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35th ICRC 12-20 July 2017, Busan, South Korea
Observation of Protons and Light Nuclei with CALET

Analysis and Preliminary Results

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for the CALET Collaboration
ISS: a cosmic-ray observatory in Low Earth Orbit
<table>
<thead>
<tr>
<th>Experiment</th>
<th>$e^+</th>
<th>e^-$</th>
<th>$e^+ + e^-$</th>
<th>CR nuclei</th>
<th>charge</th>
<th>Gamma-ray</th>
<th>Type</th>
<th>Launch</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(present data)</td>
<td>(Energy range)</td>
<td>(Energy range)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>PAMELA</td>
<td>$e^+ &lt; 300$ GeV $e^- &lt; 625$ GeV</td>
<td>1-700 GeV (3 TeV with cal)</td>
<td>1 GeV-1.2 TeV (extendable -&gt; 2TeV)</td>
<td>1-8</td>
<td>-</td>
<td>SAT</td>
<td>2006 Jun 15</td>
<td></td>
</tr>
<tr>
<td>FERMI</td>
<td>-</td>
<td>7 GeV – 2 TeV</td>
<td>50 GeV-1 TeV</td>
<td>1</td>
<td>20 MeV – 300 GeV GRB 8 GeV – 35 MeV</td>
<td>SAT</td>
<td>2008 Nov 11</td>
<td></td>
</tr>
<tr>
<td>AMS-02</td>
<td>$e^+ &lt; 500$ GeV $e^- &lt; 700$ GeV</td>
<td>1 GV-1 TV (extendable)</td>
<td>1 GV-1.9 TV (extendable)</td>
<td>1-26 ++</td>
<td>1 GeV-1 TeV (calorimeter)</td>
<td>ISS</td>
<td>2011 May 16</td>
<td></td>
</tr>
<tr>
<td>NUCLEON</td>
<td>-</td>
<td>100 GeV-3 TeV</td>
<td>100 GeV-1 PeV</td>
<td>1-30</td>
<td>-</td>
<td>SAT</td>
<td>2014 Dec 26</td>
<td></td>
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<tr>
<td>CALET</td>
<td>-</td>
<td>1 GeV-20 TeV</td>
<td>10 GeV-1 PeV</td>
<td>1-40</td>
<td>10 GeV-10 TeV GRB 7-20 MeV</td>
<td>ISS</td>
<td>2015 Aug 19</td>
<td></td>
</tr>
<tr>
<td>DAMPE</td>
<td>-</td>
<td>10 GeV-10 TeV</td>
<td>50 GeV-500 TeV</td>
<td>1-20</td>
<td>5 GeV-10 TeV</td>
<td>SAT</td>
<td>2015 Dec 17</td>
<td></td>
</tr>
<tr>
<td>ISS-CREAM</td>
<td>-</td>
<td>100 GeV-10 TeV</td>
<td>1 TeV-1 PeV</td>
<td>1-28 ++</td>
<td>-</td>
<td>ISS</td>
<td>2017</td>
<td></td>
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<tr>
<td>CSES</td>
<td>-</td>
<td>3-200 MeV</td>
<td>30-300 MeV</td>
<td>1</td>
<td>-</td>
<td>SAT</td>
<td>2017</td>
<td></td>
</tr>
<tr>
<td>GAMMA-400</td>
<td>-</td>
<td>1 GeV-20 TeV</td>
<td>1 TeV-3 PeV</td>
<td>1-26</td>
<td>20 MeV-1 TeV</td>
<td>SAT</td>
<td>~2023-25</td>
<td></td>
</tr>
<tr>
<td>HERD</td>
<td>-</td>
<td>10(s) –10^4 GeV</td>
<td>up to PeV</td>
<td>TBD</td>
<td>10(s) –10^4 GeV</td>
<td>CSS</td>
<td>~2022-25</td>
<td></td>
</tr>
<tr>
<td>HELIX</td>
<td>-</td>
<td>-</td>
<td>&lt; 10 GeV/n</td>
<td>light isotopes</td>
<td>-</td>
<td>LDB</td>
<td>proposal</td>
<td></td>
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<tr>
<td>HNX</td>
<td>-</td>
<td>-</td>
<td>~ GeV/n</td>
<td>-</td>
<td>-</td>
<td>SAT</td>
<td>proposal</td>
<td></td>
</tr>
<tr>
<td>GAPS</td>
<td>-</td>
<td>-</td>
<td>&lt; 1 GeV/n</td>
<td>Anti-p, D</td>
<td>-</td>
<td>LDB</td>
<td>proposal</td>
<td></td>
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</tbody>
</table>
**Geometric Factor:**
- 1040 cm²sr for electron, proton
- 4000 cm²sr for ultra-heavy nuclei

• **ΔE/E:**
  - ~2% (>10 GeV) for e, gamma
  - ~30-35% for protons, nuclei

• **e/p separation:** ~10⁻⁵

• **Charge resolution:** 0.15 - 0.3 e

• **Angular resolution:**
  - 0.2° for gamma-rays > ~50 GeV
## CALET main science goals

<table>
<thead>
<tr>
<th>Science Objectives</th>
<th>Observation Targets</th>
</tr>
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<tbody>
<tr>
<td>Nearby Cosmic-ray Sources</td>
<td><strong>Electron spectrum</strong> in trans-TeV region</td>
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<td>Dark Matter</td>
<td>Signatures in <strong>electron/gamma</strong> energy spectra in the 10 GeV – 10 TeV region</td>
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<tr>
<td>Origin and Acceleration of Cosmic Rays</td>
<td><strong>p-Fe</strong> up to the multi-TeV region, Ultra Heavy Nuclei</td>
</tr>
<tr>
<td>Cosmic–Ray Propagation in the Galaxy</td>
<td><strong>B/C</strong> ratio up to a few TeV /n</td>
</tr>
<tr>
<td>Solar Physics</td>
<td><strong>Electron flux</strong> below 10 GeV</td>
</tr>
<tr>
<td>Gamma-ray Transients</td>
<td>Gamma-rays and X-rays in 7 keV – 20 MeV</td>
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</table>

### CALET Detector Components

- **Charge Detector (CHD)**
  - (Charge Measurement Z=1-40)
  - Layer Number of Scifi Belts: 8 Layers × 2(X,Y)

- **Imaging Calorimeter (IMC)**
  - (Particle ID, Direction)
  - Total Thickness of Tungsten (W): 3 $X_0$, 0.1 $\lambda$

- **Total Absorption Calorimeter (TASC)**
  - (Energy Measurement, Particle ID)
  - PWO: 20mm x 20mm x 320mm
  - Total Depth of PWO: 27 $X_0$ (24 cm), 1.2 $\lambda$

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CALET: a unique set of key instruments.

- **TASC**: a thick, homogeneous calorimeter allows to extend electron measurements into the TeV energy region with ~2% energy resolution.

- **IMC**: a high granularity (1mm) imaging pre-shower with tracking capabilities identifies the starting point of electromagnetic showers.

- **TASC+IMC** provide a strong rejection power $\sim 10^5$ to separate electrons from the abundant protons.

- **CHD**: a charge detector combined with multiple dE/dx samples from IMC identifies individual elements.

### Standard Payload Size

- **Mass**: 612.8 kg
- **Power**: 507 W (Max)

### Telemetry:

- Medium rate: 600 kbps
- Low rate: 50 kbps
CALET tracking takes advantage of the IMAGING capabilities of IMC thanks to its granularity of 1 mm with Sci-fibers readout individually.

Example: A multi-prong event due to an interaction of the primary particle in the CHD is very well imaged by the IMC.
Charge Measurement: Dynamic Range

- PMT+ CSA
- 64-anode PMT(HPK) + ASIC

1 ≤ Z ≤ 40
Fit of non-linear response of CHD layers vs $Z^2$

\[ \frac{dl}{dx} = \frac{A(1-f)Z^\alpha}{1+B_s(1-f)Z^\alpha + GZ^\alpha} + A_f Z^\alpha \]

\( A_{CHDY} = 0.6032 \pm 0.004434 \)
\( f_{h,CHDY} = 0.4852 \pm 0.007406 \)
\( \alpha_{CHDY} = 2 \pm 0 \)
\( B_s,CHDY = 0.007638 \pm 0.0003257 \)
\( G_{CHDY} = 3.829e-06 \pm 7.285e-07 \)

\( \chi^2 / \text{ndf} = 2.329 / 7 \)

\( \chi^2 / \text{ndf} = 3.885 / 7 \)

R. Dwyer et al., NIM A242 171 (1985)
G. Tarle et al., NIM B6 504 (1985)
**CHD charge resolution (2 layers combined) vs Z**

![Graph showing CHD charge resolution vs Atomic number Z](image)
Fit of non-linear response of IMC fibers vs $Z^2$

\[
\frac{dl}{dx} = \frac{A(1-f_h)Z^2\alpha}{1 + B_S(1-f_h)Z^2\alpha + GZ^4\alpha^2 + A_f h Z^2\alpha}
\]

Halo model

R. Dwyer et al., NIM A242 171 (1985)
G. Tarle et al., NIM B6 504 (1985)

\[
\chi^2 / \text{ndf} = 7.226 / 7
\]

- $A = 0.5886 \pm 0.003515$
- $f_h = 0.1665 \pm 0.01276$
- $\alpha = 2 \pm 0$
- $B_S = 0.003106 \pm 5.773e-05$
- $G = 1.325e-06 \pm 3.308e-07$

[F. Stolzi]
IMC charge resolution vs Z

IMC single fibers have photoelectron yield/MIP about 1 order of magnitude lower than the CHD paddles, but due to multiple dE/dx sampling (up to 16 independent measurements) the charge resolution of IMC is adequate to identify light nuclei.

Example: B to C charge separation is $\sim 7\sigma$ with CHD and $\sim 5\sigma$ with IMC
Example of combined CHD + IMC charge identification of light elements from boron to neon
Energy Measurement: Dynamic Range & Calibrations

Calibrating full range (6 order of magnitude) is quite a challenge!

Gain Ratio Calibration

MIP Calibration

final stitching

R. Miyata et al., this conference
Y. Komiya et al., this conference

Proton Event Selection

1. Acceptance-A selection
2. Good Tracking (KF)
3. High Energy Trigger (HET)
4. Charge selection \( Z = 1 \)
5. Helium rejection cuts
6. Electron rejection cuts

Fiducial Acceptance-A

tracking (Kalman Filter) efficiency
charge selection
trigger efficiency
Example of combined CHD + IMC charge identification of proton and helium
Residual He background after rejection of $Z > 1$ nuclei
Energy unfolding

A standard procedure is to construct an energy overlap matrix $A_{ij}$ from MC data:

- matrix element $\alpha_{ij}$ and normalization factor $n_j$ are weighted with the MC event weight when the “MC truth” energy falling into bin i leads to a reconstructed energy in bin j

- the normalized matrix is defined as: $A_{ij} \equiv \frac{\alpha_{ij}}{n_j}$

We also define:

- $\epsilon_i =$ total efficiency in i-th bin

- $\beta_j =$ background contamination in j-th bin

- $M_j =$ number of events (weighted) measured in j-th bin (sum up to $M_{tot}$ in energy range)

- $N_i =$ energy unfolded number of events (weighted) in i-th bin

Then:

$$N_i = \frac{1}{\epsilon_i} \sum_{j=1}^{n} A_{ij} (M_j - \beta_j M_{tot})$$
Residual electron contamination in proton sample

Preliminary analysis:

• Loose electron rejection cut: ratio of bottom TASC layer energy deposit / $E_{TASC}$
• Efficiency of the cut decreases with energy but contamination < 2%
• Electron background contamination can be further reduced by applying full e/p discrimination criteria.
Preliminary proton flux $E^{2.7}$ from 50 GeV to 22 TeV

- 15 months of observation from December 1st, 2015 to February 28th, 2017
- subset of total acceptance: acceptance A (fiducial) with $S\Omega = 416$ cm$^2$ sr
- Assessment of the systematic errors: IN PROGRESS
Preliminary \( \frac{dN}{dE} \) for light elements: \textit{proton} to \textit{oxygen}
CALET is exploring the Multi-TeV region

- **elemental spectra & relative abundances,**
- **flux ratios** (secondary-to-primary, primary-to-primary, secondary-to-secondary)

CALET Energy reach in 5 years:

- **Proton** spectrum to \( \approx 900 \text{ TeV} \)
- **He** spectrum to \( \approx 400 \text{ TeV/n} \)
- Spectra of C, O, Ne, Mg, Si to \( \approx 20 \text{ TeV/n} \)
- **B/C** ratio to \( \approx 4 - 6 \text{ TeV/n} \)
- **Fe** spectrum to \( \approx 10 \text{ TeV/n} \)

<table>
<thead>
<tr>
<th></th>
<th>( \lambda_{\text{INT}} )</th>
<th>( X_0 ) (normal incidence)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CREAM</td>
<td>( 0.5 + 0.7 )</td>
<td>20</td>
</tr>
<tr>
<td>CALET</td>
<td>1.3</td>
<td>30</td>
</tr>
<tr>
<td>AMS-02</td>
<td>0.5</td>
<td>17</td>
</tr>
<tr>
<td>DAMPE</td>
<td>1.6</td>
<td>31</td>
</tr>
</tbody>
</table>

Conclusions

✧ CALET has been delivering science data from the ISS during the last 20 months
✧ Total observation time 627 days with live time fraction to total time close to 84%
✧ Instrument performance and stability are excellent
✧ Single elements have been identified thanks to redundant charge measurements
✧ A preliminary analysis of proton and light nuclei has been presented
✧ The so far excellent performance of CALET and the outstanding quality of the data suggest that a 5-year observation period is likely to provide a wealth of new interesting results