CALET Measurement of Ultra-Heavy Cosmic Rays

B. F. Rauch\textsuperscript{1} FOR THE CALET COLLABORATION.

\textsuperscript{1} Department of Physics and McDonnell Center for the Space Sciences, Washington University in St. Louis
brauch@physics.wustl.edu

\textbf{Abstract:} The CALorimetric Electron Telescope (CALET) is under construction for launch to the International Space Station (ISS) in 2014, and beam-test components of its main calorimeter (CAL) instrument have recently undergone calibration at the CERN SPS using a lead-fragment beam. One of the primary science objectives of the CAL is to measure the energy spectra of nuclei from protons through iron up to 1,000 TeV, and a secondary objective will be to measure the rare ultra-heavy (UH) cosmic ray (CR) abundances that provide important clues for the CR source and acceleration mechanism. The CAL will supplement the UH statistics it can measure with events passing within the full instrument geometry by utilizing the Earth’s geomagnetic field at the 51.6° inclination orbit of the ISS to select events that do not need energy determination in the Total Absorption Calorimeter (TASC). Ion-beam test data show that the Charge Detector (CHD) scintillator response is relatively insensitive to energy above minimum ionization, and the angle dependent rigidity as a function of geomagnetic latitude can be exploited to discriminate individual elements above this energy threshold. Such events require corrections for trajectory in the instrument that can be made with only the top 4 layers of the Imaging Calorimeter (IMC), which allows for considerably greater geometric acceptance than for events that require passage through the TASC for energy determination. Using this approach CALET will be able to measure UH CR relative abundances over its expected mission with \( \approx 2 \) – \( 4 \) times the statistics of TIGER.

\textbf{Keywords:} CALET, cosmic ray, ultra-heavy.

\section{Introduction}

The CALorimetric Electron Telescope (CALET) is an experiment designed principally for the detection of high energy electrons. An instrument overview is given in \cite{1}, and its main scientific objectives are presented in \cite{2,3,4}. CALET consists of the main calorimeter telescope (CAL) and Gamma-ray Burst Monitor (CGBM) \cite{5} subsystems, as shown in Fig. 1. The CAL consists from top to bottom of the charge detector module (CHD), imaging calorimeter (IMC), and a total absorption calorimeter (TASC). The CHD is composed of two crossed layers of 3.2 cm wide \( \times \) 1 cm thick \( \times \) 45 cm long EJ200 scintillator paddles. The IMC is composed of eight x-y planes of 448 1 mm\(^2\) scintillating fibers interleaved with 5 plates of 0.2 X\(_c\) thick and 2 plates of 1 X\(_c\) thick tungsten (total of 3 X\(_c\)) spaced with structural honeycomb. The TASC consists of twelve crossed layers of 16 PWO logs, each 19 mm wide \( \times \) 20 mm tall \( \times \) 326 mm long, for 27 X\(_c\).

The great depth of the CAL (30 X\(_c\)) will allow it to measure the electron energy and gamma-ray spectra from 1 GeV to 20 TeV. The CAL is also highly sensitive to gamma-rays with energies between 10 GeV and 10 TeV, with the tungsten plates in the IMC promoting electromagnetic showers above the TASC for optimal shower reconstruction. The CHD provides a charge measurement that distinguishes between electrons and gamma-rays. The CHD has the charge resolution \cite{6,7} that enables the CAL to measure the energy spectra of the more abundant nuclei with \( Z \leq 28 \) together with the energy reconstruction from the TASC.

The rarer ultra-heavy (UH) nuclei (30 \( \leq Z \leq 40 \)) will also be measured in the CAL, which has adequate dynamic range in the CHD to measure up to \( Z \approx 40 \) \cite{3}, but the statistics collected requiring full passage through the CAL will be limited as the active area decreases from 45 cm on a side at the CHD and IMC to 32 cm on a side in the TASC, yielding a total geometry factor of 0.12 m\(^2\)sr. It has been shown previously that it is possible to resolve the UH nuclei by requiring passage through only the CHD and top IMC layers that yields a larger total geometry factor of 0.4 m\(^2\)sr \cite{8,9}. In this paper we present progress in the predicted CALET UH measurement using this method.
2 Ultra-Heavy Galactic Cosmic Rays

The composition of the Galactic cosmic rays (GCR) can provide vital clues about their origin and propagation. The relative abundances of the GCR at 2 GeV/nuc are compared with Solar System (SS) relative abundances \( (\text{Si}=1) \) for \( 1 \leq Z \leq 40 \) in Fig. 2. These relative abundances are seen to be substantially similar, with the most outstanding difference between them being the enhancement of the odd-Z elements and the sub-\( ^{26}\text{Fe} \) and \( ^{13}\text{Be} \) isotopes, which result from spallation of more abundant higher-Z elements as the GCR propagate from their source to earth. Studying this secondary component of the GCR makes it possible to determine the conditions in which the GCR propagate from their source, and to derive corrections for propagation effects to arrive at GCR source (GCRS) abundances. This plot also shows the enormous range in the relative abundances of the GCR over many orders of magnitude, with the UH GCR being about \( 10^5 \) less abundant than \( ^{26}\text{Fe} \) and hence particularly difficult to measure.

![Figure 2: Solar System (SS) relative abundances \( (\text{Si}=1) \) and Galactic cosmic rays (GCR) relative abundances at 2 GeV/nuc \( (1 \leq Z \leq 2 \text{ from } \[1\]), Z = 3 \text{ from } \[1\]), \( 4 \leq Z \leq 28 \text{ from } \[1\]), \( 29 \leq Z \leq 38 \text{ from } \[1\]), and \( 39 \leq Z \leq 40 \text{ from } \[1\]) normalized to \( \text{Si}=1 \).](image)

The UH GCR are worth measuring because they provide important insight into the GCRS material and acceleration mechanism. Previous UH results \([1\]) along with isotopic measurements of \( ^{10}\text{Be} \) and \( ^{26}\text{Fe} \) \([1\]) support a source composition that includes a \( \sim 20\% \) enrichment of massive star outflow (MSO) material to a \( \sim 80\% \) SS composition base. Fig. 2 shows that refractory elements (blue circles) with higher condensation temperatures \( (T_{\text{C50%}} > 1200 \text{ K}) \) are more abundant than the volatile elements (red squares), and that there is a mass dependence \( (A) \) to refractory elements as well as volatile elements, which is an elaboration on the original chemical fractionation model based on condensation temperature \([1\) \( ]\).]

3 Scintillator Based Charge Determination

The two layers of 1 cm thick scintillator that the CALET CHD uses are similar to the 0.8 cm thick scintillators at the top of the TIGER instrument \([1\]). The signal dependence of the TIGER scintillators in the UH region is expected to be representative of those used in CALET as the CHD EJ200 scintillator has shown a saturated response proportional to \( S \sim Z^{1.71} \) \([6\]), and the TIGER Saint-Gobain BC-416 scintillator has a response \( S \sim Z^{1.59} \) \([5\]). In addition, accelerator studies of scintillator response have been similar scintillator saturation results for nuclei up to \( ^{47}\text{Ag} \) \([1\]), which indicates that the response will be the same for the UH GCR.

Fig. 3 shows the dependence of the combined signals of the two TIGER scintillators \( (S1 + S2) \) as a function of acrylic Cherenkov signal \( (C1) \) for cosmic ray nuclei on the 2003 TIGER flight \([5\]). The clear charge contours show that the scintillator signal decreases with increasing energy to minimum ionization and then increases.

![Figure 3: Ratio of measured GCRS abundances \( (Z \leq 26 \text{ from } \[1\]) \) and \( 26 \leq Z \text{ from } \[1\]) \) to mixture of 80\% SS \([1\]) and 20\% MO (right plot) normalized to \( \text{Fe}=1 \) plotted against atomic mass.](image)

![Figure 4: Scatter plot of the sum of top scintillator signals \( (S1 + S2) \) versus acrylic Cherenkov signal \( (C1) \) for TIGER \([5\]). Curve is 600 MeV/nucleon threshold.](image)
at the relativistic rise and quickly saturates. Taking events with energies above the threshold line shown selects from roughly flat regions of the charge contours. Fig. 5 shows histograms of summed scintillator \( S1 + S2 \) signals for 2003 TIGER \( ^{56}\text{Fe} \) events for all energies in the black histogram, and for all energies above the threshold \( (C1 > 5000, \sim 600 \text{ MeV/nucleon}) \) in the red histogram, which yields a nearly Gaussian distribution for the charge peak. This shows that above the \( \sim 600 \text{ MeV/nucleon} \) threshold charges can be determined without an energy correction that would require passage through the TASC.

Figure 6: Contour plot of geomagnetic latitude at 450 km in 1° longitude and latitude bins derived from [20]. ISS orbit of 51.6° inclination is shown in solid curves.

4 Geomagnetic Rigidity Threshold Selection

The energy threshold cut described in the last section can be realized by utilizing the earth's magnetic field. Previous work [8, 11] estimated the events that CALET could discriminate above 600 MeV/nucleon based on the vertical cutoff rigidities seen in the orbit of the International Space Station (ISS) over its planned 5 year mission. In this work we consider the impact of the dependence of cutoff rigidity on the East-West angle \( (\gamma \text{ relative to West vector}) \). Fig. 7 shows the geomagnetic latitude \( (\lambda) \) at an altitude of 450 km derived from [20] using Störmer theory \( R_{\text{eff}} = 15 \cos^4(\lambda) \text{ GV} \), with black curves showing the ISS 51.6° inclination orbit. The ISS orbit residence time as a function of geographic latitude can be used with the geomagnetic latitude map to derive the orbital residence time as a function of geomagnetic latitude, which is shown in greater detail in [21]. This can be used with the critical momentum \( p_{\text{crit}}(\gamma, \lambda) \), Eq. 1 to determine CALET’s exposure above the 600 MeV/nucleon threshold for each element. Fig. 7 shows that \( p_{\text{crit}}(\gamma, \lambda)/Z \) varies strongly with East-West angle \( (\gamma) \), especially at low geomagnetic latitudes \( (\lambda) \).

\[
p_{\text{crit}}(\gamma, \lambda) = 60Z \left[ \frac{1 - \sqrt{1 - \cos(\gamma) \cos^3(\lambda)}}{\cos(\gamma) \cos(\lambda)} \right]^2
\]  

(1)

5 Predicted CALET UH Measurements

The UH fluxes are necessary in order to estimate the UH events CALET will see, and since the energy spectra of elements above \( ^{26}\text{Ni} \) have not been measured in the GCR these have to be estimated based on measured or assumed relative abundances. The UH GCR are mostly primary in composition, so their integral spectra are derived by scaling the \( ^{26}\text{Fe} \) spectrum with relative abundances: TIGER for \( 26 \leq Z \leq 40 \) [14] and HEAO-3-HNE for \( Z > 40 \) [12]. CALET is expected to see intermediate Solar modulation during its mission, so integral spectra derived from averaged differential spectra in [13] for Solar min and max are used.

At each geomagnetic rigidity the integral spectra of each element is evaluated where the critical momentum corresponds to kinetic energy per nucleon (Eq. 1) greater than

Figure 7: Critical momentum per charge.
Figure 8: Differential geometry factor for passage through CHD and top 4 IMC layers as a function of East-West angle (\(\gamma\)) and zenith angle (\(\theta\)).

the 600 MeV/nucleon threshold and weighted by the geomagnetic latitude orbit fraction and multiplied by the expected exposure (5 years). The flux at each such East-West angle is then multiplied by the differential geometry factor for the CHD and top four IMC layers as a function of East-West angle and zenith angle, shown in Fig. 8, and by the nuclear interaction survival probability in the CHD derived from total charge changing cross sections [24].

\[
E_{\text{crit}} = \sqrt{p_{\text{crit}}^2 / A^2 - m_{\text{amu}} - m_{\text{amu}}} \quad (2)
\]

6 Discussion

Fig. 8 shows the expected CALET event numbers over an anticipated 5 year mission compared with those from TIGER (black squares) [14] for the estimate based on vertical cutoff rigidity (red) and the preliminary estimate based on East-West rigidity (black). It is seen that the preliminary estimate based on East-West rigidity is approximately half of that obtained using vertical cutoff rigidities alone, where the assumption was that the East-West dependence would approximately average out. Asymmetry in the critical momentum distribution coupled with limits in the differential geometry factor at higher zenith angles could result in the \(\sim 2\) difference in the CALET predictions. For the East-West based approach CALET would see approximately twice the statistics that TIGER did. However, since CALET is a space mission it is not necessary to make interaction corrections to the top of the atmosphere, as is the case for a balloon-borne instrument such as TIGER.

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References