Simulations for hadron calorimeter of the hybrid experiment at Mt.Chacaltaya

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Abstract: In order to analyze the data of hadron calorimeters of the hybrid experiment on Mt.Chacaltaya, shower developments in the burst detector are calculated using GEANT4 simulation code, taking into accounts the exact structure of experimental hadron calorimeter. The distributions of shower particles at the scintillation counter of the burst detector, their dependence on the energy and on the direction of incident hadrons, obtained by the GEANT4 simulations, are approximated by numerical functions in order to save computing time. Applying these functions to every particle, incident upon the hadron calorimeters, in the air-showers simulated using CORSIKA, we get the burst-density in each block of hadron calorimeter. In this paper we describe in detail our calculations of the burst-density. Some of the results, the distribution of burst-size, lateral distribution of the burst etc., of the simulated events, are compared with those of experimental data. Discussions are also given on the dependence on the nature of primary particle.

Keywords: simulation, GEANT4, hadron-calorimeter, burst, mountain experiment

1 Introduction

The hybrid experiments operating simultaneously an air-shower array, a hadron calorimeter and an emulsion chamber have been carried out at Mt. Chacaltaya (5200m, Bolivia)[1, 2], for studying cosmic-ray nuclear interaction and chemical composition of primary cosmic-rays in the energy region around $10^{15} - 10^{17}$ eV. In the hybrid experiments, we can obtain air-shower size, $N_e$, from the air-shower array data, particle-density (burst-density), $n_b$, which are closely connected to the hadron component in the air-shower, from hadron calorimeter (burst detector) and energy and geometrical position of individual high energy electromagnetic particle by the emulsion chamber. Correlations between air-showers and accompanying families were studied so far by comparing experimental data and simulated data[3, 4]. In the paper[5] we have also shown some results on the characteristics of hadron component (data of hadron calorimeters) in the air-showers observed by Chacaltaya hybrid experiment by comparing with simulated data. In the simulations, the burst-size due to incoming hadrons in the air-showers was calculated using average value of particle number at the scintillator obtained by using GEANT4 simulation code in order to save computation time. A use of the average value is, however, too simplified, because the particle numbers at the scintillator fluctuate very widely. In this paper we describe some details of calculation method of the burst-size based on GEANT4 simulation which describe well the fluctuation of the particle number in exact GEANT4 simulations. The simulated results are compared with experimental data.

2 Hadron Calorimeter of Chacaltaya Hybrid experiment

In the center of the air-shower array of the Chacaltaya hybrid experiment, 32 blocks of emulsion chambers (0.25 m$^2$ each) are installed (see Fig.1). Each block of the emulsion chamber consists of 30 lead plates of 0.5 cm thick each and 14 sensitive layers of X-ray film which are inserted at every 1 cm lead. The thickness of each package of X-ray film is 0.1125 cm. The total area of the emulsion chambers is 8 m$^2$. Hadron calorimeters with plastic scintillator of 5cm thick are installed underneath the respective blocks of the emulsion chamber (see Fig.2). Iron support of 2 cm thick is inserted between the emulsion chamber and the hadron calorimeter. Some detail of the Chacaltaya hybrid experiment are described in Refs.[1, 2]

3 Simulations

3.1 Air-showers

For generating extensive air-showers we use CORSIKA simulation code(version 6.735) [6] employing QGSJET model (QGSJET01c)[7] for the cosmic-ray nuclear interaction. 40,000 primary particles of $E_0 \geq 10^{15}$ eV are sampled respectively from the power low energy spectrum of integral power index $-1.7$, for pure protons and pure irons respectively. The thinning energy is fixed to be 1 GeV. The shower size, $N_e$, at the observation point is calculated by using NKG option in the simulation. Air-shower center is
randomly sampled within an area of $\pm 2.5$ m in X and Y direction from the center of hadron detectors (see Fig. 1).

3.2 Simulations for burst detector

We use GEANT4 code[8] with QGSP model for hadronic interactions for calculating the burst-density. We calculate nuclear and electromagnetic cascades in the emulsion chamber and get the number of charged particles (mainly electrons and positrons) $^1$ at the scintillator of the hadron calorimeter for the hadrons (pions, protons, neutrons and kaons) and also muons and $\gamma$, $\epsilon$ with 5 different energies of 10 GeV, 100 GeV, 1 TeV, 10 TeV and 100 TeV, and 5 different zenith tangent of arrival direction, $\tan \theta = 0.0, 0.2, 0.4, 0.6, 0.8$. In Fig. 3 we show examples of distributions of the number of charged particles which respond to the scintillator for pion incidence, obtained by using GEANT4 code. The distributions of particle number in log-scale, $\log(n_{ch})$, are approximated by numerical functions, composed of a Gaussian and an uniform distribution and a peak of single particle. The peak position and its dispersion of Gaussian distribution, fraction of Gaussian part, of uniform part and of a single peak depend on the energy, angle and a nature of the incident particle. The energy dependences of these parameters are also approximated by numerical functions. We can then sample the number of charged particles at the scintillator for the incident particles with any energy and

1. Here we take into accounts a scintillator response of charged particles. Gamma-rays gives some energy deposit in the scintillator. Then the scintillator response of gamma-rays are also taken into accounts.[9]
incident angle. In the figure, also shown are the distributions of particle number obtained by sampling from these numerical functions which approximate GEANT4 results. The distributions are well agree with those obtained by exact simulations using GEANT4.

3.3 Calculation of burst-density in the air-shower

Applying the above sampling procedure to each particle incident upon the emulsion chamber, we get the burst-density (the number of particles per 0.25m²) , \(n_b\), in each block of 32 hadron calorimeters in the EAS simulated by CORSIKA. Here we take into accounts particles with energy larger than 10 GeV, because the contribution of lower energy particles to the burst-size is negligibly small. Fig.4 shows a comparison of the distribution of the burst-density in a block obtained by using GEANT4 code exactly and that obtained by sampling from the approximated functions. We can see no systematic difference between the two and the present sampling procedure works well. Fig.5 shows a correlation between burst-density and energy-flow-density (energy sum) of hadron component in a block of the hadron calorimeter. We can see the burst-density is roughly proportional to the energy flow of hadrons in a block and the fluctuations of burst-density seen in exact GEANT4 simulations is well reproduced by the present method.

4 Lateral distribution of the burst-density

We define \(n_b^{\text{max}}\) as the largest burst-density among 32 blocks of hadron calorimeters and \(\Sigma n_b\) as the sum of burst-density of 32 blocks. In the following we pick up the events which satisfy the following criteria:

- \(N_e \geq 10^6\),
- \(n_b^{\text{max}} \geq 10^4\),
- no. of blocks \(n_b \geq 100\) \(\geq 10\),
- \(R_{AS-Bs} \leq 1\text{m}\),

where \(R_{AS-Bs}\) is a distance between burst center and air-shower center.

The burst center is determined by the algorithm described in Ref.[2]. Here the blocks with \(n_b \geq 100\) are taken into account in 32 blocks in a event. In the Chacaltaya data, 1,037 events satisfy the above criteria in \(\sim 40\ \text{m}^2\text{year}\) exposure of hadron calorimeters. Fig.6 show lateral distribution on the average burst-density and on the average energy-flow of hadron component in a block of the calorimeter. The shape of the lateral distribution of the burst-density is nearly same to that of the energy-flow of hadrons. That is, we can get informations on the lateral distribution of hadrons in the core of the air-showers from the data of burst-density. Energy per one burst particle is \(\sim 3.6\ \text{GeV}\) as is seen in the figure. A comparison of experimental data with simulations shows the burst-density in the experimental data is systematically larger than the expectation of simulations at the peripheral region \((R > 1\ \text{m})^3\).

5 Air shower-size and burst-size

Fig.7 shows a scatter diagram between air-shower size, \(N_e\), and a sum of burst-density, \(\Sigma n_b\), of the event for the experimental data and for the simulated data of proton- and Fe-primaries. In the events of iron-primaries, \(\Sigma n_b\) is nearly proportional to \(N_e\) though \(\Sigma n_b\) is weakly correlated to \(N_e\) for the events of proton primaries. It is very natural because Fe-air-nucleus interactions are assumed to be superposition of a number of low energy nucleon-air-nucleus collisions and then the fluctuation becomes small. But for proton-air-nucleus interactions, the position of interactions and/or released energy at the interaction fluctuate widely event by event. The distribution in the experimental data looks close to that in proton-primaries. Fig.8 show distributions of \(\Sigma n_b/N_e\) for four different chemical composition of primary particles, pure proton, pure iron, proton-dominant and heavy-dominant. The shape of the distribution for pure-iron primaries is very different from that for the others. There is almost no event with \(\Sigma n_b/N_e > 0.03\) (indicated by broken line in the figure) in the iron-induced air-showers. On the contrary, considerable number of events are found in this region of the distribution in the proton-induced air-showers. There is no systematic difference in shape for the other three chemical compositions, pure protons, proton-dominant and heavy dominant. The experim.
Figure 7: Scatter diagram between air-shower size, $N_e$, and burst-size (sum of burst-density), $\Sigma n_b$, of the event. Lines indicate $\Sigma n_b/N_e = 0.03$.

Figure 8: Distributions of the burst-size normalized by the accompanied air-shower size. Circles are for Chacaltaya data. Curves are for simulated data using CORSIKA with QGSJET01 model; proton-primaries (solid), iron-primaries (dotted), proton-dominant (thick solid) and heavy-dominant (thick dotted).

Experimental data are well described by the model calculation for these three chemical compositions of primary particles though the number of events with smaller burst-size is less in the experimental data. The almost same analysis was done by Tibet group and they concluded that their data are well described by heavy dominant composition (see Ref.[10]).

6 Summary and Discussion

We have shown that the burst-density detected by the hadron calorimeter of the hybrid experiment at Mt.Chacaltaya was efficiently calculated by approximating the results of GEANT4 simulations without losing fluctuations in nuclear and electromagnetic cascade development in the emulsion chamber. The lateral distribution of hadrons in the core of air-showers can be estimated by that of the burst-density, because the shape of the two is almost same. The difference between proton-primaries and Fe-primaries are well seen in the burst-size distribution but it is not easy to discriminate between proton-dominant composition and heavy dominant one from the shape of the distributions. The difference of the chemical composition of primaries will be seen in the absolute intensity of burst events. The arguments on the intensity will be given in the succeeding paper.

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References