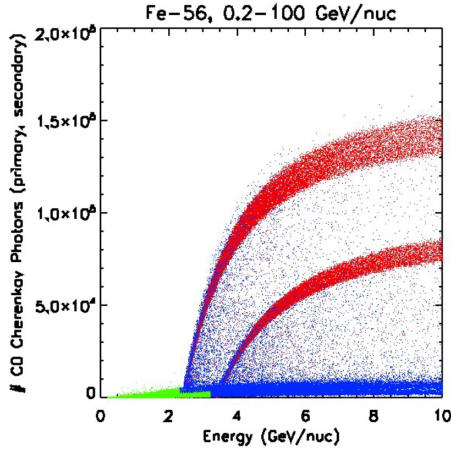


Figure 6: Geant4 simulated Aerogel Cherenkov signals due to the primary particles (red), knock-on electrons due to primary particles above threshold energy (blue), and knock-on electrons due to primary particles below threshold energy (green).

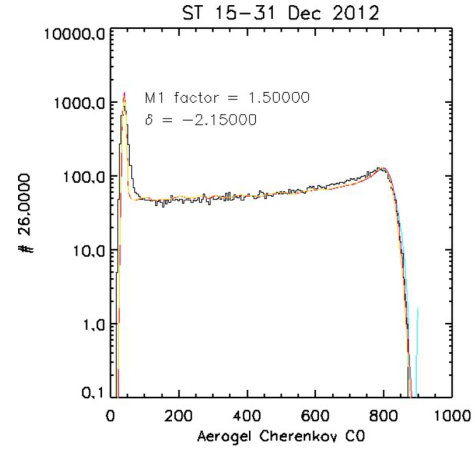


Figure 7: Fits of the aerogel Cherenkov signal for $Z=26$, assuming power law index of -2.15 , and ~ 1.5 - 2 pe's for $Z=1$, $\beta=1$.

6. Energy Calibration

Particle energies are obtained first by obtaining the charge and assumed isotopic mass from the S vs C1 or C1 vs C0 particle identification regions (Figure 2), and then by obtaining velocities from the Cherenkov data.

Figure 7 shows a sample fit of the aerogel Cherenkov signal, from SuperTIGER I flight data for Fe. The soft edge at saturation (β approaching 1) is a result of both the maximum photoelectron yield and resultant photoelectron fluctuations of the aerogel signal as well as the power-law index of the particle spectrum. The slope and curve of the “shoulder” between Cherenkov threshold (peak at left) and the saturation edge is largely due to the spectrum power law index (~ 2.15), and the threshold peak offset from zero is due to scintillation in plastic film in the detector, some Goretex Cherenkov signal, and knock-on electrons

Conclusion

Although work remains to be done in analyzing the simulation data, the Geant4 SuperTIGER instrument model is sufficiently complete that useful data may be generated. To date, test runs for elements from $Z=10$ to $Z=29$ have been successfully executed for millions of test particles at energies from 200 MeV/nuc to 40 GeV/nuc. Energy losses and interaction losses may now be calculated so that element abundances measured at the instrument can be corrected to the top of the instrument and top of the atmosphere.

Acknowledgements

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