Measurements of Cosmic-ray Electron and Gamma-ray Flux with Balloon-Borne CALET Prototype

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Abstract: We carried out the balloon experiments using CALET (CALorimetric Electron Telescope) prototype detectors in May 2006 (bCALET-1) and August 2009 (bCALET-2) for verification of both the detector performance and the capability of measuring the cosmic rays at higher atmosphere. The bCALET-2 instrument for observing the electrons and the gamma rays at energies in 1-100 GeV is composed of an imaging calorimeter consisting of 4096 scintillating fibers with a total of 3.6 radiation lengths of tungsten plates, and a total absorption calorimeter consisting of crossed 60 BGO logs with a total of 13.4 radiation lengths depth. The bCALET-2 was launched from the Taiki Aerospace Research Field, Japan Aerospace Exploration Agency, in Hokkaido, and flew successfully for 2.5 hours at a level altitude of 35 km. In this paper, we will present the spectra of electrons and gamma rays in the energy range of 1-100 GeV measured by bCALET-2, comparing with our previous observations, bCALET-1 and BETS. The detector performance is studied by comparing with the simulations, and the observed fluxes are found to be compatible with the expected.

Keywords: electrons, atmospheric gamma-rays, direct measurement, balloon experiment

1 Introduction

CALET (CALorimetric Electron Telescope) has been developed as an instrument to observe high energy electrons and gamma-rays at International Space Station (ISS) [1]. For the verification of the detector performance, we have carried out 2 balloon experiments. First balloon experiment was carried out at Sanriku in May 2006 using a prototype detector, bCALET-1. From the data taken at an altitude 35-37 km, we obtained the electron energy spectrum in 0.5-20 GeV. bCALET-2 is a second prototype detector with several new functions installed on it. In this paper, we report mainly the results by the bCALET-2 observation.

2 Detector

bCALET-2 has generally the same configuration as CALET [2], that is, main part of the detector can be divided into two parts. The upper part is an imaging calorimeter (IMC), which is composed of 7 tungsten plates and 8 detection layers for tracking particles. Each layer is composed of two fiber belts arranged in x and y direction, and each belt consists of 256 scintillating fibers with 1 mm square cross section. The lower part of the detector is a total absorption calorimeter (TASC), which measures the energy of the incident particle and the shower development. TASC consists of 6 layers, each composed of 10 BGO logs. The cross section of each BGO is 2.5 cm. Those layers are arranged in x and y direction alternately. The total thickness of the detector is 17.0 r.l. A trigger signal is generated by the plastic scintillators (S1,S2,Anti) and the TASC top layer (BS), as presented in Fig.1. There are several patterns of trigger dedicated for electron or gamma-ray observation with variable energy thresholds. For more detail about the bCALET-2 detector, see an accompanied paper in this volume [3].

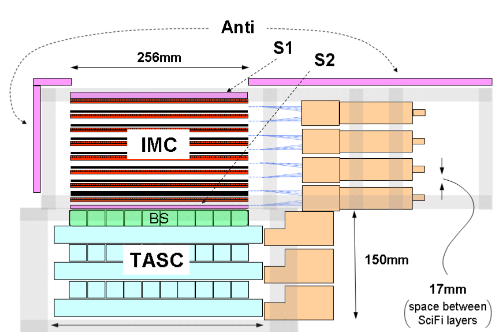

Figure 1: bCALET-2 detector

3 Balloon experiment

The observation by bCALET-2 was carried out at the Taiki Aerospace Research Field in Hokkaido on August 27th, 2009. The detector was successfully launched and flew for 2.5 hours at a level altitude of 35 km. We measured electrons with an energy threshold around 1 GeV and gamma-rays around 200 MeV for the first one hour, and changed the trigger mode subsequently to perform intensive measurement of high energy electrons with an energy threshold of 10 GeV. As a whole, we collected about 8,400 electron-like events and 3,400 gamma-ray-like events through the level flight.

4 Calibration

We measured cosmic-ray muons for calibration at Sagamihara campus of Institute of Space and Astronautical Science (ISAS) and at the Taiki Aerospace Research Field. All of the 4096 scintillating fibers and the 60 BGO scintillators were calibrated using these data. The light yields of the BGO scintillators were corrected with consideration for temperature dependence. Figure 2 shows a fitting example of muon peaks shifting through the temperature changing. Average value of the temperature coefficient for all the BGO logs is -1.27 %/°C.

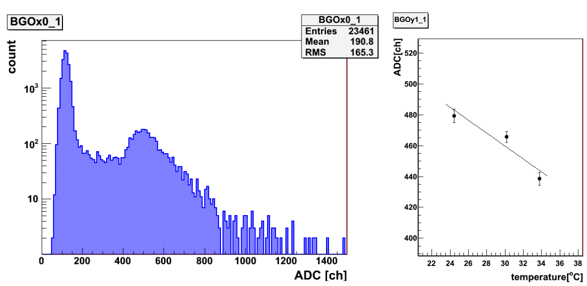

Figure 2: Distribution of ADC counts during muon-run (left), and the temperature dependence(right)

The accurate positions of scintillating fibers were also estimated from the muon data. Figure 3 shows an example of muon track reconstruction. The misalignment between layers was assumed as the position deference between the reconstructed track and the luminous fiber.

5 Data Analysis

We analyzed about 12,000 events collected through the level flight, estimating the incident energy and reconstructing the track. Proton background was rejected using shower profiles measured by IMC and TASC. The detector capabilities such as angular resolution and proton rejection power were estimated by Monte-Carlo simulation using the EPICS code [4].

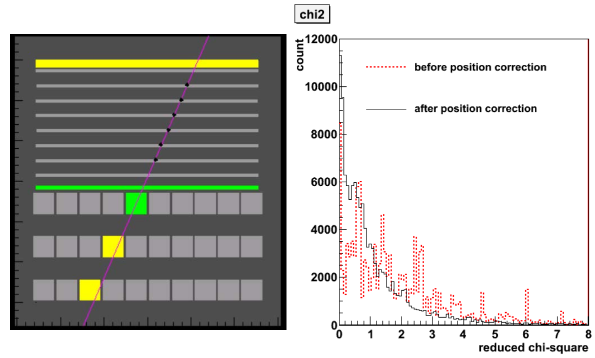

Figure 3: Example of muon track reconstruction(left), and distribution of chi-square values in muon track fitting before and after position correction(right)

5.1 Energy estimation

The incident energy was estimated by the sum of the deposited energy in TASC. We selected the events which pass through the top of the detector and the bottom of the third BGO layer so as to retain good energy resolution. The definition of this geometrical condition is described in Fig.4. Energy resolution for electrons and gamma-rays at 10 GeV is 7.4% and 6.4%, respectively.

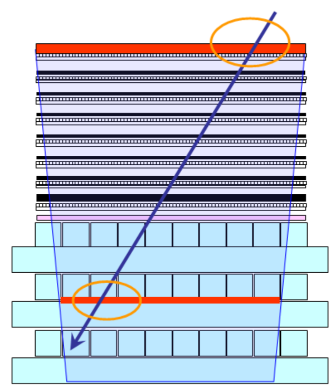

Figure 4: The events which pass through both the top of the detector and the third BGO layer are analyzed

5.2 Track reconstruction

The electron shower axis was determined by the least-square fitting of shower cores in IMC, avoiding the effects of dead channels. The gamma-ray shower axis was obtained in almost the same way as electron, but shower cores in the TASC top 4 layers were also used for fitting. The angular resolution estimated by Monte-Carlo simulation is 1.4 ° for electrons and 1.6 ° for gamma-rays.

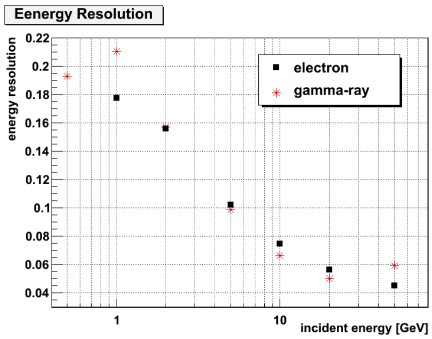

Figure 5: Expected energy resolution by simulation

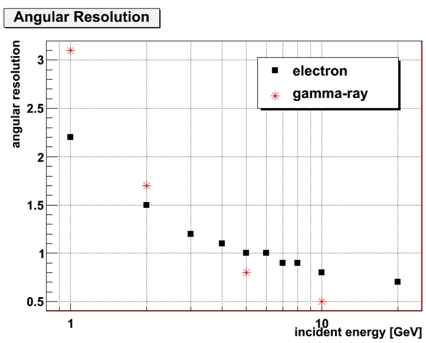

Figure 6: Expected angular resolution by simulation

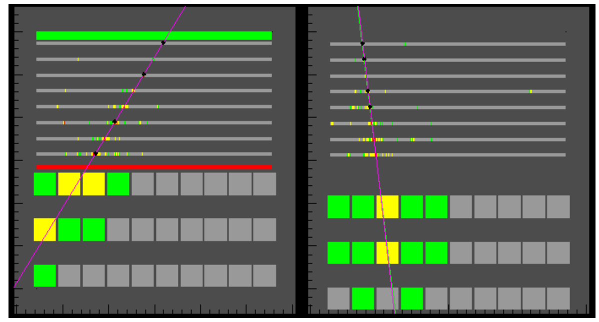

Figure 7: Example of electron track reconstruction

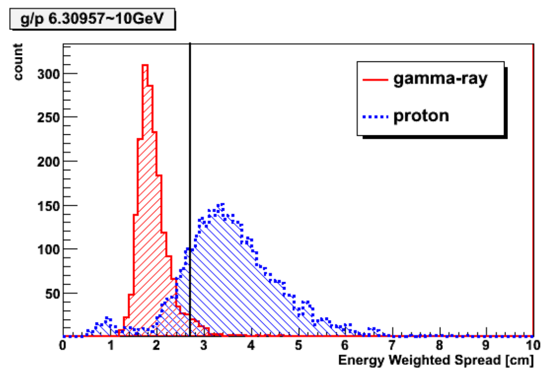

Figure 8: Distribution of the lateral spread of simulated gamma-ray trigger events

5.3 Proton rejection

A lateral spread of a proton-induced shower is expected to be wider than that of electromagnetic shower. The lateral spread in TASC can be defined as below :

$$R_E = \sqrt{\frac{\sum_i (\Delta E_{layer_i} \times R_i^2)}{\sum_i \Delta E_{layer_i}}} \quad (1)$$

where ΔE_{layer_i} is energy deposition in the i-th layer, and R_i is the lateral spread in the i-th layer. It is described as below :

$$R_i = \sqrt{\frac{\sum_j \left(\Delta E_{BGO_j} \times (x_j - x_c)^2\right)}{\sum_j \Delta E_{BGO_j}}} \quad (2)$$

where ΔE_{BGO_j} is energy deposition in the j-th BGO, x_j is the position of the j-th BGO, and x_c is the position of the shower center.

Gamma-rays Proton background to the gamma-ray-like events was rejected before the track reconstruction, using R_E. x_c in Eq.1 was estimated as the energy weighted center of each layer. Figure 8 shows R_E distribution of simulated events. Proton contamination rate is estimated as 21.1% at 5 GeV and 15.6% at 20 GeV, while 97% of gamma-ray events are retained.

High-energy electrons To reject background protons from the electron-like events, a shape of vertical shower development was also used as a parameter. The transition of the electron energy deposition in detectors can be formulated as below :

$$\frac{dE}{dt} = E_0 \, b \, \frac{(bt)^{a-1} \, e^{-bt}}{\Gamma(a)} \quad (3)$$

where t is a thickness in radiation length, E_0 is the incident energy, a and b are parameters. Shower maximum depth can be described as $(a-1)/b$. Figure 9 shows the correlation map of the shower maximum depth and the lateral spread in TASC. The proton contamination rate is estimated as 6.1% while 82.2% electrons are retained.

Low-energy electrons The electron events, which has an energy lower than about 6.7 GeV, develop the shower mainly in IMC. Therefore proton rejection was carried out using energy concentration in IMC, which is defined as the ratio of energy deposition within 5 mm from the shower axis to the total. Figure 10 shows the correlation map of the lateral spread in TASC and the energy concentration in IMC.

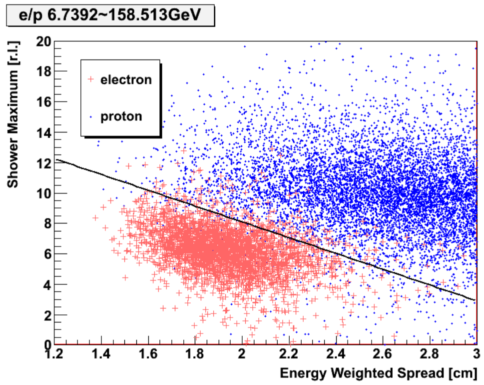

Figure 9: Correlation map of the shower maximum depth and the lateral spread in TASC (simulation)

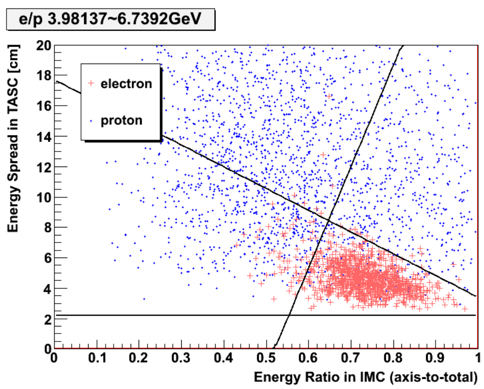

Figure 10: Correlation map of the lateral spread in TASC and the energy concentration in IMC (simulation)

5.4 Energy spectra

The energy spectra of electrons and gamma-rays at an altitude of 35 km were derived from the events selected through the geometrical restriction shown in Fig.4 and the proton rejection. The proton contamination and the electron or gamma-ray retain ratio were corrected as below :

$$f\left[\mathrm{m^{-2}sr^{-1}s^{-1}GeV^{-1}}\right] = \frac{N}{\Delta E \cdot t \cdot S\Omega} \cdot \frac{1}{\epsilon} \cdot \delta \qquad (4)$$

where N is number of events, ΔE is energy range, t is actual observation time, $S\Omega$ is geometric factor (= 314 $\mathrm{cm^2 sr}$), ϵ is electron or gamma-ray retain ratio, and δ is contamination factor of other particles. It includes the contamination of gamma-rays into the electron trigger events by backscattering or interaction above the detector.

6 Summary and Results

The second balloon experiment using the CALET prototype detector bCALET-2 was carried out. The detector collected about 12,000 events through 2.5 hours of level flight at an altitude of 35 km. Selection of electron and gamma-ray candidates from a large amount of background protons was carried out by criteria imposed by analysis of simulated events. As a result, we have successfully derived the energy spectra of electrons and gamma-rays in energy range of 1-100 GeV. As shown in Fig.11, the power-law spectra of primary and atmospheric electrons and atmospheric gamma-rays were observed. The present result is compatible with the expected values of simulation using the COSMOS code [4] and with the results of BETS and bCALET-1 experiment.

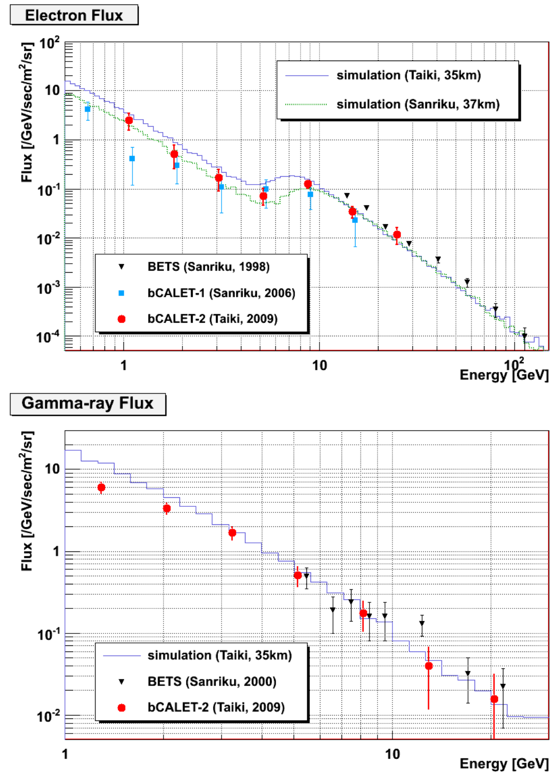

Figure 11: bCALET-2 results of electron and gamma-ray flux compared with previous experiments and simulation

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