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Simulation Study on High Energy Cosmic Electron Detection by Shower Image *

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Abstract Many projects have recently been carried out and proposed for observing high energy electrons since it is realized that cosmic ray electrons are very important when studying the dark matter particles and the acceleration mechanism of cosmic rays. An imaging calorimeter, BETS (Balloon-borne Electron Telescope with Scintillator fiber), has been developed for this purpose. Using pattern analysis of the shower development, the electrons can be selected from those primary cosmic ray proton events with flux heights one-tenth that of the electrons. The Monte-Carlo simulation is indispensable for the instrument design, the signal trigger and the data analysis. We present different shower simulation codes and compare the simulation results with the beam test and the flight data of BETS. We conclude that the code FLUKA2002 gives the most consistent results with the experimental data.

Key words: methods: analytical — Monte-Carlo simulation — cosmic rays

1 INTRODUCTION

High energy electron observation is a very important subject in astrophysics. In recent years the existence of dark matter has been widely accepted, but the exact nature of this major component in the universe is not clear. Over the last several decades both experimental and theoretical studies have essentially eliminated all known particles as dark matter candidates, leaving only a few exotic species possible (see a brief review by Drees & Gerbier 2004). The candidates include weakly interacting particles from supersymmetric theories, such as neutralinos, which can annihilate and produce gamma rays, electrons and positrons. The particles, recently suggested (another candidate) by Cheng, Feng & Matchev (2002), and predicted by theories involving compactified extra dimensions particles (Kaluza-Klein(KK) particles), can annihilate in the galactic halo and produce an excess of electrons and positrons, which are observable above the Earth. High resolution observation of positron and electron is a possible way to search dark matter particles. It is also a very important tool to study the origin, acceleration and propagation of cosmic ray (Nishimura et al. 1980; Ormes 1985; Kobayashi et al. 2004; Evenson 1998). Since the energy spectrum of electrons is steeper than that of protons, the ratio of background protons to electrons increases with the energy; from about a few hundred around 10 GeV to a few thousand around 1000 GeV. Therefore, an electron detector should have both large acceptance and excellent rejection power against the background hadrons.

As a promising technique to identify the electrons from proton background, several kinds of imaging calorimeters have recently been developed, for example, BETS (Torii et al. 2000, 2001), PPB-BETS (Torii et al. 2003a; Kitamura et al. 2003), ATIC (Chang et al. 2003; Guzik et al. 2004), AMS

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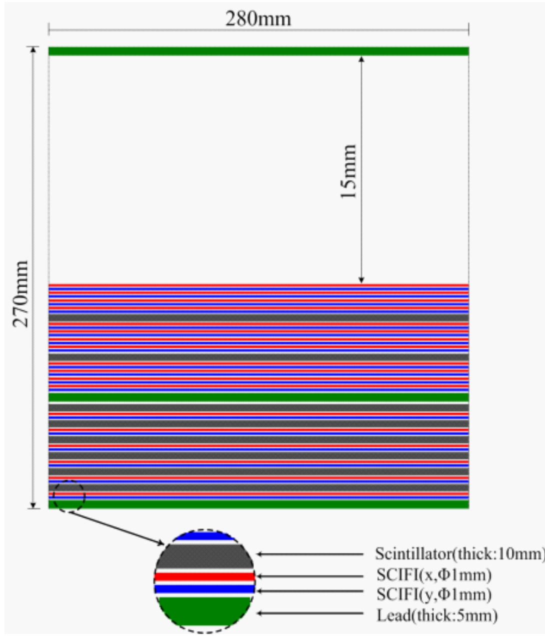

Fig. 1 Schematic configuration of the BETS detector.

(Choumilov et al. 1999), CALET (Torii et al. 2003b). The most important method in such kind of imaging calorimeters is to detect the shower development in lateral spreads. The rejection power of background protons depends on the thickness of the detector and the granularity of the shower imaging.

Simulation study by Monte-Carlo method is an indispensable tool in optimizing the performance of the calorimeter and for analyzing the observed data. For example, by the simulation, the shower development can be investigated in detail and the rejection efficiency can be modified. However, simulation results obtained by different codes do not always give similar results, and the discrepancy often throws us in confusion. In this paper we present the differences in shower simulations result from major calculation codes: GEANT3-FLUKA, GEANT3-GHEISHA (Brun et al. 1994), FLUKA2002 (Fasso' et al. 2000a,b). The most reliable code has been selected by comparing the simulation results with balloon flight data obtained by the BETS detector (Torii et al. 2000, 2001; Kitamura et al. 2003) and with the CERN beam test.

2 BETS AND PPB-BETS DETECTOR

The BETS detector was developed for the observation of electrons in the energy band from 10 GeV up to 1 TeV at the balloon altitude. It has enough imaging resolution to observe the details of shower starting points and lateral distributions. By using the imaging capability of shower profile, electrons can be selected from the background protons.

BETS consists of eight lead plates, each 5 mm (0.9 radiation length) thick, nine belts of scintillating fibers and three plastic scintillators, each 10 mm thick. Plastic scintillators were adopted for the instrument trigger and the energy measurement. Scintillating optical fibers were used for observing the shower particles developing in lead with an image-intensifier CCD camera. These 280 fibers form a layer with one millimeter pitch. In each belt two layers were set in right angles to each other to observe the projected shower profile in both x and y directions. The effective area covered by these orthogonal layers is nearly $28 \times 28\,\mathrm{cm}^2$. In the converter part shown in Figure 1, there are three fiber belts with $4x$ and $4y$ layers each to ensure the detection of minimum ionizing particles (MIP) incident on the top of the detector. The starting point of the shower was determined with an accuracy of 0.9 radiation lengths. The detection efficiency of MIP of the four-layer belt is 98% with the requirement that more than two of the layers have signals. There are six belts in the calorimeter part: one layer in each direction. The total number of layers is 36 (18 in each of the two orthogonal directions, x and y); the total number of scintillating fibers is 10080.

PPB-BETS is developed for long duration TeV electron observation in Antarctic. The basic structure is similar to the BETS, but several improvements were adopted to modify the energy resolution. For example, the height of PPB-BETS is 9 radiation lengths (7.2 in BETS), and the number of scintillator detectors is 9 in PPB-BETS to measure the shower profile (3 in BETS).

Some simulation results of the imaging capability of BETS are shown in Figures 2 and 3, respectively, for electron and proton induced showers. One can see that the electrons can be easily discriminated on the basis of the differing shower images. If the first interaction point of proton is within one radiation length from the top the proton deposits about 1/3 of its total energy on average in the detector. We use the result of 50 GeV of electrons and 150 GeV of protons for comparison. The BETS group defined a parameter, RE, by the ratio of energy deposit within 5 mm from the shower axis to the total energy deposit in the fiber detector to characterize the lateral spread of shower (Torii et al. 2000, 2001).

In order to understand the reason why the RE can be used for electron identification, a Monte-Carlo simulation was done by FLUKA2002, and the angular distribution of secondary particles at the proton-lead interaction is shown in Figure 4. It can be seen that the average lateral spread is much narrower for an electron-induced shower than a proton-induced shower because of the wider spread of secondary particles in the proton-lead interaction. As a result, electron showers have large RE values. In Table 1, the number of multiplicities and the average angles (median angle) between the secondary particles and incident direction at different energies for protons and electrons are presented.

Fig. 2 Simulated by FLUKA, the 50 GeV electron shower image in the X direction.

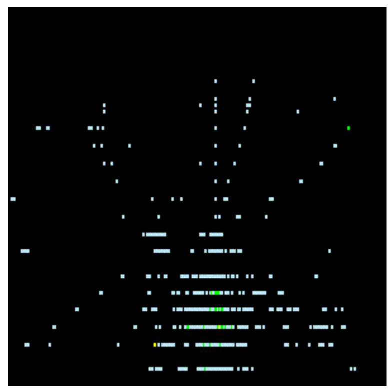

Fig. 3 A 150 GeV proton shower image in the X direction, simulated by FLUKA.

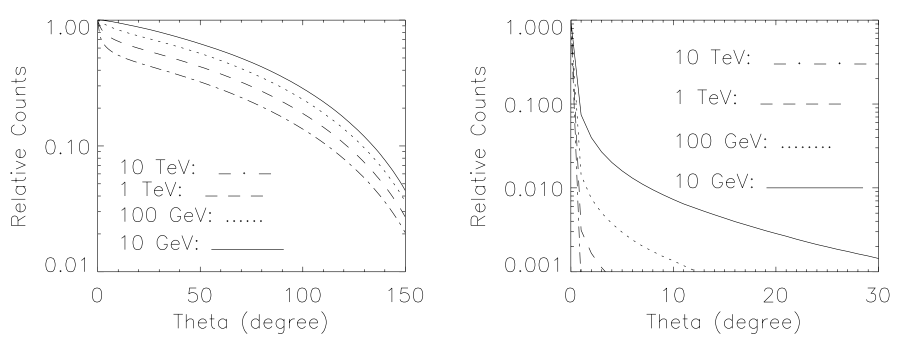

Fig. 4 Angular distribution of secondaries from proton-lead (left) and electron-lead (right) interaction, simulated by FLUKA.

Table 1 Multiplicities, angular dependence of proton-lead nuclear interaction.

Energy (GeV)	10	100	10^3	10^4
Multiplicity	43.8	67.0	101.0	142.7
Median angle (deg.)	69.6	56.4	36.5	13.5

Table 2 The electron detection efficiency and proton rejection power from beam test and simulations.

	Electron detection efficiency (%)	Proton rejection power
Beam Test	90.0	18.1
FLUKA2002	89.7	17.8
GEANT3-FLUKA	98.0	30.2
GEANT3-GEHEISHA	98.0	85.2

3 BETS FLIGHT DATA AND COMPARISON WITH SIMULATION

3.1 Simulation Codes

At present, GEANT3-FLUKA, GEANT3-GHEISHA and FLUKA codes are widely used in high energy physics and cosmic ray simulations. GEANT3 is a code developed at CERN for high energy physics experiment. FLUKA is a stand-alone code and only the parts dealing with hadronic interaction were included in GEANT. GEANT does not usually represent the latest FLUKA developments. Originally these codes are developed for different purposes. Monte Carlo techniques and physics models are different in these codes, as regards for example, the secondary particle productions, angular energy at every transport step, and energy deposition along the track. One should choose suitable codes for different experiments.

For BETS experiment, Monte Carlo simulations are essential in the detector design, trigger and data analysis. BETS is a balloon experiment, the data will be transferred to the ground by commercial telephone line, the telemetry is limited. For saving data size, most of the background will be rejected by the trigger. BETS Monte Carlo simulations were performed using three different codes: GEANT3-FLUKA, GEANT-GHEISHA, and FLUKA2002. After comparison, the most suitable one will be selected for the data analysis.

3.2 Beam Test Results

The accelerator beam tests at CERN-SPS were carried out to study the performance of the PPB-BETS detector for electrons and protons. The observed events are analyzed by the same method as for the BETS. Figure 5 compares the observed events with the simulation results obtained by the different codes. The energy of electrons is 100 GeV and that of protons is 250 GeV. Both beams strike perpendicular to the top surface of detector at the center position. We selected proton events with first interaction point on the top of BETS and energy deposit in BETS is the same as 100 GeV electron. After this, about 99% protons were rejected. It can be seen that the electron and proton profiles from FLUKA2002 agree well with those from the beam test. In general the simulated electron profiles from GEANT3-FLUKA, GEANT3-GHEISHA agree with the beam test, but there are large differences between the simulated and the beam test profiles of protons.

We use the ratio between total proton events and the proton events which mimic electrons to define the proton rejection power. We set $\mathrm{RE} > 0.8$ to select electron events, and the electron detection efficiency and proton rejection power are shown in Table 2. It can be seen that FLUKA2002 agrees well with the beam test. For the flight data analysis we can use FLUKA2002 simulation results to obtain the detection efficiency and proton rejection power.

3.3 BETS Flight Data

The BETS balloon flights were carried out at the Sanriku Balloon Center in Japan, on 1997 June 2, and 1998 May 24–25. The data were collected for 4.5 h at an altitude of 35–36 km (35.7 km on average) in 1997 and for 8.3 h at nearly 35 km in 1998. A total of 190503 events were recorded, and 1349 events are electron candidates.

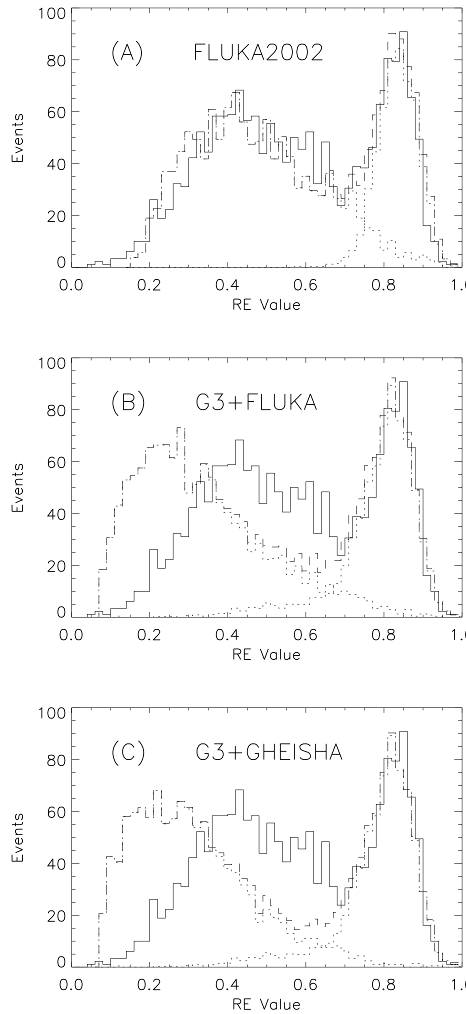

Fig. 5 RE distribution from CERN calibration and comparison with simulation. Solid lines are protons (250 GeV) and electrons (100 GeV) from CERN calibration, dashed lines are expected results from the simulations (A) FLUKA2002, (B) GEANT3 with FLUKA, (C): GEANT3 with GHEISHA.

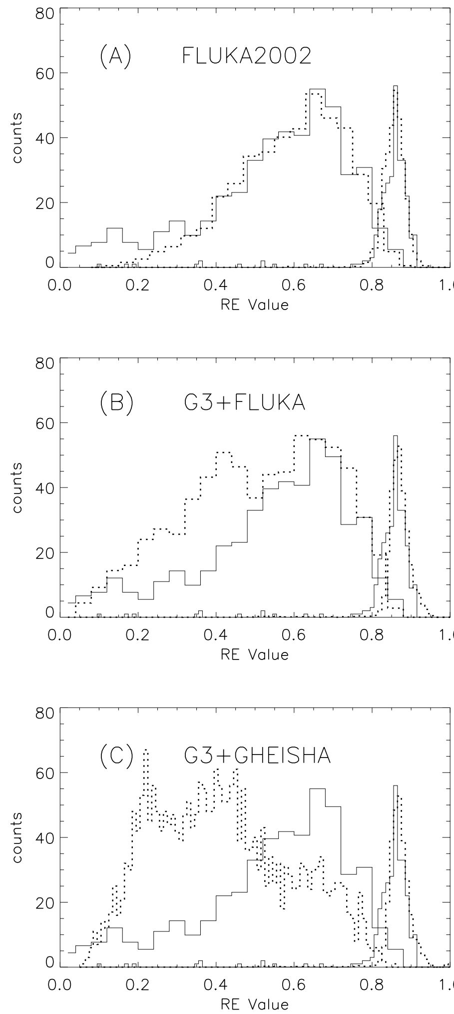

Fig. 6 RE distribution from BETS flight data and simulation. Dashed lines are expected results from the simulations (A) FLUKA2002, (B) GEANT3 with FLUKA, (C) GEANT3 with GHEISHA.

An isotropic event generator was developed for the BETS geometry with particles incident from the upper hemisphere. According to the beam test and the simulation result (Torii et al. 2000, 2001), electrons with energies below 5 GeV and protons below 10 GeV could not satisfy the trigger criteria. The proton ($\geq$10 GeV) and electron ($\geq$5 GeV) spectra in the simulations were derived from the published observation data (Nishimura et al. 1980; Kobayashi et al. 2004; Sanuki et al. 2000). The proton and electron spectra for the simulations are:

$$\text{Proton}: \quad \frac{dN}{dE} = 1.6 \times 10^4 E^{-2.75},$$
$$\text{Electron}: \quad \frac{dN}{dE} = 475 E^{-3.26}.$$

For comparison of the BETS flight data with the simulations, we have reanalyzed the data by using the method described in the reference (Torii et al. 2000, 2001). Initially, we set a trigger condition using the energy deposit information in three plastic scintillators arranged at different depths in the BETS calorimeter (see Fig. 1). Most of proton events can be distinguished if they have not the first interaction at the top of the calorimeter and if the secondary particles are not dominated by neutral pions. According to the simulation results, the proton-rejection power by the trigger condition is about 100 (heavier primaries can not be triggered by the higher energy threshold in the top scintillator S1) at a trigger efficiency of electrons above 85%. This power was also confirmed by any analysis of the CERN beam test.

Since most of the background events mis-triggered during the flight were particles hitting the side of the detector, we have to remove such events by image analysis. After the image analysis reconstructed all the events, the events are selected by the following cut criteria. 1) The shower axis from the top to the bottom lies within 20 mm of the inside of the detector edge. 2) The zenith angle of the shower axis is less than 30 degrees. 3) The particle charge is single (according to the energy deposit in the top scintillator S1). The criteria 2) and 3) are used to enhance the primary electrons. After these cuts, only a few percent of the proton events survived. Figure 5 shows the RE distribution of the observed events which have passed the selection criteria. It is found that electron 'signal' around $\mathrm{RE} = 0.8$, well separated from the protons, can be easily selected.

After considering the instrumental correction in the image reconstruction, the simulations are compared with the flight data in Figure 6. It can be seen that the result by FLUKA2002 agrees with the flight results very well.

4 SUMMARY

To observe the cosmic high energy electron spectrum, the difference in the three dimension shower development inside the detector is used to separate electron events from proton background for several projects. Monte-Carol simulation is essential for the detector design and the flight-data analysis. We have tried to choose a reliable simulation code by comparing the simulated results with the flight data observed by the BETS detector and with the CERN beam test done for the PPB-BETS. Of the three simulation codes, FLUKA2002, GEANT3 with FLUKA, and GEANT3 with GHEISHA, we find that only FLUKA2002 can give consistent results with both of the experimental data.

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References

Brun R.,Carminati F.,Giani S., 1994, GEANT detector description and simulation too, Program Library Long Writeup W5013, Eur. Organ. For Nucl. Res., Geneva
Chang J. et al., 2003, Proc. 28th ICRC, 1817
Cheng H. C., Feng J. L., Matchev K. T., 2002, Phy. Rev. Lett., 89, 211301
Choumilov E., Galaktionov Yu., Plyaskin V., 1999, NIMA, 426, 625
Drees M., Gerbier G., 2004, Physics Letters B, 592, 216
Evenson P., 1998, Space Science Reviews, 83, 63
Fasso' A., Ferrari A., Ranft J., Sala P. R., 2001a, In: A. Kling, F. Barao, M. Nakagawa et al. eds., Proceedings of the MonteCarlo 2000 Conference, Lisbon, October 23–26 2000, Springer-Verlag Berlin, p.955
Fasso' A., Ferrari A., Sala P. R., 2001b, In: A. Kling, F. Barao, M. Nakagawa et al. eds., Proceedings of the MonteCarlo 2000 Conference, Lisbon, October 23–26, 2000, Berlin: Springer-Verlag, p.159
Guzik T. G. et al., 2004, Advances in Space Research, 33, 1763
Kitamura H. et al., 2003, Proc. 28th ICRC, 2089
Kobayashi T. et al., 2004, ApJ, 601, 340
Nishimura J. et al., 1980, ApJ, 238, 394
Ormes J. F., 1985, Bulletin of the American Astronomical Society, 17, 856
Sanuki T. et al., 2000, ApJ, 545, 1135
Torii S. et al., 2000, NIMA, 452, 81
Torii S. et al., 2001, ApJ, 559, 973
Torii S. et al., 2003a, Proc. 28th ICRC, 2085
Torii S. et al., 2003b, Proc. 28th ICRC, 2177