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Cubic calorimeter for study of high energy cosmic rays

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Abstract. A hadronic calorimeter for the detection of high energy cosmic rays, optimized for a space experiment, is described in this paper. Making use of the fact that cosmic rays are isotropic and that the available aperture for experiments in near-Earth orbit is more than 2π, our calorimeter is sensitive to all directions of arriving cosmic rays. This calorimeter has the shape of a cube and is made of consecutive alternating rows of logs. Each log has a plastic scintillator core with an outer shell made of high-Z material. This approach provides an increased geometric factor by a factor of 2-3 with respect to the more conventional "flat" calorimeter where area is traded for depth.

We found that a face-to-face calorimeter thickness of ~300 g/cm^2 is sufficient to provide energy resolution of 35-40%, independent of the density. To maximize the geometric factor for a given available mass, we use low density material. Event selection is based on the measured particle path in the calorimeter after the first interaction. Our design leads to a calorimeter of "variable depth". This approach leaves for the analysis the choice of trading collecting power against energy resolution.

For the ACCESS mission, the calorimeter is allocated approximately 3,000 kg. For this mass, the geometric factor of such calorimeter could be up to 5 m^{2}sr, compared to less than 2 m^{2}sr for a flat calorimeter of the same mass. The ACCESS mission has a goal of extending the range of measured cosmic ray protons up to at least 10^{15} eV. This cubic calorimeter can extend the geometric factor beyond the current baseline mission to provide improved statistical precision.

1 Introduction

The origin of cosmic rays is one of unsolved problems in astrophysics. The most common explanation is that cosmic rays are accelerated by supernova shocks, but available experimental data demonstrate the existence of cosmic rays of energy 5-6 orders of magnitude higher than it is thought possible to produce by supernovae (around 10^{15} eV). Precise measurement of cosmic ray nuclear spectra and their features would lead to the resolution of the problem. There are a number of ground-based facilities to detect high energy cosmic rays but none of them is capable of measuring cosmic ray nuclei separately – cosmic ray composition can only be crudely inferred. The only way to measure directly the cosmic ray nuclei is to move the instrument into space.

The problem for space-borne experiments is very limited resources – mass, power, size. If we want to measure the cosmic ray proton spectrum above 10^{14} eV, there will be about 500 proton and helium events per year per m^{2}sr, and about 10 of each of them for energies above 10^{15} eV! Thus the instrument should have a geometric factor of at least several m^{2}sr - a very challenging design for a space experiment.

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2 Calorimeter concept

A hadronic calorimeter is the most direct way to measure the energy of the detected charged cosmic ray particle. At the entrance to the calorimeter the Z of the particle should be measured. This could be accomplished by a layer of the calorimeter itself, or by a separate charge measuring detector.

The traditional cosmic ray calorimeter would be flat to achieve the largest area with thickness adequate for the proton energy to be measured. Limited resources for a space experiment pushed us to reconsider this design. It is obvious that use of the side-entering events improves the collecting power. This is a great advantage of an experiment onboard a spacecraft. We believe that for measurement of the isotropic flux of cosmic rays on-board a spacecraft (equal observation conditions for at-least upper hemisphere) the 3-dimensional calorimeter, sensitive to all particle direction arrival, would be the optimal design. We also found that the same idea was suggested in Grigorov and Tolstaya (1996).

We propose the following concept:

- uniform 3-D structure (e.g. sphere; use a cube as practical alternative)

- use 100% of the top entry and 50% of the side entry aperture (reduced to account for the Earth obscuration)
- choose material(s) to optimize the geometric factor at given energy resolution

3 Approach to the design

3.1 Tracking

A primary consideration is that the calorimeter should be uniform and segmented to allow finding the first interaction point with a precision of 1-2 radiation length. All detected events will be separated into groups by the pathlength in a calorimeter after the interaction, and the energy of detected particle will be reconstructed according to this path. The direction of particle arrival will be determined by analyzing the event pattern in the calorimeter segments, and particle charge will be determined by the pixelized charge detector.

3.2 Simulation validation

The GEANT 3.21/FLUKA simulation package was used for the instrument simulations. We understand that the simulation of hadronic interactions is complicated, and we tested our simulations with a beam test. We simulated a sampling calorimeter prototype designed and built by the Texas Technical University group and compared simulation

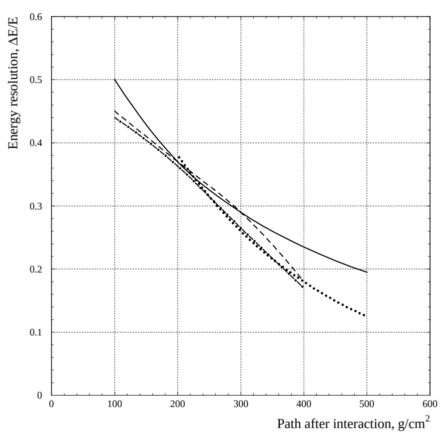

Fig.1. Simulated energy resolution for homogenious calorimeters made of pure W (Z=74, solid line), BGO (Z=27.5, dashed line), CsI (Z=54, dashed-dotted line), and pure Cu (Z=29, dotted line)

results with the CERN/SPS beam test of their calorimeter (Nagaslaev, Sill and Wigmans, 2001)[1]. They report an energy resolution of 36% for the proton energy range from 150 GeV to 375 GeV, and our simulations yielded 38%. We were sufficiently satisfied by this agreement to use GEANT/FLUKA simulations to design our calorimeter.

3.3 Energy resolution.

It was demonstrated by Howell (2000), that assuming realistic values for the space flight calorimeter mass and energy range of our interest, an energy resolution of 35-40% would be adequate to measure cosmic ray spectra parameters, but the geometrical factor should be maximized. In our design we require 35% energy resolution and maximize the geometric factor.

3.4 Material choice

We simulated energy resolution of the homogeneous calorimeter made of materials with different Z. We found that the total grammage on the particle path defines energy resolution (Fig.1).

3.5 Density choice

Using Fig.1 and accepting 35% energy resolution for a 3,000 kg calorimeter, we conclude that a thickness of 300 g/cm^2 would be sufficient (50 g/cm^2 is added for the interaction). This thickness corresponds to a density of 3 g/cm^3 assuming a cubic shape.

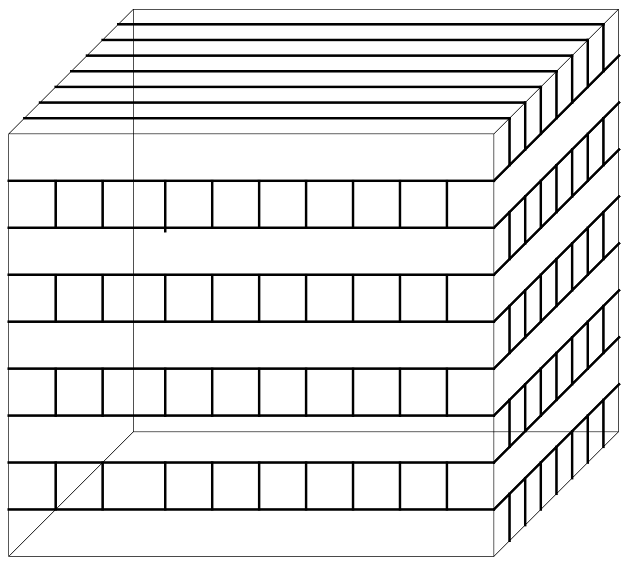

Fig.2. Calorimeter layout. Number of logs and layers is reduced for simplicity

3.6 Other considerations.

- Our calorimeter does not have a separate target for the initial particle interaction. The interaction can occur in any place of the calorimeter, and the events will be selected by the path after the first interaction.

[1] Nagaslaev, Sill and Wigmans (2001) report in their paper a way to significantly improve energy resolution by using Cherenkov fibers in addition to the scintillating fibers. We are not considering use of Cherenkov fibers and use only their scintillating fibers in our simulations.

- Sampling is on the scale of less than the Moliere radius
- Simple, inexpensive construction
- Well-proven detecting principle

4 Proposed Calorimeter

After size, sampling, and materials optimization we came to a cubic calorimeter, with overall dimension 95cm×95cm×95cm, made of composite scintillator/lead logs (Fig.2). Each log (calorimeter segment) is 0.85cm×0.85cm×95cm with the core (0.73 cm on side) made of plastic scintillator, and 0.6 mm thick Pb walls. The 9,025 logs are laid out alternately in two orthogonal directions. Each log is viewed by PIN photodiodes or small PMTs on both ends. Weighting the signals from both ends, the position of the center of gravity in each log is determined, improving the trajectory reconstruction. Readout at both ends also provides redundancy in case of photodiode/PMT failure. All logs are mounted in a mechanical supporting structure – grid, made of carbon composite, with 1.5mm thick walls between logs.

Parameters of the calorimeter:

Mass - ~ 2,800 kg
Number of logs – 9,025
Number of electronics channels – 18,050
Average density - 3.3 g/cm^3
Average X_0 - 2.75 cm (34.5 X_0 in total face-to-face)
Average Λ_0 - 42.6 cm (2.23 Λ_0 in total face-to-face)
Average ρ_M - 2.6 cm

Triggering. Events are read out (trigger created) if the total energy in the calorimeter is above some given threshold. A viable way to implement this is that the trigger is created if one of the following conditions is true:

a) signal from one log is above T1
b) signals from any three logs are above T2 (T2<T1)
c) signals from any six logs are above T3 (T3<T2)

Thresholds T1, T2, and T3 are adjustable and define the low energy limit and data rate.

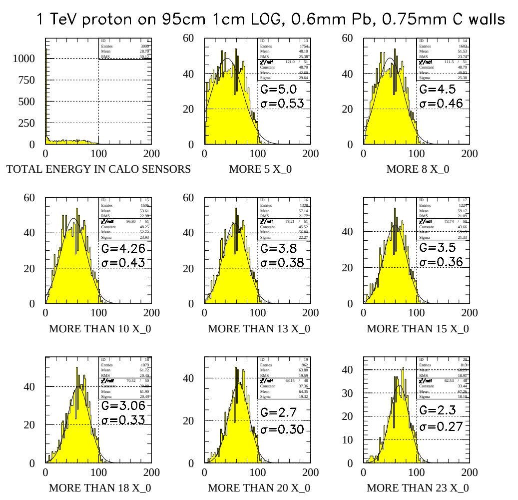

Fig.3. Typical set of histograms

5 Expected performance

5.1 Geometric Factor.

The expected performance of the described design was simulated by GEANT 3.21/FLUKA. Figure 3 shows a typical set of histograms obtained with 1 TeV protons, for isotropic and uniform illumination of the top surface of the calorimeter. Events are selected by their path-length in the calorimeter (in X_0 after the interaction occurs), and shown in the series of boxes. The approximate energy resolution $\Delta E/E$ is determined from a Gaussian fit. We also made a very simple improvement by correcting the energy for the path after the interaction. The effective geometric factor G is determined as follows:

$$G = \frac{Number\ of\ events\ passed\ selection}{Total\ number\ of\ trials} \times K \times \pi \times A$$

where K=3 accounts for the use of the sides (1 for the top + 4×0.5 for the sides), and A is the area of the top surface.

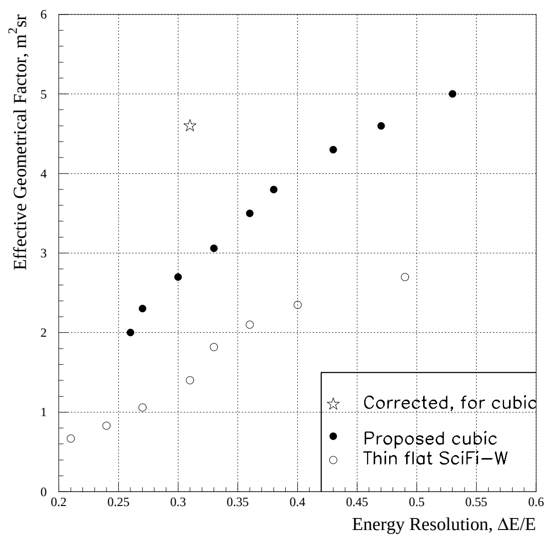

Fig.4. Comparison of the effective geometric factor for cubic and "flat" caloirimeters.

Figure 4 shows a comparison of the proposed cubic design with the traditional approach such as a "flat" calorimeter. The corrected energy response is shown by the "star". The side entries for the "flat" calorimeter are also included for fair comparison. The significant advantage of the cubic approach is seen. Events can be selected based on their pathlengths after interaction during data analysis and the resulting spectra intercompared. Less G and better $\Delta E/E$

vs. more G but poorer $\Delta E/E$ will be the choice of the scientist.

5.2 Uniformity of energy response

Practically no difference in energy response was detected in the simulations for uniform and isotropic illumination of two adjacent sides – normal to the logs and along the logs, for the energies up to 100 TeV (highest energy we have simulated).

5.3 Direction reconstruction

The trajectory direction reconstruction is not a very critical requirement in the study of high energy cosmic rays, which are assumed to be isotropic. There will be a need to remove events arriving from the atmosphere, but this does not require high angular precision. But the required capability to measure the charge Z of detected particle does require high precision in the reconstruction of the entry point. Charge measurement is provided by the charge detector, which surrounds the calorimeter from all entry sides and measures the energy deposition. A serious problem in this measurement is the effect of backsplash – secondary particles produced in the calorimeter by the primary one. Backsplash particles create signals in charge detector distorting the charge measurement. To minimize this effect, the charge detector is divided in pixels, and the charge of a detected particle will be measured by the pixel which was crossed by the reconstructed trajectory. Based on the backsplash study (Moiseev and Ormes, 2001) we estimate a backsplash-originated signal above 3 mip (imitation of the helium event) in 5% of the proton events in the calorimeter, in the surface spot of ~1 cm^2 for $E_p = 10^{15}$ eV. This area can be taken as a requirement for the precision of entry point reconstruction.

Using a very simple direction reconstruction algorithm we obtained from the simulation that this requirement can be met keeping 80-90% of the events. This is more critical for the events entering through the side along the logs.

5.4 Dynamic range

Simulations show that with the deposited energy threshold for every single log at 10 mip, the energy reconstruction and resolution does not suffer at the lowest energy of the interest (~100 GeV). Simulations also show that the maximum energy released in a single log with the flux incident from the side along the the logs, is about 2% of the incident proton energy. This results in a required dynamic range for single log of $\sim 1.3\times 10^6$, if we want to achieve the energy 1 PeV. This dynamic range can be achieved, for example, by having 3 photodiodes of different areas readout by a single ASIC at each log end.

5.5 High energy electrons

This calorimeter will provide a unique opportunity to measure high energy cosmic ray electrons in the energy range from 100-200 GeV to about 10 TeV. This would address the topics of high energy electrons origin and propagation and acceleration of cosmic rays in the galaxy (Nishimura et al., 1997). It was shown in Ormes et al. (1997) that the calorimeter itself is capable of distinguishing high energy (above 200 GeV) electrons from protons at the required level of efficiency. For a reliable selection the path in a calorimeter should be more than 40 X_0. Selecting appropriate events in our calorimeter, a geometric factor of 1.5 –2 m^2sr can be achieved for such electrons with energy resolution of the order of 20%.

6 Summary

A design trade-off between area and thickness of calorimeter (in X_0) is not the best way to think about optimizing G if use of side entering events is included.

The cubic calorimeter optimizes the geometric factor at the same energy resolution over all other designs we have studied. A factor of at least 2 in the increase of geometric factor over a "flat" calorimeter (or "top-entry) is realistic. We used a total mass of 3,000 kg as an example; this mass might be available for the ACCESS project onboard ISS. A geometric factor of 4-5 m^2sr is achievable with energy resolution of about 30%. The calorimeter can be easily scaled down according to the available resources, always keeping a maximum possible geometric factor.

There is an optimal density that depends on mass and required energy resolution, which implies a minimum calorimeter depth of 300 g/cm^2 for a case considered.

Measurement of high energy electrons up to ~ 10 TeV could be a very attractive bonus with significant scientific output.

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