Cubic Calorimeter for High-Energy Electrons in Ultra-Long Ballooning

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Abstract

The concept and optimization study of a balloon-borne instrument to study high-energy (from 100 GeV to 5 TeV) cosmic ray electrons will be presented. This energy range of electrons is very interesting for the study of cosmic ray propagation and the search for nearby sources of high-energy electrons. The instrument is based on a cubic design that allows detection from all sides. Proton rejection is provided by stringent track analysis, which detects when an electron shower is exhausted while a hadron shower continues development. The collecting power of a nominal balloon-borne instrument using this concept will be over 2 m^2 sr. This will provide $\sim$3,000 electron events above 500 GeV for a 3-month long Ultra-long-duration Balloon (ULDB) flight. This instrument will also be capable of detecting sharp features in the high energy gamma-ray spectrum such as gamma-ray lines originating from dark matter annihilation.

1. Introduction

The importance of detection of cosmic ray electrons with energy above 50–100 GeV has been discussed in a number of papers [1–4]. Due to the short lifetime of TeV electrons, they can reveal near-by sources at distance of several hundred parsecs. The measured electron spectrum is also very important to determine diffusion coefficients.

All currently available data in high energy electrons has been obtained in balloon experiments (see [5]) with very limited statistics at higher energy (very few events above 1 TeV). There are a number of future experiments considering the detection of high energy electrons (ATIC [6], CALET [7], Pamela [8], GLAST [9]), where the three latter ones are experiments in space. We are studying an electron "cubic" spectrometer for ULDB Flight (3 months or longer), that combines powerful electron identification with a large geometrical factor.

The principal approach to the high energy cosmic ray calorimeter of the "cubic" design was presented in [10]. The idea is based on the observation that to measure isotropic radiation the detection of particles arriving from all directions

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would be very beneficial to increase the critical feature for this experiment - the geometrical factor (also suggested in [11]).

2. Calorimeter design

2.1. The basic idea

The basic idea is to design a simple, self-triggering cheap calorimeter, capable of measuring the energy of electrons with the precision of ∼20%, and of rejecting protons with a rejection power of order 10^4. This requirement arises from comparing the proton [12] and electron [3] fluxes. Their ratios, taking into account that the proton will deposit in average 60–70% of the full energy in our calorimeter, will range from ∼100 at 100 GeV to ∼1,200 at 5 TeV. Requiring not more that 10% of the proton contamination in the measured electron flux, we come to the mentioned required rejection.

Traditional calorimeter designs are based on accelerator techniques and primarily measure particles that enter through a single surface. Such "flat" designs are appropriate in an accelerator setting where particles arrive from a well-defined direction or location. However, cosmic rays are, in the first approximation, isotropic except as obscured by the Earth. To exploit this fact, we developed a 3-dimensional calorimeter that will measure cosmic rays coming from above and from all sides. This design makes use of the fact that, within certain limits, trajectories of incident cosmic rays do not have to pass through the same thickness of calorimeter material. While the ideal shape of a 3-D calorimeter would be a sphere, a cube will also perform well, and is more practical in manufacture.

Using Monte Carlo simulations we optimized the basic design parameters for high energy electron detection. The calorimeter is a cube made of square cross-section logs (fig.1). Each log is a separate scitnillating detector, made of BGO in the current design, and layed out alternately in two orthogonal directions. Each log is viewed by a PIN photodiode (or PMT) on both ends. Weighting the signals from both ends, the position of the gravity center of energy released is determined for each log.

2.2. Triggering and event selection

- The trigger to record an event is created when the number of calorimeter segments (logs) with released energy above some (programmable) threshold exceeds some (programmable) number. The data is recorded and transmitted to the ground without any on-board selection.

- The expected trigger rate for the calorimeter with a geometrical factor of 2 m^2 sr and trigger threshold corresponding to a proton energy of 100 GeV (electron energy ∼60 GeV) will be under 10 Hz.

- Event selection is carried out in ground data analysis: the detected particle trajectory through the calorimeter is determined, and a set of selection criteria is applied according to a) trajectory length, and b) total energy released in the calorimeter sensors. These are the main criteria to select electrons from protons and are based on the trajectory in the calorimeter being long enough to exhaust the electron shower while the hadron shower continues development. Other additional criteria such as the total number of logs with energy above some (low, around single particle energy loss) threshold and the shape of the shower will also be utilized.

2.3. Geometrical factor

This parameter is the most important, because it determines the upper energy limit (where we run out of statistics) and the duration of the experiment. It is determined by Monte Carlo for events which enter through the top and the sides. A factor of 0.5 is applied to the events entering through the sides to account for Earth and atmosphere obscuration.

Assuming the available weight for the calorimeter to be 2 metric Tons (reasonable for ULDB), the values of possible geometrical factors as a function of the required particle path for calorimeters made of different materials are shown in fig.2. It is seen that if shorter trajectory length is sufficient for the electron/proton separation, a lower density calorimeter would be preferable.

2.4. Performance simulation

A number of different calorimeter modifications have been simulated. For a “cube”, made of BGO with a side size of 68cm, and with a required minimal path length of 40 X_0, efficiency of selecting electrons is 84%, and no one proton in 20,000 trials passed the selections. Energies 200 GeV and 500 GeV were simulated. Requiring 30 X_0 as minimal path, four 500 GeV protons of 40,000 trials passed electron selections, which is still acceptable.

2.5. Expected results and conclusion

Assuming a geometrical factor of 2.5 m^2 sr, the following number of electron events can be expected for an electron flux index –3.3 and a 100-day long flight: above 100 GeV – 1.5×10^5 electrons; above 500 GeV – 3,500 electrons; above 1 TeV – 700 electrons. These statistics will be sufficient to see any spectral cutoff in the energy range up to 5 TeV and consequently the presence of any nearby electron source. The proposed calorimeter is simple, inexpensive and straightforward to design and fabricate. The prospects for practical ULDB instrument are encouraging.

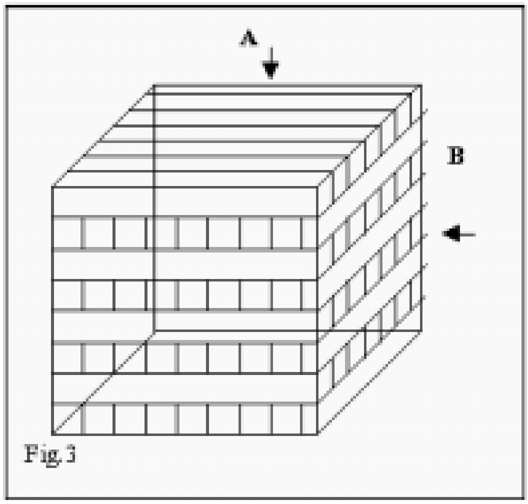

Fig. 1. Schematic view of the calorimeter.

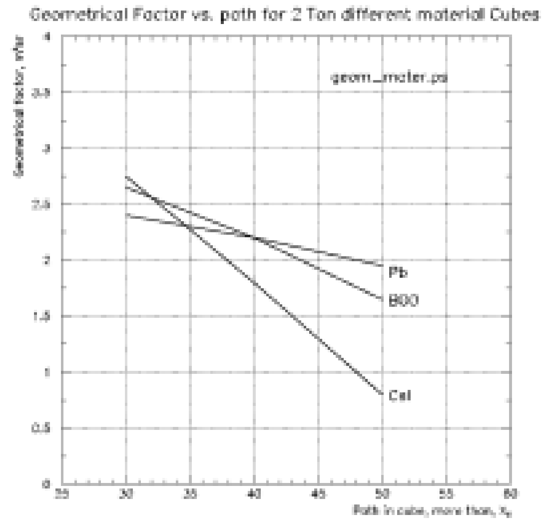

Fig. 2. Geometrical factor for different calorimeters.

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