Preliminary results of the CREAM-III Cherenkov Camera

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Abstract. **Precise measurements of cosmic rays in an energy range from 10^{12} eV to 10^{15} eV, over the elemental range from hydrogen to iron, allow one to study the mechanism of acceleration of primary cosmic rays up to very high energy, to characterise their possible sources, and to clarify their interactions with the interstellar medium. For this purpose a Cherenkov imager, CherCam (Cherenkov Camera), has been designed and built for the CREAM (Cosmic Ray Energetics And Mass) balloon-borne experiment. CherCam is a proximity focused imager optimised for charge measurements with a constant resolution through the whole considered range of nuclear charges. The detector was implemented for the first time in the third flight of the CREAM payload, which was carried out in the Antarctic Summer 07/08. The instrument performance during this flight and charge reconstruction results from the on-going data analysis are presented.**

***Keywords*: CREAM, CherCam, cosmic rays, composition, Cherenkov detector, charge measurement**

I. Introduction

The precise measurement of the elemental abundances in the cosmic-ray flux, and in particular of the so-called secondary-to-primary ratios (e.g., B/C or subFe/Fe) leads to strong constraints on the galactic propagation models, because such ratios are directly dependent on the total amount of material encountered by the particles during their propagation. The elucidation of particle propagation details in turn leads to a determination of the cosmic-ray source spectrum, and therefore to constraints on the acceleration processes.

The CREAM balloon-borne experiment measures the cosmic-ray spectrum of nuclear elements from proton to iron between 10^{12} eV and up to 10^{15} eV with excellent charge and energy resolution. In order to accomplish such a challenging task, the instrument consists of complementary and redundant detectors for charge identification and energy measurements. A detailed description of the CREAM instrument can be found in [1].

The CREAM-III instrument, which flew successfully for 29 days over the Antarctic continent during the summer season 2007/08, consists of multiple charge and energy detectors. A Timing Charge Detector (TCD), made up of two crossed layers of large-area thin scintillator paddles, the Cherenkov Camera (CherCam), a proximity focusing Cherenkov imager for which this was the first flight, and a double-layer Silicon Charge Detector (SCD) measure the incoming particle charge. A calorimeter, namely a sampling tungsten/scintillating fiber device, measures the incident energy through the showers induced by thick carbon targets, and provides additionally tracking information on the incident particle.

II. CherCam, a Cherenkov imager for CREAM

The CherCam is a proximity-focusing imager derived from the solution developed for the AMS experiment [2]. The detector is optimised for charge measurements, with a constant resolution through the range of nuclear charge from hydrogen to iron [3].

The Cherenkov radiator consists of a 20.8 mm thick silica aerogel plane, made of two superimposed layers of $10.5 \times 10.5\,\mathrm{cm}^2$ Matsushita-Panasonic SP50 tiles, with a refractive index n close to 1.05. The radiator plane is separated from the photon detector plane by a 110.5 mm drift space. The detector plane consists of an array of 1600 photomultiplier tubes (PMT, 1 inch diameter Photonis XP3112), backed with dedicated front-

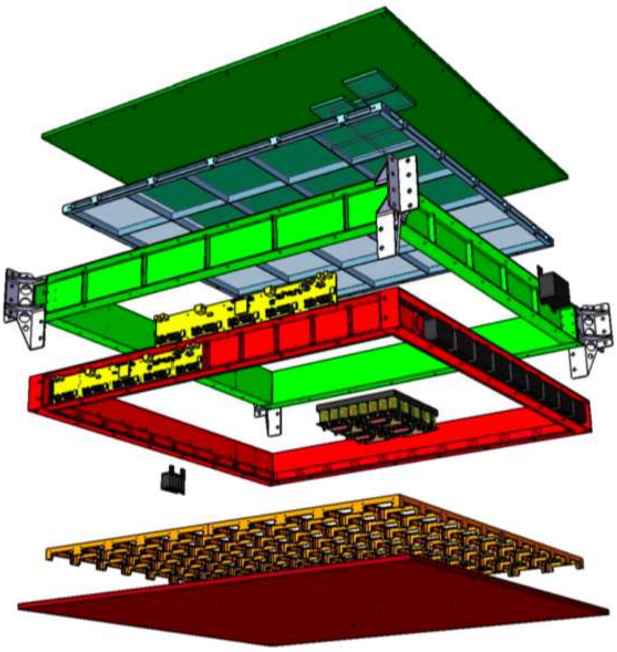

Fig. 1. Exploded CAD view of the CherCam mechanical structure

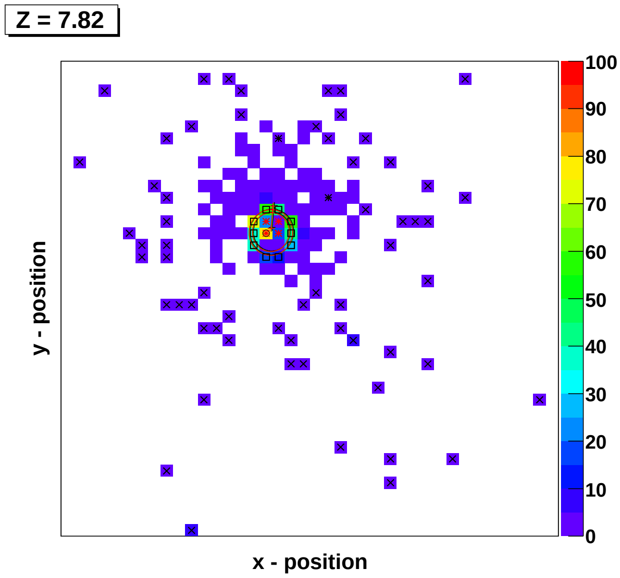

Fig. 2. High-charge particle event in the CherCam. Each pixel represents one PMT, where the color code indicates the number of Cherenkov photons seen. The Cherenkov ring and impact point of the incoming particle are clearly visible. The photons in the "halo" around the impact point correspond to the Rayleigh scattered photons. The reconstructed Cherenkov ring is represented by the ellipses.

end electronics, power supply, and readout electronics. The PMTs are arranged in a square pattern with a 27.5 mm pitch. This arrangement provides an active photon detection surface of about 50%. A light guide option had been studied to minimise the dead-space, but the reconstruction algorithm proved to be more efficient without the complex reflections introduced by guides.

The mechanical structure of the detector is illustrated in Fig. 1. The upper frame includes the radiator plane fixed to the top lid, and the (empty) drift space. The lower frame supports the PMT array and the first-level readout electronics. A more detailed description of this instrument can be found in [3].

The CherCam has to operate under physical conditions close to space experiments with only radiative thermal dissipation, a low-pressure environment and large temperature excursions. A complete validation of the instrument through dedicated thermal test and vacuum exposure was successfully carried out. Additionally, a CherCam prototype had been tested in a secondary $Z = 1$ particle beam at CERN in October 2006 and 2007.

III. CherCam event reconstruction

A. Constraints on the charge reconstruction

The principle of the CherCam detector is based on the detection of Cherenkov photons, emitted by an incoming high-energy particle passing through the radiator plane. A typical high-charge particle event in the CherCam is represented in Fig. 2. The number of these emitted Cherenkov photons N_γ for a given wavelength range $\mathrm{d}\lambda$ is given by the Franck-Tamm formula, which reads, for $\beta = 1$, where β is the particle velocity in units of the speed of light (which is a good approximation given the energy of the particles measured by CREAM), and integrating over the path length in the radiator:

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}\lambda} = 2\pi\alpha \frac{Z^2}{\lambda^2} \frac{d}{\cos\tau} \left(1 - \frac{1}{n(\lambda)^2}\right), \qquad (1)$$

where α is the fine-structure constant ($\approx 1/137$), Z the particle charge, d the radiator thickness, τ the zenith angle of the incoming particle and $n(\lambda)$ the refractive index of the radiator material. The number of emitted Cherenkov photons is proportional to the square of the incoming particle charge, hence allowing particle-charge identification.

The number of Cherenkov photons detected by the CherCam $N_{\mathrm{det}}(x, y, \tau, \psi, Z)$ depends on the detection efficiency, which includes the quantum efficiency $\varepsilon_{\mathrm{QE}}$ of the photomultiplier tubes, and the collection efficiency $\varepsilon_{\mathrm{coll}}(x, y, \tau, \psi)$, defined as the detected-to-emitted photon ratio due to the CherCam architecture and Rayleigh scattering:

$$N_{\mathrm{det}}(x, y, \tau, \psi, Z) = \varepsilon_{\mathrm{coll}}(x, y, \tau, \psi) \cdot N_\gamma(\tau, Z), \qquad (2)$$

where

$$\begin{aligned} N_\gamma(\tau, Z) &= \int_{\lambda_{\min}}^{\lambda_{\max}} \varepsilon_{\mathrm{QE}}(\lambda) \cdot \frac{\mathrm{d}N_\gamma}{\mathrm{d}\lambda}\, \mathrm{d}\lambda \\ &= \frac{2\pi\alpha Z^2 d}{\cos\tau} \int_{\lambda_{\min}}^{\lambda_{\max}} \left(1 - \frac{1}{n(\lambda)^2}\right) \frac{\varepsilon_{\mathrm{QE}}(\lambda)}{\lambda^2}\, \mathrm{d}\lambda \\ &= N_\gamma^{Z=1} \frac{Z^2}{\cos\tau}, \end{aligned} \qquad (3)$$

where $N_\gamma^{Z=1}$ represents the mean number of detected photons for a particle of charge $Z = 1$ with normal incidence and a collection efficiency $\varepsilon_{\rm coll}$ equal to 1. Equation 2 then becomes

$$N_{\rm det}(x,y,\tau,\psi,Z) = \varepsilon_{\rm coll}(x,y,\tau,\psi) N_\gamma^{Z=1} \frac{Z^2}{\cos\tau}. \quad (4)$$

$N_{\rm det}$ depends strongly, through $\varepsilon_{\rm coll}$, on the impact position (x,y) of the incoming particle on the radiator plane and its zenith and azimuth angles τ and ψ, respectively. Therefore, in order to ensure the required precision of $\Delta Z < 0.3$ on the particle-charge reconstruction up to iron ($Z = 26$), it is necessary to have a good knowledge of the particle trajectory. Indeed, based on the equation

$$\Delta Z = \frac{1}{2}\left(\frac{1}{\sqrt{N_{\rm det}^{Z=1}}} \oplus Z\frac{\Delta\varepsilon_{\rm coll}}{\varepsilon_{\rm coll}} \oplus Z\frac{\Delta\cos\tau}{\cos\tau}\right), \quad (5)$$

the condition $\Delta Z < 0.3$ gives for $Z = 26$ and $N_{\rm det}^{Z=1} = 10$ an upper limit on $\frac{\Delta\varepsilon_{\rm coll}}{\varepsilon_{\rm coll}}$ of about 2%. This number can be translated into a precision on the impact point (Δx and Δy), which must be known to within less than 1 mm for the two space directions [4].

B. Charge reconstruction in three steps

The CREAM calorimeter yields a 3D track for the incoming particle. This leads to the identification of the region of interest within the multiple charge detectors of the CREAM-III instrument, but also generates background noise for the charge measurement. Combining the knowledge of the track reconstructed in the calorimeter and of the impact points in the two layers of the SCD, the impact point within the CherCam detector can be extrapolated with good precision ($\sim 11\,\rm mm$). However, this is insufficient for the charge reconstruction accuracy required as described in the section above. Therefore it is necessary to add the CherCam event information to the track reconstruction.

For the track reconstruction in the CherCam an overlap method is used. The idea is to superpose a simulated event over the measured event and to minimise the following χ^2:

$$\chi^2 = \sum_i^{\rm PMT\ hit} \frac{1}{n_i^{\rm det}} \left(n_i^{\rm det} - n_i^{\rm est}(x,y,\tau,\psi)\right)^2, \quad (6)$$

where $n_i^{\rm det}$ and $n_i^{\rm est}$ are the detected and estimated photon numbers in the hit PMT i, respectively.

The track reconstruction is done in three steps. In a first step the particle-track information given by the calorimeter and the SCD is used to select a region on the CherCam PMT plane for a further impact point search. A grid is defined in this region and for each grid point the χ^2, given by equation 6, is calculated. The point with the best χ^2 defines the centre of a new grid of smaller size and same grid point number. This procedure is repeated three times in order to extract the particle impact point position (x,y) on the PMT plane. This track is then used to exclude the PMTs close to the impact point in the next step, during which all four track parameters (x,y,τ,ψ) are released and the χ^2 is minimised. The event reconstruction algorithm was successfully tested on events simulated with a GEANT4 toolkit (described in [4], [3]) and a resolution $\Delta Z < 0.3$ for $1 \le Z \le 26$ was achieved.

C. Preliminary results

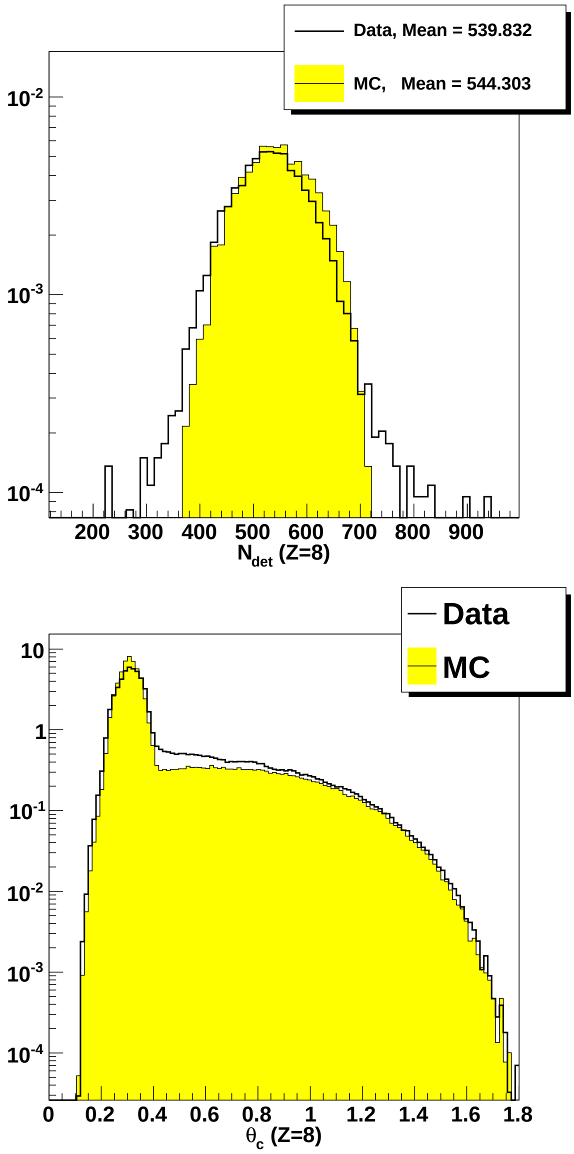

Fig. 3. Normalised distributions of the detected photon number (top panel) and the reconstructed Cherenkov angle (bottom panel) of these photons, for incident oxygen nuclei ($Z = 8$). The filled areas correspond to simulated events and the thick lines to events reconstructed by the CherCam.

For the CherCam event reconstruction only the so-called golden events are used: the incoming particle must have traversed the CherCam, both SCD layers and the calorimeter, leaving a signal in each single detector. Additional purity cuts are performed based on energetic and geometric criteria.

First results of the on-going data analysis are represented in Fig. 3 for CR oxygen nuclei ($Z = 8$).

In the top panel the normalised detected photon distributions for simulated (filled area) and reconstructed (thick line) events are shown. A good agreement between the expected and measured number of photons can be observed. The normalised Cherenkov angle θ_C distribution of detected photons for simulated (filled area) and reconstructed (thick line) events are shown in the bottom panel. The peak centred at $0.31\,\mathrm{rad}$ corresponds to the photons of the Cherenkov ring and the broad distribution tail to the Rayleigh-scattered photons. The incident particle is excluded, as described in the previous section. It can be observed that the measured Cherenkov-ring peak contains slightly fewer photons than the simulated one and that the missing photons are distributed over the whole Rayleigh tail. Different processes are currently investigated with the aim to explain this phenomenon.

As the total number of detected photons corresponds to our estimations through simulation, a charge reconstruction can be done. The charge of the incoming CR particle reconstructed by the CherCam as a function of the charge reconstructed by the SCD is represented in Fig. 4. This first preliminary CherCam charge distribution gives $\Delta Z < 0.3$ only for $Z = 1$ and 2. This is probably due to the different features between the data and expected results of the Monte Carlo simulation, resulting in a misevaluation of the collection efficiency $\varepsilon_{\mathrm{coll}}$ and thus degrading the resolution.

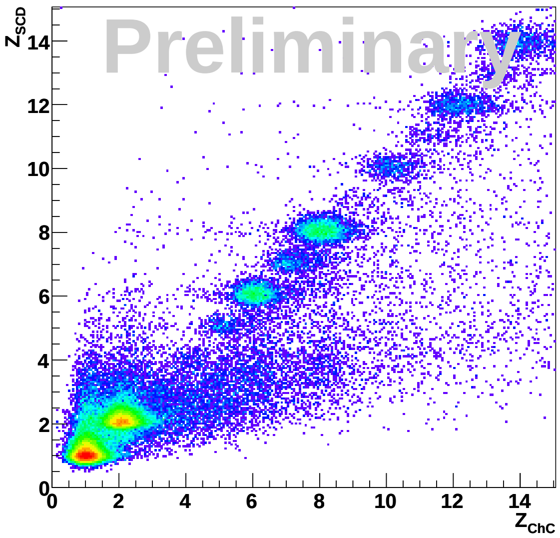

Fig. 4. Particle charge reconstructed by the CherCam (x-axis) as a function of charge reconstructed by the SCD (y-axis)

IV. Conclusions and Perspectives

After two previous successful campaigns of the CREAM instrument, the detector completed a third flight during the Antarctic summer 2007/2008. During the 29 day-long flight, about 1.5×10^6 events were collected, achieving a cumulative flight exposure of about 100 days. This is the longest cumulative flight exposure of all previous balloon experiments, representing the largest event set collected so far. The CREAM-III instrument is composed of multiple charge and energy detectors, including the CherCam, a Cherenkov imager, for which this was the first flight. The detector, measuring the incoming particle charge with a constant resolution from hydrogen to iron, was designed and fully integrated in less than two years, and tested in space-like conditions. The maximum charge resolution requires a good knowledge of the particle trajectory, which is determined by two other subdetectors of the CREAM instrument: the calorimeter and the SCD. The resulting spatial resolution was found not to be sufficient, and an additionnal CherCam event fit, based on an overlap between a simulated and real event, was needed. Preliminary results of the charge reconstruction of simulated events show that the desired charge resolution is obtained over the whole charge range studied. The data analysis of the events collected during the flight is in progress.

In the meantime a fifth flight of CREAM is in preparation. The instrument will be launched in December 2009 with the CherCam on board.

Acknowledgments

The authors thank NASA Wallops Flight Facility, Columbia Scientific Balloon Facility, National Science Foundation Office of Polar Programs, and Raytheon Polar Services Company for the successful balloon launch, flight operations, and payload recovery. This work is supported by NASA in the U.S, KICOS and Ministry of Science and Technology in Korea, and IN2P3-CNRS, CNES, and ANR in France.

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