The CALET CHD for determination of nuclear charge

Yuki Shimizu[1], Oscar Adriani[4], Yosui Akaike[2], Carlo Avanzini[5], Maria Grazia Bagliesi[3], Andrea Basti[5], Gabriele Bigongiari[3], Massimo Bongi[4], Guido Castellini[4], Daijiro Ito[2], Mikihiko Karube[2], Katsuaki Kasahara[2], Me Young Kim[3], Keinosuke Kondo[2], Temuriaz Lomtadze[5], Masanori Nakamura[2], Paolo Maestro[3], Pier Simone Marrocchesi[3], Fabio Morsani[5], Tae Niita[2], Sergio Bruno Ricciarini[4], Shoji Torii[2], Yoshitaka Ueyama[2]

[1]*Human Space Systems and Utilization Mission Directorate, Japan Aerospace Exploration Agency, Ibaraki 305-8505, Japan*

[2]*Researh Institute for Science and Engineering, Waseda University, Tokyo 169-8555, Japan*

[3]*Department of Physics, University of Siena, V. Roma 56, 53100 Siena, Italy*

[4]*Department of Physics, University of Florence and IFAC(CNR), Italy*

[5]*Department of Physics, University of Pisa and INFN, Largo B.Pontecorvo 3, 56127 Pisa, Italy*

shimizu.yuuki@jaxa.jp

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Abstract: Calorimetric Electron Telescope (CALET) will be a high energy cosmic ray observatory on the Japanese Experimental Module – Exposed Facility of the International Space Station. In addition to electrons and gamma-rays, CALET has an excellent detection capability of cosmic ray nuclei. In order to determine the atomic number of measured nuclei, the CHarge Detector (CHD) is placed on the top of the calorimeter. The CALET-CHD consists of two orthogonal layers of plastic scintillator charge-measuring modules. Each layer is segmented into 14 scintillator paddles (45 cm×3.2 cm×1 cm) for the reduction of back scattering effects. We evaluated the charge resolution of the plastic scintillators with heavy ion accelerators. In this presentation, we will report the design of the CALET-CHD and its nuclei identification capability as inferred from heavy ion beam tests.

Keywords: nuclei, nuclear charge, plastic scintillator

1 Introduction

CALorimetric Electron Telescope (CALET) is a mission instrument which is scheduled to be installed on the Japanese Experiment Module – Exposed Facility of the International Space Station [1]. The main part of the instrument is an electromagnetic calorimeter for the observation of high energy cosmic rays. The calorimeter has capability to measure primary electrons from 1 GeV to 20 TeV and γ-rays from 10 GeV to 10 TeV. The thickness of the calorimeter of 30 radiation lengths enables to observe electrons and γ-rays with high energy resolution and accurate discrimination from proton background. The main objectives of the mission are to search nearby sources of high energy cosmic rays and signatures of the dark matter by means of electron and γ-ray measurements.

Since the calorimeter has excellent separation between the electromagnetic shower initiated by electrons and γ-rays and the hadron shower by nuclei, it should be straightforward to measure primary cosmic ray nuclei with CALET. According to our Monte-Carlo studies, the calorimeter can measure nuclei with good energy resolution less than about 30% from tens GeV to 1000TeV. This capability enables to study the acceleration mechanisms and the propagation of cosmic rays with CALET.

Supernova remnants (SNRs) have long been regarded as the most probable sources of cosmic rays up to PeV. However, the spectrum of all the cosmic rays observed so far extends several orders of magnitude beyond the highest energy thought to be possible for SNR shock acceleration. In addition, the “knee” structure of the spectrum, change of index, has been observed above 1000 TeV. Direct measurement of individual spectra of nuclei can solve these puzzles and provide the convincing evidence for the SNR acceleration. So far, energy spectra of individual nuclei has been measured by long duration balloon experiments. However, the highest measurable energy of nuclei is limited by only by exposure. With five years exposure on the ISS, CALET will observe the individual nuclear spectrum with much larger statistics than the present balloon experiments. Figure 1 shows energy spectra of various nuclei measured by previous experiments, on which expected results of 5 years observation of CALET is superimposed. Another scientific objective related to measurement of nuclei is the study of cosmic ray propagation in the galaxy with secondary to primary ratios. CALET can also extend the measurement

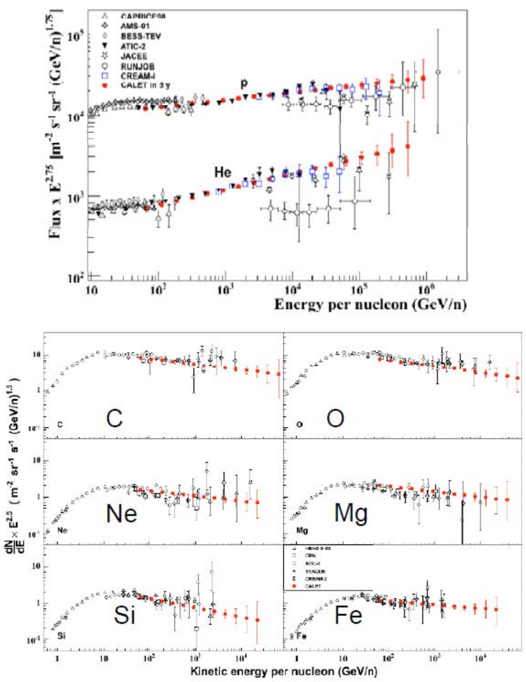

Figure 1: Energy spectra of proton, He, C, O, Ne, Mg, Si and Fe measured by previous experiments. The expected results of 5 years observation of CALET are superimposed.

of B/C ratio up to several TeV/nucleon. Furthermore, observation of the relative abundances of ultra heavy nuclei ($Z \geq 35$) is proposed [2].

In order to identify the atomic number of incident nuclei, the calorimeter will be equipped with the CHarge Detector (CHD) employing plastic scintillator. In this paper, we report the design of CALET-CHD and heavy ion beam experiments with its prototype.

2 Design of CALET-CHD

The calorimeter of CALET consists of the IMaging Calorimeter (IMC) with 3 radiation lengths of tungsten plates interleaved with 8 planes of scintillating fibers (SciFi), the Total AbSorption Calorimeter (TASC) with 27 radiation lengths of $PbWO_4$ (PWO) scintillator logs, and CHD [1]. CHD is located on the top of the calorimeter to determine the charge of incident particles before entering the main volume of the calorimeter. The structural design of CHD is shown in Fig 2. As shown in the figure, the scintillator planes and the front-end circuit (FEC) boxes of CHD are stacked up directly on the SciFi planes and the FEC boxes of IMC so as to make a rigid structure and minimize the distance between CHD and IMC.

CHD is composed of two layers made of plastic scintillator, EJ204 (ELJEN technology). Each layer is segmented into 14 scintillator paddles. The size of each paddle is 45 cm × 3.2 cm × 1 cm thick, which is almost the same size as each SciFi belt consisting of 32 fibers. With the segmented configuration, multi-hits on each paddle caused by back scattering particles are reduced. Two set of the 14 paddles are orthogonally arranged to determine the incident position of the cosmic rays. Taking advantage of the precise tracking with IMC and the energy determination with TASC, CHD can provide the charge identification for incident particles.

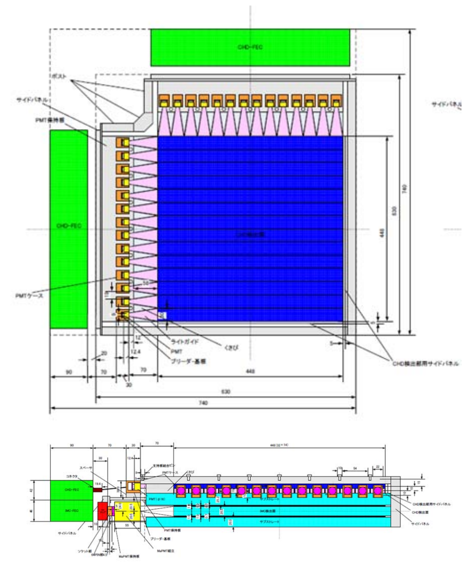

Figure 2: Structural design of CALET-CHD. The top (upper) and side (lower) views are shown. CHD is stacked up on the first layer of IMC.

Scintillation photons from each paddle are detected by a PMT with a photocathode of 8 mm diameter (R7400-06 type, Hamamatsu) through a acrylic light guide. These paddles are covered with Vikuiti ESR films (3M) in order to increase correction efficiency of photons. Design of CHD-FEC is almost the same as TASC-FEC [4]. While TASC-FEC employs dual range readout for each photo sensor to achieve the wide dynamic range, CHD-FEC employs single readout. The dynamic range of readout for CHD covers about three orders of magnitude with a 16-bit ADC, which is sufficient to measure the charge of Fe ($Z = 26$). Taking account of the quenching effect described in the next section, the range is expected to reach $Z \sim 40$.

3 Scintillation response to nuclei

It is well known that the scintillation efficiency is reduced in the case of the large linear energy transfer, dE/dx, which is known as quenching effect. When the local ionization density is large, the fraction of radiationless de-excitation is increased. For measurement of heavy nuclei, quenching reduces the scintillation photon yield, so that the charge resolution is decreased. The response of the scintillator was conventionally described as the following semi-empirical model [5];

$$\frac{dL}{dx} = \frac{S\frac{dE}{dx}}{1 + kB\frac{dE}{dx}}, \tag{1}$$

where L and S represent the light yield and scintillation efficiency, and kB is a quenching parameter which is known as Birks's constant. For several types of plastic scintillator, kB is of order of 10^{-2} g/cm^2/MeV [6]. According to Eq. 1, light yield is almost saturated when kB(dE/dx) $\gg 1$. On the other hand, it is reported that such saturation of the light yield from plastic scintillator is not observed for relativistic heavy nuclei although kB(dE/dx) $\gg 1$ in Ref. [7], where an extension of Eq. 1 is described in order to satisfy the experimental results;

$$\frac{dL}{dx} = \frac{S(1-F_s)\frac{dE}{dx}}{1 + kB(1-F_s)\frac{dE}{dx}} + SF_s\frac{dE}{dx}, \tag{2}$$

where F_s is the fraction of energy deposited away from the core of the ionization. Assuming this model and non-negligible F_s, nuclear charge identification with plastic scintillator is not severely interfered by quenching even for heavier nuclei.

We measured the scintillation response of EJ204 in order to estimate the charge identification capability of CALET-CHD paddles for heavy relativistic nuclei.

4 Beam experiments

We conducted beam experiments with prototype scintillator paddles in two accelerator facilities. One is GSI Helmholtz Centre for Heavy Ion Research GmbH in Germany, and the other is the Heavy Ion Medical Accelerator at National Institute of Radiological Sciences in Chiba (NIRS-HIMAC). GSI beam test was performed with Ni primary beam with the energy between 1000 and 1300 MeV/nucleon in October 2010. Utilizing the projectile fragment separator (FRS), relativistic nuclear fragments produced in a Be target (1.03 g/cm^2) were focused achromatically and irradiated to the scintillator paddles. The details of the GSI tests are described in Ref. [10]. HIMAC beam test was performed in January and May 2011. We used several types of ion sources, proton (240 MeV/nucleon), He (230 MeV/nucleon), C (430 MeV/nucleon), Si (800 MeV/nucleon) and Fe (500 MeV/nucleon). Nuclear fragments were produced with Si and Fe beams by using an acrylic target of 1 cm thickness, which was placed about 1 m upstream of the paddles along the beam axis.

The scintillator paddles were composed of EJ204 with the size of 45 cm $\times$ 3 cm $\times$ 1 cm thick and an acrylic light guide (Fig. 3). An end of the light guide was coupled to a PMT, R9880U-110 (Hamamatsu) for GSI test and R7400-06 for HIMAC test. In both tests, silicon semiconductor tracker modules consisting of 4 layers of silicon pixel arrays and X–Y silicon strips were employed for the identification of the nuclear charge and the position of incident fragments onto the paddles [8]. The gain of the PMTs was set between about 10^4 and 10^6. Figure 4 shows an example of nuclear charge spectra of low-Z fragments with one of the paddles in GSI test.

Figure 3: Picture of a prototype scintillator paddle of CALET-CHD. The paddle is composed of EJ204 scintillator and an acrylic light guide.

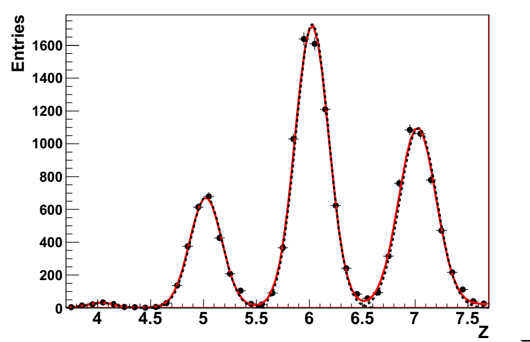

Figure 4: Nuclear charge spectrum obtained with a prototype scintillator paddle in GSI test. Peaks corresponding to Z = 4 – 7 were fitted with Gaussian.

The scintillation response of the prototype paddles was evaluated with obtained peaks of fragmented nuclei. For HIMAC test, since incident fragments were not selected by their energy per nucleon after production in the acrylic target, it was rather difficult to determine the incident energy. Therefore, the mean value of the energy deposited in the paddles was estimated with Monte-Carlo simulation. We used the Particle and Heavy Ion Transport code System (PHITS) developed by Japan Atomic Energy Agency [9].

Correlation plots of dE/dx versus the pulse height obtained from HIMAC test are shown in Fig. 5. Results from Fe and Si beams are superimposed. Fitting with Eq. 2. we

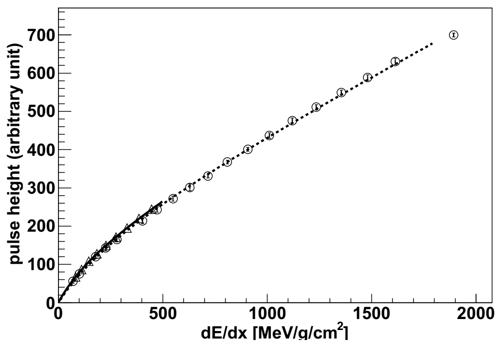

Figure 5: Correlation plots of dE/dx versus the pulse height of EJ204. Results from fragments generated from 500 MeV/nucleon Fe (circle) and 800 MeV/nucleon Si (triangle) in HIMAC test are shown. Fitting curves for Fe and Si data are shown by dashed and solid lines, respectively.

obtained kB = $(8.0 \pm 0.3) \times 10^{-3}$, $(7.0 \pm 1.6) \times 10^{-3}$, $(7.2 \pm 1.8) \times 10^{-3}$ g/cm^2/MeV and F_s = 0.36 $\pm$ 0.01, F_s = 0.34 $\pm$ 0.02, 0.34 $\pm$ 0.02 from GSI, HIMAC Fe and Si results, respectively. The three sets of the obtained parameters were consistent with each other while the velocity of fragments were different ($\beta \sim$ 0.9 for GSI, 0.84 and 0.7 for HIMAC). We found the scintillation response of EJ204 was well explained by Eq. 2 that depends only on dE/dx, not on β. Although the results showed the scintillation light yield was decreased to about 40% for relativistic Fe ($\sim$ 1350 MeV/g/cm^2), the yield was found not to be saturated significantly.

The charge resolution of each species of nuclei was also estimated by fitting the nuclear charge spectra with Gaussian. We obtained the charge resolution between 0.15 and 0.3 for nuclei with the charge Z = 2 – 26 and β = 0.7 – 0.9. Results of GSI test are described in Ref. [10] in detail.

5 Summary and discussion

CALET has the capability to observe cosmic ray nuclei up to 1000TeV. The charge of incident nuclei will be measured with CHD placed on the top of the calorimeter. In order to evaluate the charge discrimination capability of scintillator paddles, we measured the scintillation response of prototype paddles with heavy ion beams in GSI and NIRS-HIMAC. We performed measurement of nuclear fragments generated from Ni (1000 – 1300 MeV/nucleon), Fe (500 MeV/nucleon) and Si (800 MeV/nucleon) beams. We obtained the scintillation response curve as a function of dE/dx. This curve was well explained by one of the extension of Birks's model of quenching (Eq. 1). No significant saturation of the scintillation yield was observed up to $\sim$ 2000 MeV/g/cm^2. We obtained the charge resolution by fitting obtained charge spectra with Gaussian. The resolution was ranged from 0.15 to 0.3. Further analysis for HIMAC test is ongoing.

In addition to the charge resolution of CHD, the effect of back scattering particles on to CHD should also be taken into account in order to the estimate the practical charge identification capability of CALET. According to our Monte-Carlo simulation studies, CHD is available for discrimination between primary and secondary nuclei such as B and C up to 10 TeV. For the observation in the higher energy region, especially for abundant nuclei such as proton, He and Fe, CHD is expected to be exposed to much more back scattering particles. Together with CHD, IMC will be employed to identify the charge of the higher energy nuclei since the SciFi belts are more segmented than the scintillator paddles.

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