Measurements of Nuclei Fluxes in Cosmic-rays with CALET

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Measurements of Cosmic-Ray Nuclei

Nuclei measurement in GeV – TeV energy region

- Primary individual spectra
  - cosmic-ray acceleration and propagation
  - hardening of spectra
- Secondary-to-primary flux ratio
  - cosmic-ray propagation
  - energy dependence of diffusion coefficient

Measurements with CALET

**Energy spectra from Proton to Iron**

- Charge measurement in Z = 1 – 40
  - Charge resolution: 0.18e(C)-0.3e(Fe)
- Energy measurement in 10GeV - 1000TeV
  - Dynamic range: 1-10⁶MIP (~1000TeV)

This presentation:

- Energy spectra of heavy primary elements
- Boron-to-carbon flux ratio
Calorimeter

A 30 radiation length deep calorimeter designed to detect electrons and gammas to 20 TeV and cosmic rays up to 1 PeV

CHD: Charge Detector
- Charge measurements (Z=1-40)
  - Plastic scintillator paddles 14 x (X, Y)
  - Unit size: 32mm x 10 mm x 450 mm

IMC: Imaging Calorimeter
- Arrival direction, Particle ID
  - Scintillating fiber belts 448 x 16 layers
  - Unit size: 1 mm² x 448 mm
  - Tungsten plates 7 layers
  - $3X_0 (=0.2X_0 \times 5 + 1.0X_0 \times 2)$

TASC: Total Absorption Calorimeter
- Energy measurement, Particle ID
  - PWO logs 16 x 12 layers
  - Unit size: 19 mm x 20 mm x 326 mm
  - $27X_0$ for electrons
  - 1.2 interaction length for protons
Energy measurements

TASC read-out system

APD: 100mm$^2$
- MIP calibration using cosmic-ray proton and helium is carried out to equalize all channel gains and monitor long-term stability
- The correlation between adjacent gain ranges is calibrated by using in-flight data in each channel
- The linearity was calibrated using UV laser irradiation on ground

Distributions of deposit energies in TASC

Example of energy distribution of one PWO log

Calibration:

- MIP calibration using cosmic-ray proton and helium is carried out to equalize all channel gains and monitor long-term stability
- The correlation between adjacent gain ranges is calibrated by using in-flight data in each channel
- The linearity was calibrated using UV laser irradiation on ground

The TASC energy measurements have successfully been carried out in the dynamic range of 1 GeV – 1PeV

APS April Meeting 2019, Denver, Colorado
Nuclei analysis procedure

1. **Onboard High energy trigger**
   - Coincidence of IMC-X78, IMC-Y78 and TASC-X1
   - Energy threshold is set to detect 10 GeV electrons

2. **Offline shower trigger**
   - NmipIMC-X78, Y78 > 50MIP & NmipTASC-X1 > 100MIP

3. **Tracking with IMC**
   - select events satisfied geometrical condition
   - identify the impact point

4. **Charge consistency with CHD and IMC**
   - remove backgrounds
   - maintain charge resolution

5. **Charge selection with CHD**
   - estimate background

6. **Energy measurements and unfolding**
   - measure energy with TASC
   - unfold energy spectrum by Iterative Bayesian process

7. **Flux Calculation**
Tracking for nuclei events

- Reconstruct shower axis with IMC signals
- Heavy nuclei can make many shower particles in IMC, which could be a large background for track; the signal of primary particle is commonly larger than the signals of the shower particles

⇒ Simple tracking methods: Least chi-square fitting is applied for the maximum clusters in upper 4 IMC layers.

Carbon $\Delta E_{TASC} = 2.06$ TeV

Pulse height of IMC

Accuracy of impact point at CHD
Charge resolution

- Non-linear response to $Z^2$ is corrected both in CHD and IMC using a model
- A clear separation between p, He, ~$Z=8$, can be seen from CHD+IMC data analysis
Charge identification and Background estimation

- Particle charge is identified with CHD
- Background is estimated by means of MC

**MC data:**
- EPICS v9.21 (Cosmos8.01)
- DPMJET-III

Consider quenching, noise and etc.
Apply the same selection with flight data.

**Pre-selection**
- HE trigger
  - Tracking + geometrical condition
  - Charge consistency with CHD-X, Y and IMC
  - Track width selection

**dN/dE and BG for Boron**

**dN/dE and BG for Carbon**

**Background ratio**
- Boron: 3%
- Carbon: 0.3%
Energy unfolding

Characteristics of nuclei measurements with CALET calorimeter:
- thickness: 30 $X_0$ for electron, 1.3$\lambda$ for proton
- $\sigma(E)/E$ : 2% for electron, 30% for nuclei
  ➡ Need energy unfolding for nuclei to obtain primary energy spectrum

Iterative Bayesian unfolding
- Initial assuming spectra: $f(E)=A \times E^{-2.60}$
  $A$ is normalized by charge distribution in CHD
- Response function:
  $\Delta E$ [GeV] (deposit energy in calorimeter) vs $E_0$ [GeV]
Preliminary Flux of Primary Components

Flux measurements:
\[ \Phi(E) = \frac{N(E)}{S\Omega\varepsilon(E)T\Delta E} \]

- \( N(E) \): Events in unfolded energy bin
- \( S\Omega \): Geometrical acceptance
- \( \varepsilon(E) \): Efficiency
- \( T \): Live Time
- \( \Delta E \): Energy bin width

Observation period:
- Oct. 13 2015 – May 31 2018
  - (962 days)
- \( 5.6 \times 10^6 \) events (C-Fe, \( \Delta E > 10 \text{GeV} \))
Boron-to-carbon flux ratio

Source of systematic uncertainties

- Trigger efficiency
- Charge consistency cuts
- Track width selection
- Window range for charge identification
- Background model of p and He spectra
- Initial assumed spectra for energy unfolding
- Energy correction base on beam test results
- Difference of beam test model and flight model
- Long term stability

\[ \frac{^{10}\text{B}}{^{11}\text{B}} = 3:7 \]
Conclusions

• The ability of CALET to measure heavy cosmic-ray nuclei has been successfully demonstrated
  – Dynamic range for energy measurement: 1-10^6 MIP (1GeV – 1PeV)
  – Charge resolution: 0.18 for carbon, 0.30 for iron

• Using data from the 962 days of operation, preliminary analysis of nuclei has been successfully carried out
  – B/C ratio up to 200 GeV/n
  – primary cosmic-ray elements up to 100 TeV

• Independent analyses were carried out using different event selection procedures and MC simulations. Preliminary results are consistent.

• Further studies will provide the excellent energy spectra with high statistics in a wide energy range, and reveal details spectral features