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Polar balloon flights with a scaled version of CALET

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Abstract. The CALorimetric Electron Telescope (CALET) is a candidate instrument to be installed on the JEM-EF facility on the International Space Station (ISS). It is optimized for the search of nearby sources of acceleration of cosmic ray electrons in the TeV energy range. In addition, the combination of a large collection power and long observation time allows for precision studies of the elemental composition of VHE nuclei and of their spectral features. Earlier versions of the instrument have been flown on balloons in Japan and Antarctica; a 1/64 scaled version (bCALET-1) was launched from Sanriku in 2006 and a 4 times larger payload is in preparation. In this paper, a 1/4 version of CALET is proposed as a candidate balloon payload for Arctic flights.

1. Introduction

The CALorimetric Electron Telescope (CALET) is designed to achieve high precision measurements of the spectrum of cosmic ray (CR) electrons in the range from GeV to about 10 TeV and high energy resolution measurements of gamma rays in the range 20 MeV to TeV. In the absence of a magnetic spectrometer, CALET has to provide an electron-proton discrimination in excess of 10^5 taking advantage of the very small granularity and fine sampling of the Imaging Calorimeter (IMC) - that covers the first 4 radiation lengths - and by a 27 X_0 thick total absorption BGO calorimeter (TASC), as shown in Fig. 1. A pixelated double-layered silicon array (SIA), placed above the calorimeters, allows to identify individual chemical species in the CR flux and to carry out precision measurements of elemental composition and secondary-to-primary ratios. The main physics goals and the layout of the experiment are described in more detail elsewhere (Torii, 2006).

In this paper, we discuss the rationale behind a balloon-borne version of CALET and its potentialities in terms of science reach and instrument validation.

2. The B/C ratio: from CREAM to CALET

Direct measurements of the spectra of secondary elements are essential to get a consistent picture of the propagation of cosmic rays through the Galaxy and of their interactions with the interstellar medium.

Measurements of secondary-to-primary ratios allow the determination of the parameter δ, whose value is critical to discriminate among different models that predict an energy dependence of the form $E^{-\delta}$ for the propagation pathlength. Once the value of this parameter is known with sufficient accuracy, it is possible to infer the shape of the acceleration spectra of individual elements at the source. Recently, an

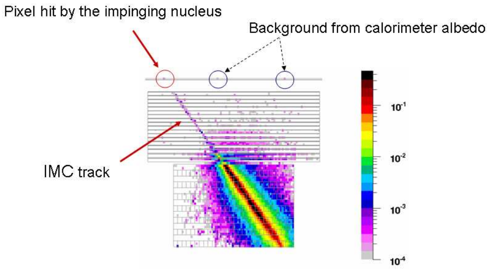

Fig. 1. Fluka event simulation : a 1 TeV/n Carbon nucleus interacting in CALET

analysis of the data from the first flight of the CREAM balloon experiment (Wakely, 2006, 2007) has been able to push the measurement of B/C up to about 1 TeV/n.

The CREAM instrument was designed to provide a redundant charge identification by means of dedicated detectors using different techniques (Cherenkov light, specific ionization in scintillators, silicon sensors and gas proportional tubes). A redundant energy measurement was provided by means of two different subdetectors: a calorimeter with an energy threshold below 1 TeV and an almost energy independent resolution up to about 1 PeV, and a Transition Radiation (TRD) energy meter for $Z > 3$ nuclei, with a threshold close to 500 GeV/n and saturation around 20 TeV/n. During the first flight, due to the large geometric factor of the TRD (with a trigger aperture close to 2.2 m^2 sr), the CREAM instrument configuration allowed to collect a large sample of high-Z nuclei. Unfortunately, during the second flight of CREAM the instrument configuration was different from the first flight and did not include a large acceptance TRD. Therefore, for measurements with heavy nuclei, the geometry factor of the instrument was limited by the smaller acceptance of the calorimeter module. Further flights of CREAM are foreseen and a new TRD is scheduled for the fifth flight.

Taking advantage of its huge geometric factor (about 5 m^2 sr, the largest among the current generation of balloon-borne experiments), TRACER measured the spectra of heavy nuclei above (and including) Oxygen during a 10 days Antarctic flight (Boyle, 2007) in 2003. A shorter flight (4.5 days) in 2006 from Esrange to Canada, with an improved instrument and lower thresholds, allowed to extend the data to lighter elements and have access to the B/C ratio, but with limited statistics. The next flight, in preparation, should be able to provide a high statistics measurement of B/C and an important cross-check with the findings of CREAM.

However, secondary-to-primary measurements on balloons suffer from the severe limitation of the residual systematic uncertainty on the subtraction of the irreducible background due to the atmospheric overburden at flight altitude. This sets an effective limit to the highest energy points of the Boron-to-Carbon ratio (B/C) obtainable with measurements on balloons. On the other hand, experiments in space are free from this limitation and CALET is expected to measure B/C up to several TeV/n, thus providing information about the rigidity dependence of the diffusion coefficient, an essential ingredient to discriminate among different propagation models, and to infer the slope of acceleration spectra at the source.

Though not optimized for hadrons, CALET will be able to identify cosmic ray nuclei with individual element resolution and measure their energies in the range from about 1 TeV to the PeV scale. This will allow to extend to higher energies (Fig. 2) the present data on the secondary-to-primary ratios and cosmic ray composition from direct measurements. In particular, CALET will be able to verify the findings of balloon missions like ATIC (Panov, 2006), CREAM, TRACER and of space missions like PAMELA and AMS.

3. The Silicon Array of CALET

An important requirement for a direct measurement of CR composition is the ability to identify individual chemical elements in the cosmic ray flux. The Z^2 dependence of the specific ionization loss of an ultra-relativistic nucleus of charge Z in a thin silicon sensor can provide a sufficient charge discrimination capability, provided the electronics noise is kept suffi-

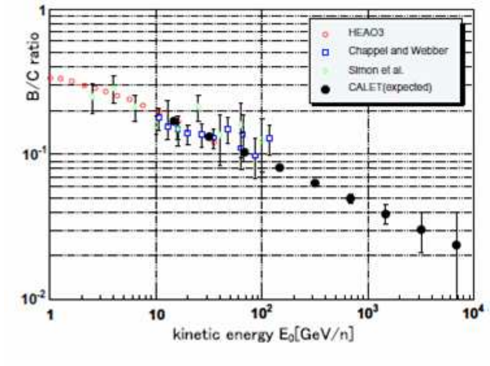

Fig. 2. Expected energy reach with CALET compared with earlier B/C measurements.

ciently low. A pixel geometry has been cho-

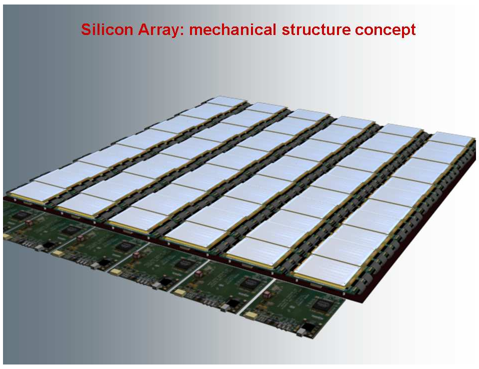

Fig. 3. Artist's view of the integrated assembly of the lower module of the Silicon Array;

sen to isolate the ionization signal generated by the incoming particle, in the presence of albedo particles due to backscattering from the calorimeter. This background may strongly degrade the track reconstruction performance of the apparatus. In order to provide an unique assignment of the pixel hit by the incoming cosmic ray, the detector segmentation has to match the track reconstruction accuracy of the instrument. The fine granularity of the IMC (Fig. 1) allows the determination of the track parameters and the extrapolation of the trajectory to the silicon plane with millimiter accuracy.

The baseline configuration of the Silicon Array (SIA) proposed for CALET is a mosaic of PIN diodes, arranged in 12 ladders, covering a sensitive area of about 1 m^2 with no dead regions. Each sensor has 64 pixels of dimension 11.25×11.25 mm^2, with inter-pixel distance of 0.1 mm. In order to achieve a seamless active region over the whole array, the sensors are overlapped in both dimensions (along each ladder and along the orthogonal direction). The SIA detector consists of two layers of sensors for a total of 288 units. This allows to have two independent measurements of the charge of the same particle with a great benefit in terms of background rejection and increase in the purity of the data sample when a single cosmic ray element is selected. The sensors are produced from 6″ wafers of 500 micron thicknes with high resistivity (not less than 10 kOhm·cm). They are specified to have a full depletion voltage below 80 V and a dark current per pixel typically lower than 2 nA.

A first generation of sensors with smaller pad size (1 cm $\times$ 1 cm) were manufactured and successfully tested with atmospheric muons and particle beams (Marrocchesi, 2007; Kim, 2007) achieving a S/N close to 8 for $Z = 1$ ultra-relativistic particles. A second generation of sensor prototypes, implementing the CALET pixel geometry were produced at the end of 2007. Their electrical characterization showed a full depletion voltage below 30 V and leakage current around 0.5 nA. Along each ladder, sensors are mounted in pairs for a total of 24 sensors. The mechanical arrangement of each pair of sensors allows an accurate knowledge of the relative position of the respective pixels. The SIA is mechanically divided in two halves: a lower section, where 6 (odd numbered) ladders are arranged, is shown in (Fig. 3), and an upper section that provides the mechanical support for the remaining 6 (even numbered) ladders. The upper section is mounted on top of the lower one after a 180° rotation. This design allows to achieve a complete overlap of all sensors, while providing two independent measurements of the charge of the incoming cosmic ray at all angles within the acceptance of CALET.

The readout of the two ladders is integrated with the mechanical structure. All the electronics cards are placed on the upper and lower surfaces of the detector in a symmetric way. This simplifies the design of the cooling system and minimizes temperature gradients across the instrument.

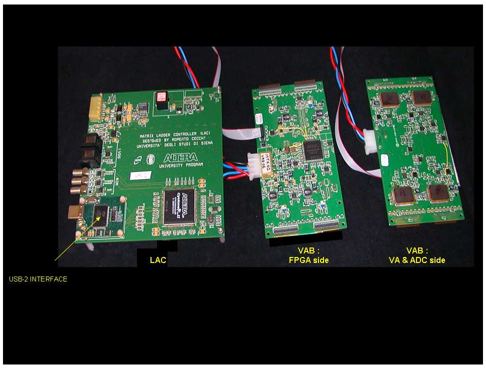

Fig. 4. Prototypes of the LAC and VAB boards for the readout of one ladder.

4. The readout architecture

Each pair of sensors (128 channels) is readout by a dedicated board (VAB) hosting 4 chips of the VA family. The front-end chip VA32-HDR14: a sample-and-hold, low-noise, low-power, large dynamic range ASIC with multiplexed readout of 32 channels, was first developed for CALET in collaboration with IDEAS (Norway). A later version HDR14.2, with epitaxial layer protection against SEE effects, and optimized for positive charge inputs, was developed under the support of INFN (Bagliesi, 2007). The VAB board implements a sequencer for the readout of 4 VA chips with 16 bits digitization, using 4 independent ADC units. The 12 VAB units of each ladder are readout by a Ladder Controller (LAC) that formats the sub-event with no sparsification (Fig. 4). The unit also supervises the distribution of physics and calibration triggers. Gain calibrations of individual channels are performed by each VAB under the control of the LAC by using a charge injection facility built into the ASIC.

The global readout and sparsification of the 12 event fragments from the LAC boards is done by a ReadOut Controller (ROC) interfaced to the main DAQ. Redundance will be implemented for the flight version. The ROC reads the LAC boards, assembles the event fragments and applies a sparsification threshold. A suitable scheme of event buffering is implemented in the ROC. A number of control (e.g.: hold-signal delay, gain calibrations) and housekeeping functions (e.g.: temperature sensors readout, pedestal monitoring) is performed by the LAC under the control of the ROC.

5. CALET on a balloon

The possibility to identify nearby sources of particle acceleration by direct observations of the electron spectrum above 1 TeV is one of the main science goals of CALET. However, these measurements require a long exposure on the ISS and the full collecting-power of the instrument. On the other hand, the recent electron data from ATIC show a hint of a possible spectral feature around 600 GeV, whose nature might be related to dark matter (Yoshida et.al, 2005). A balloon-borne version of CALET might shed light on this controversial portion of the electron spectrum with room for a potential discovery.

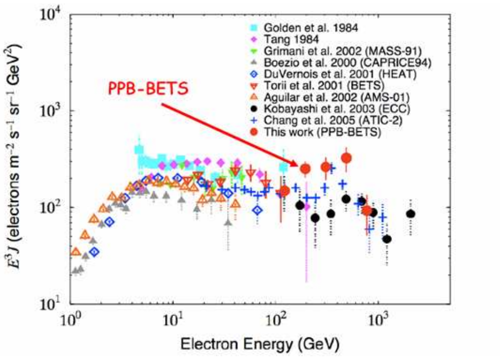

Fig. 5. Electron spectrum below 1 TeV with data points from PPB-BETS balloon experiment.

The CALET collaboration conducted a series of balloon flight starting with BETS (Balloon-borne Electron Telescope with Scintillation Fibers) in 1996 and 1997 and measured the electron spectrum between 10 and 100 GeV. The BETS detector included 36 scintillating fiber belts, lead plates for a total of 7.1 radiation lengths, 3 plastic scintillators for trigger and 2 image intensifiers with CCD readout. In order to observe electrons above 100 GeV, BETS was upgraded into PPB-BETS and flown on a 13 days flight with the the Polar Patrol Ballon from Syowa Station (Antarctica) in 2004. The PPB-BETS contributed data points on the electron spectrum below 1 TeV (Fig. 5).

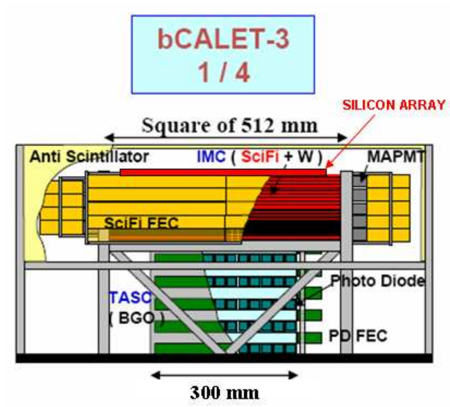

Fig. 6. Schematic layout of b-CALET3 as being proposed for a long duration Polar flight.

A new series of balloon flights, with reduced-scale versions of the CALET instrument, started in 2006 with b-CALET1 that was flown from the Sanriku Balloon Center in Japan and carried a 1/64 version of CALET. The next payload (b-CALET2) - with a 1/16 version of the instrument - is under preparation for a flight of 1 day (or more) from the new Japanese balloon center of Taikicho in Hokkaido.

A more demanding task is required for b-CALET3, both in terms of uplift mass (1/4 of CALET) and in terms of flight duration. A schematic layout of the instrument is shown in Fig. 6.

A circumnavigation flight in the Arctic on a Long Duration Balloon (LDB), with an average of 15 days per revolution, will allow CALET to meet a number of objectives. In addition to the validation of the instrument in terms of proton rejection (a key issue both at trigger level and for the calorimetric discrimination), physics data will be collected that might confirm or not the presence of a possibe structure in the electron spectrum below 1000 GeV, as suggested by the most recent electron data. While the limited statistics will preclude observations at larger electron energies, accurate measurements of the fluxes of high-Z nuclei will be possible up to several hundreds of GeV/n, taking advantage of the outstanding charge discrimination capability of the instrument.

6. Conclusions

According to the present plans, CALET might be selected for a flight to the ISS to take place not earlier than 2013. Such a schedule would open a time window for a balloon flight of a reduced-scale version of the instrument in the Arctic to be performed during the Summer 2010.

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