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Development of a homogeneous, isotropic and high dynamic range calorimeter for the study of primary cosmic rays in space experiments

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The concept of a homogeneous, isotropic, and high dynamic range calorimeter has been developed and a prototype has been built and tested. The most suitable geometry was found to be cubic and isotropic, so as to detect particles arriving from every direction in space, thus maximizing the acceptance; granularity is achieved by subdividing the cubic volume in smaller cubic crystals. A dual readout of each crystal with two independent photodiodes ensures the high dynamic range.

The prototype calorimeter consists of cubic CsI(Tl) crystals with a 36 mm edge. Each is coupled to two photodiodes. One with a large area for small signals and a second of much smaller area for large signals from showers. For the preliminary tests only the large area diodes have been used coupled to a CASIS chip especially developed for high dynamic range applications. Two prototypes have been built and preliminary tests with high energy ions and muon beams are reported.

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1. Introduction

The all-particle cosmic-ray energy spectrum – extending from a few tens of GeV up to the highest detected energies of roughly 10^{20} eV – follows a power law broken around the PeV range. In this region a softening of the spectrum is observed (the so-called “knee”), which carries information about the physics of acceleration and propagation of cosmic rays. In particular, the origin of the knee, albeit still debated, is believed to be due to intrinsic energy limits of the acceleration process or to the particle leakage from our Galaxy or to a combination of both [1]. Given the rapidly decreasing intensity of the flux with energy, until now observations around the region of the knee have been carried out by ground-based experiments. These experiments rely on the observation of the fluorescence and Cherenkov light produced by air showers initiated by the interactions of primary cosmic rays with the top of the atmosphere, as well as the detection of the penetrating particle component of the showers [2–4]. Despite the advantage of a very large exposure, these techniques rely on MC simulations for energy reconstruction and particle identification. On the other hand, direct-detection experiments can identify the particle species by means of several techniques including ionization measurements; however, balloon-borne [5–7] and space-based [8–10] experiments suffer from limited exposure time and a small geometrical factor. An experimental breakthrough would therefore require a large acceptance, long-duration, space-based experiment to collect a statistically significant amount of data in the knee region. According to the polygonato model [11], one can expect ~4 protons and 8 helium nuclei above 4 PeV for a 1 m^2sr acceptance and a 10 years exposure. In order to observe the knee, a calorimeter with a geometric factor of at least a few m^2sr with an energy resolution for hadrons of ~40% or better is therefore mandatory [12]. Such a device could also obtain significant results for the observation of the electron+positron component. Signals from new physics like dark matter annihilation/decay [13,14] or nearby astrophysical sources [15] might show up in this observational channel. Recent measurements show some spectral features in the electron/positron components [16,17], although not all of them are confirmed by other independent measurements [18]. A large acceptance device with an energy resolution of 1%–2% for electrons would allow precise spectral studies also at energies above 1 TeV, where the electron+positron spectrum shows a sharp softening [19]. A 1 m^2sr device is capable of detecting ~220 electrons/positrons above 4 TeV in 10 years. Space missions, however, pose severe constraints on deployable mass and power budget. An innovative design for a space-based detector which tries to maximize acceptance and energy resolution within a given mass envelope is described in the next section.

2. A homogeneous and isotropic calorimeter

Particle detectors used in cosmic-ray experiments usually accept particles only from the top side, i.e. they detect only particles coming from the zenith. However the cosmic-ray flux is isotropic up to very high energies, so particles cross the detector also from side to side. A detector that could collect particles from any direction would then be able to observe a much larger solid angle, increasing its geometrical factor while keeping dimensions and mass unchanged. A cubic device, for example, could accept particles from 5 of its 6 sides (the bottom one would be sacrificed for mechanical support and instrumentation), resulting in a five-fold increase of the single-face acceptance. According to these principles, an isotropic and homogeneous calorimeter, designed as a 3D mesh of small cubic scintillating crystals is proposed. The cubes are separated by a small gap which has two purposes: to increase the dimensions of the device (thus increasing the acceptance) and to accommodate support structures and photosensors (see fig. 1).

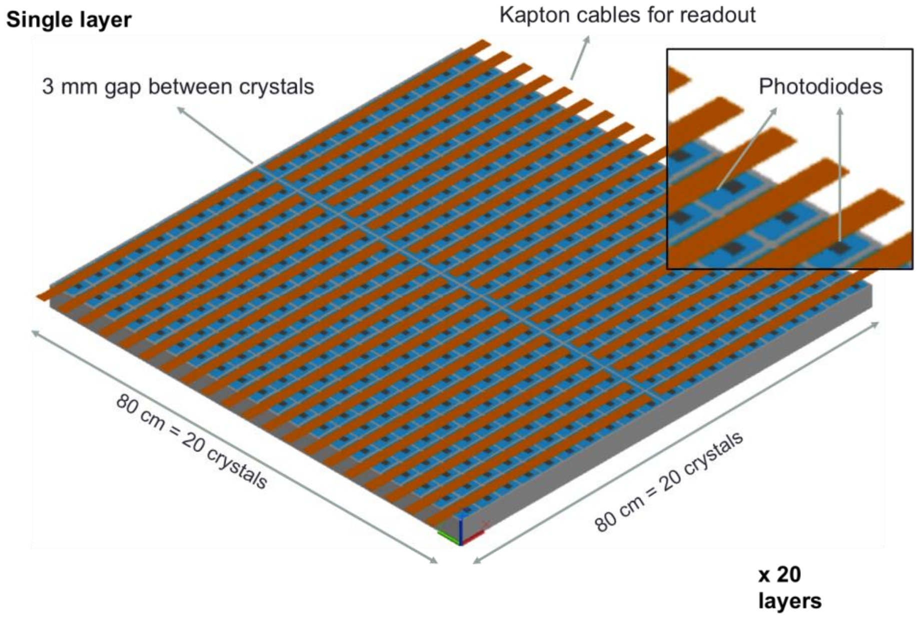

Fig.1 Support structure designe of single layer.

The choice for the scintillating material is Thallium-doped Cesium Iodide (CsI(Tl)): this material is the best compromise in terms of density (a relatively light material which allows to maximize geometric dimensions for a given mass) and radiation and interaction lengths (a large depth allows for good shower containment and thus good energy resolution). By assuming a mass budget of ~1.6 t, a crystal size of ~1 Molière radius and a 0.3 cm gap between crystals, the resulting design is a mesh of 20×20×20 crystals of $78\times78\times78\ \mathrm{cm}^3$.

The calorimeter is very deep in terms of both radiation and interaction lengths (for a space project), and features a planar geometric factor of $(1.91\times5)=9.55\ \mathrm{m}^2\mathrm{sr}$. Monte Carlo simulations show that up to 10% of a particle's energy can be deposited in a single crystal during shower development. The resulting required dynamic range to be covered by the single crystals varies from 0.5 MIP (to be able to detect non-interacting protons) to10^7 MIPs. To cover such a huge range the proposed readout scheme consists of two photodiodes coupled to each crystal: a large area photodiode ($\sim9.2\times9.2\ \mathrm{mm}^2$) for small signals and a small area one($\sim0.5\times0.5\ \mathrm{mm}^2$) for large signals, each one readout by a high and a low gain amplification circuit, for a total of 4 channels per cube. Signals are extracted by means of kapton cables (see Fig. 1).

3. Simulations

The performance of the design described above has been studied by means of Monte Carlo simulations [20].

The resulting value of the energy resolution for electrons is 2% up to 1 TeV. The efficiency of the selection is 36%, which gives an overall effective geometric factor GF_{eff} = 3.4 m^2sr.

The resolution at various energies of the primary proton is around 30%–40% (RMS). The selection efficiency for protons has been found from 35% at 100 GeV to 47% at 10 TeV, the effective geometric factor varies accordingly from $3.3m^2sr$ to 4.5 m^2sr.

4. Experimental results

First, the single crystals and photodiodes have been studied. Than two small-scale prototypes of the proposed detector have been built and tested at the CERN SPS accelerator facility.

4.1 Scintillators and photosensors

The expected single-crystal signals have been studied. CsI(Tl) provides 1 MIP/cm = 5.62 MeV/cm. Thus, for a cube of $3.6\times3.6\times3.6$ cm^3 size, 1 MIP gives 20 MeV. Light yield of CsI(Tl) is 54 photons/keV. For 1 MIP we have on average 1080000 photons.

For measurements large area photodiode VTH 2090 has been used. This diode, by Excelitas, has area 9.2×9.2 mm^2, operation voltage 45 V, dark current < 5 nA, junction capacitance 70 pF and quantum efficiency 68% at 550 nm. Geometry factor for this diode is the ratio between cube’s one side area and diode area and equals to 0,0653. Light collection efficiency for CsI(Tl) cube covered with teflon is about of 90%. For 1 MIP we have the following signal estimation: 1e6 photons×geometry factor×quantum efficiency×light collection efficiency that gives about 43 000 electrons or 2,7 fC.

A single-channel high accuracy spectrometer by Amptek has been used for diode readout. The spectrometer consist of charge-sensitive preamplifier A250 and digital pulse analyzer PX5.

Am 241 source has been used for spectrometer calibration and studies of crystals. This source emits 5.5 MeV alpha particles and few gamma lines (13.7, 17 and 59.6 keV are most interesting for us). First of all, spectrometer has been calibrated in energy, using photodiode only and gamma lines of Am 241. At the second step the crystal has been added and the energy deposited by 5.5 MeV alpha has been measured. Fig.2 shows both spectra with the scales in ADC channels, energy and electrons. Using the fact that silicon needs 3.6 eV for creation of one electron-hole pair, we can convert measured energy in number of electrons. Measured value has been compared with calculated one. Calculation is similar to MIP one, described above, but for energy 5.5 MeV and gives about of 12 000 electrons.

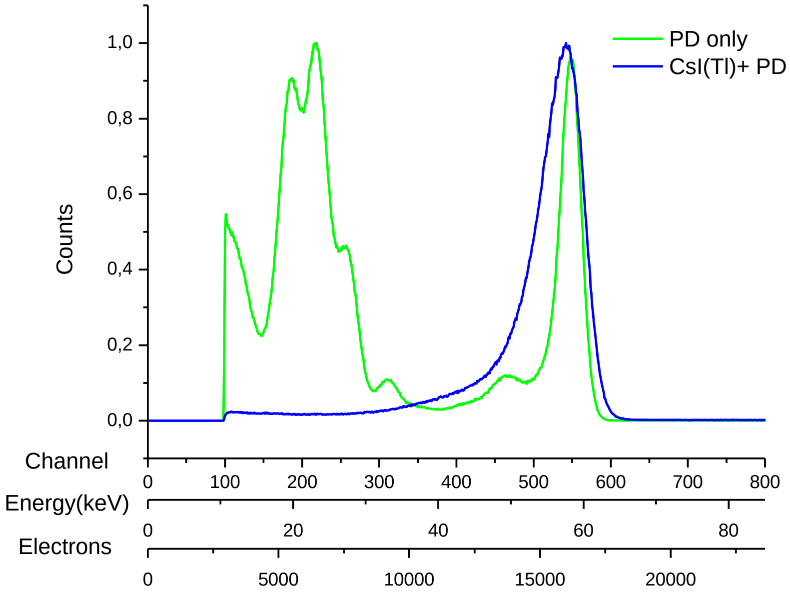

Fig.2. Calibration γ spectra (green) and spectra of α particles (blue)

4.2 Prototypes

Two prototypes of the proposed detector have been built: a smaller one, so-called "pre-prototype", and a larger one properly called "prototype"(Fig. 3). For both prototypes, one 9.2×9.2 mm^2 Excelitas VTH2090 photodiode per crystal has been used (no small photodiode was present). Signal readout has been done by means of a CASIS chip [21], a double-gain charge sensitive amplifier with real-time automatic gain selection.

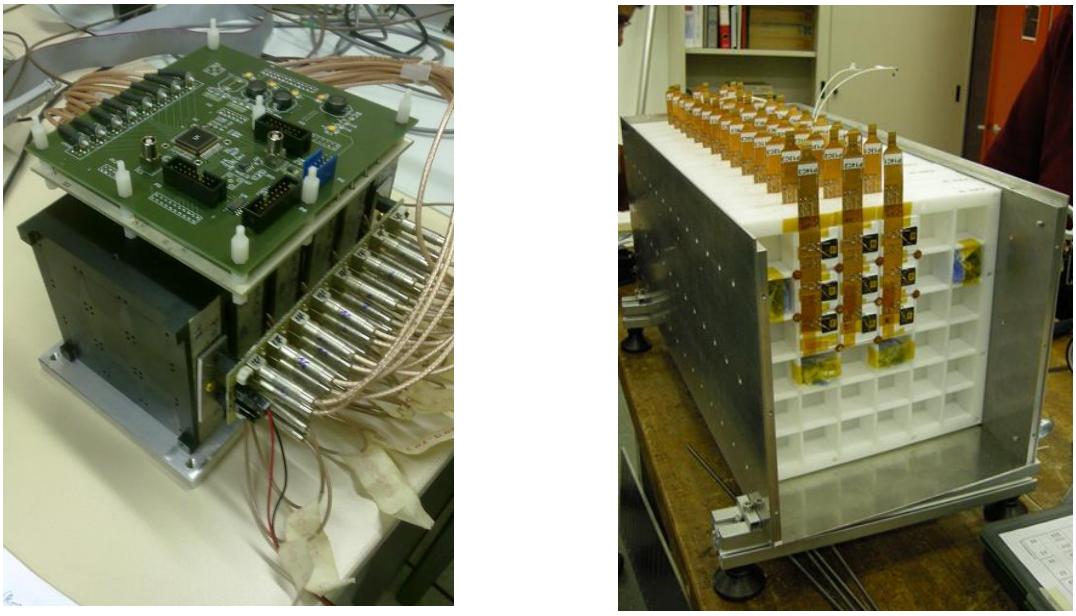

Fig.3. Pre-prototype (left) and prototype (right) calorimeters

The pre-prototype is made of 12 CsI(Tl) crystals of 2.5 cm side, arranged in 4 layers of 3 crystals each. Calorimeter consists of 6 layers with size 3×3 cubes. CsI(Tl) crystals are situated in central layers from second to fifth (3 crystals per layer). Iron cubes have been placed in the rest of calorimeter to allow the shower formation. One CASIS have been used for read-out. To use all 16 channels of CASIS, four photodiodes have been placed on iron cubes, one in the center of first layer and three in the central row of the last layer. A muon beam of 150GeV/c has been used for the pre-prototype; the signal of MIPs is clearly visible with a signal-to-noise ratio of 17.8 (Fig. 4) The signal-to-noise ratio for a different channels varies from 14.4 to 19.4.

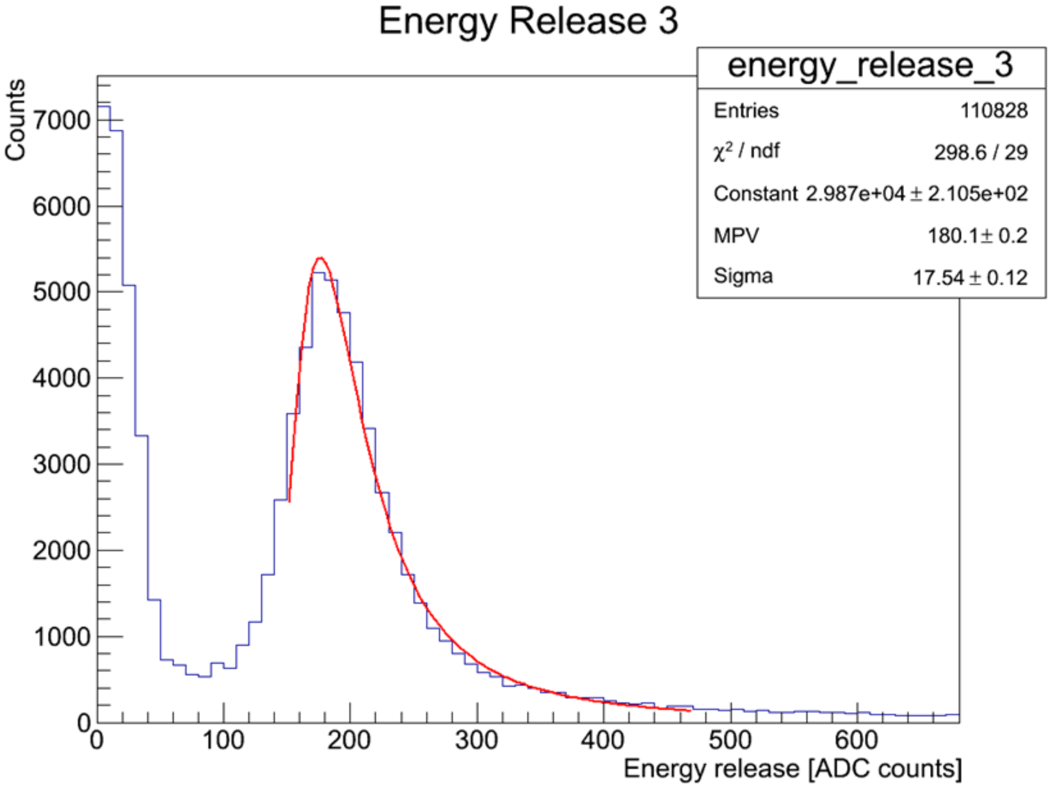

Fig.4. Energy release of 150 MeV muon beam in the central crystal of the first layer.

The prototype has 126 CsI(Tl) crystals of 3.6 cm side, arranged in 14 layers of 9 cubes. Nine CASIS have been used for readout. Connection between PD and CASIS is made by kapton cables. Ions with A/Z=2 at 30 GeV/amu and 12.8 GeV/amu kinetic energy have been used for the prototype. As Fig.5 (a) shows, the peaks of 2H and 4He are very well resolved in layer 1, with a signal-to-noise ratio of 14 for the deuterium peak.

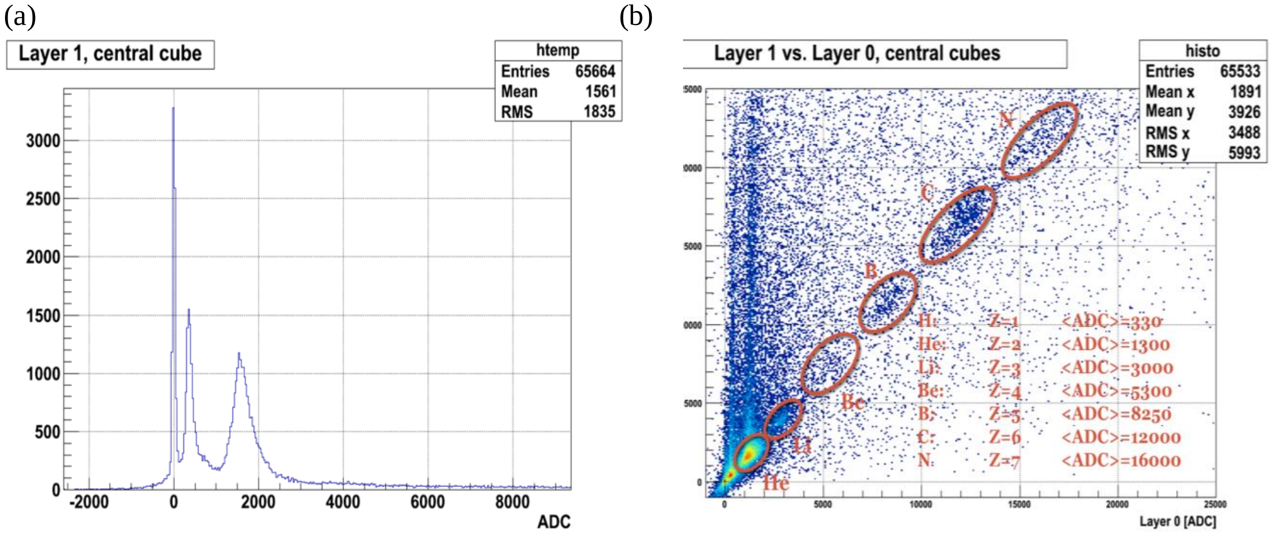

Fig.5. (a) peaks of 2H and 4He, (b) scatter plot of the first two layers

Fig.5 (b) shows the scatter plot between the signals from central cubes of the first two layers. The nuclei with Z from 1 up to 7 are clearly visible. Please note: we can use the data from a precise Z-measuring Silicon system located in front of the prototype to have an exact identification of the nucleus charge.

Data analysis is currently on going; the results will be the subject of a future publication.

5. Conclusions

Direct cosmic-ray measurements at high energies (PeV for nuclei, TeV for electrons) are needed to understand the fundamental processes of acceleration and propagation inside the Galaxy, as well as to indirectly search for dark matter. A large detector is needed to collect a reasonable amount of such rare events. The proposed homogeneous and isotropic calorimeter has been carefully designed to maximize acceptance within the constrained framework of a space mission, with a good energy resolution to detect the knee of the cosmic-ray spectrum and to resolve possible spectral structures in the electron+positron component. MonteCarlo simulations show that a geometric factor of 3-4 m^2sr can be achieved by detecting particles impinging on 5sides of the cube, with 2% energy resolution for electrons and 30-40% for protons. Two prototypes have been built and tested at the CERN SPS to demonstrate the measurement principle. Test beam data analysis is ongoing, together with MonteCarlo simulation and electron/ proton rejection studies.

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