Study of Hadronic Component in Air Showers at Mt. Chacaltaya

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The experiment to operate an air shower array, a burst detector (or a hadron calorimeter) and an emulsion chamber is under way at Mt. Chacaltaya (5,200 m, Bolivia), in order to study the hadron interactions and the primary cosmic rays in the energy region exceeding 10^{15} eV. The number of hadronic component in the air shower, detected by the burst detector, indicates that the proton fraction among the primary cosmic rays exceeds 50 %.

1. Introduction

The experiment to operate an air shower array, a burst detector (or a hadron calorimeter) and an emulsion chamber is under way at Mt. Chacaltaya (5,200 m, Bolivia), in order to study the hadron interactions and the primary cosmic rays in the energy region exceeding 10^{15} eV.

The hadron component in the air shower bears more direct information on the subjects, mentioned above, than other components, *i.e.* electro-magnetic, muonic, etc., because the former is at the upper stream of the nuclear and electro-magnetic cascade processes in the atmosphere. We obtain the differential number of hadrons in the air shower from the data by the burst detector, and discuss in the present report the chemical composition of the primary cosmic-ray particles which initiate the air showers.

2. Experimental Procedure

The air shower array consists of 35 plastic scintillators, which are distributed over a circular area of the radius 50 m. The emulsion chamber and the burst detector are located at the center of the air shower array. The burst detector consists of 32 units of plastic scintillator ($50 \times 50 \times 5$ cm³), which are located beneath the emulsion chamber of 15 cm Pb thick. Each unit of the burst detector measures the number of charged particles, incident upon the detector, and therefore the 32 units determine the lateral distribution of the charged particles on the burst detector.

These charged particles are produced by the hadrons, incident upon the emulsion chamber, through nuclear and subsequent electro-magnetic cascade processes in Pb of the emulsion chamber. Hence we can estimate the number of hadrons in the air shower from the burst data.

It is the selection condition of the events for the present analysis that at least one unit of the burst detector has a signal $n_b > 10^4$ and the air shower has the size $N_e > 5 \times 10^6$ (corresponding to $E_0 > 10^{16}$ eV on the average). These events are found unbiased by the selection criterion of the burst of $n_b > 10^4$, by comparing the size spectrum of the selected events with that of all the air showers.

The lateral distribution of the burst (particle density) is fitted by the formula

$$n_b(r) = A \left(\frac{r}{r_0} \right)^{-\alpha} \quad (r_0 = 1 \text{ m}) \quad (1)$$

where A and α are the adjustable parameters. If one assumes the energy-lateral distribution of hadrons, incident upon the emulsion chamber, as

$$F(E, r) dE = \frac{N_0}{\pi} \left(\frac{dE}{E_c} \right)^{-\gamma-1} \frac{dE}{E_c} \times \frac{1}{\left(\frac{K}{E} \right)^2 - \left(\frac{K}{E_2} \right)^2} \theta(K - Er) \quad (2)$$

one obtains the relations

$$\alpha = \beta - \gamma + 2 \quad A = \frac{N_0}{\pi \alpha} \left(\frac{K}{r_0 E_c} \right)^{\alpha-2} \quad (3)$$

where γ is the exponent of the energy spectrum of hadrons, incident upon the chamber. (See Appendix II.) The parameter β relates the energy of a hadron, incident upon the emulsion chamber, to the particle number on the burst detector. (See Appendix I.)

As can be seen in the procedure (Appendix II) to derive the particle density distribution from the assumed energy spectrum of hadrons, incident upon the chamber, the energy spectrum which is constructed from A and α is valid in the region $E < K/r$. And, because the range of the distance r , observed by the experiment, is between 0.5 and 5 (m), the spectrum is valid below ~ 1 TeV. Hence we take the differential number of hadrons at $E = 1$ TeV for the purpose of the various comparisons below. It is given by

$$n_h \equiv \left(\frac{dN}{dE} \right)_{1 \text{ TeV}} = \pi \alpha A \left(\frac{K}{1 \text{ TeV}} \right)^{2-\alpha} \left(\frac{E_c}{1 \text{ TeV}} \right)^\beta \left(\frac{1}{1 \text{ TeV}} \right) \quad (4)$$

Figure 1. The histogram of n_h (the differential number of hadrons at $E = 1$ TeV) for the air showers of $N_e = 5 \times 10^6 \sim 10^7$ with the age parameter of $s = 0.4 \sim 1.4$.

3. Results and discussion

Fig. 1 shows the histogram of differential number of hadrons at $E = 1$ TeV, n_h , for the air showers of $N_e = 5 \times 10^6 \sim 10^7$ with the age parameter of $s = 0.4 \sim 1.4$.

Fig. 2 shows the histogram of n_h by the simulation where the normal composition is assumed for the primary cosmic rays and UA5 codes is for nuclear interactions in the atmosphere. The event number in Fig. 2 is normalized to the experimental data. The distribution in Fig. 2 can be approximated by Gaussian distribution, which is shown in Fig. 3.

There is a discrepancy of the number of hadrons, n_h , between the experimental data and the simulation. Similar tendency is pointed out

Figure 2. The histogram of n_h by the simulation.

previously by the present authors in the relation between the total observed energy of the family and the air shower size.[1] It may indicate that the nuclear interaction changes its feature appreciably in the energy region exceeding 10^{16} eV, as was discussed in Ref.[1]. The discussion below, which is made in terms of $\log n_h$, is free from the absolute value of n_h .

Fig. 3 shows the Gaussian distribution which fits to the distribution in Fig. 2, together with those for the events whose air showers are produced by the primary particles of protons and irons. One can see in Fig. 3 that the left-hand side of the histogram consists of the events which are produced by the light component, mainly by protons. Hence we can estimate the fraction of air showers induced by protons by the left-hand side of the distribution.

Fig. 4 shows the distribution of n_h in integral form from the experimental data. And Fig. 5

Figure 3. The histogram of n_h by the simulation, which is fitted by the Gauss function. The distributions of n_h for the air showers which are initiated by protons and irons are shown together.

shows the one by simulation for the cases of 20, 30, 40 and 50 events of proton-induced air showers. One can see that the experimental distribution is greater than 30 events, indicating that the proton fraction in the primary cosmic rays is more than 50 % in the energy region exceeding 10^{16} eV

Figure 4. The distribution of n_h by the experiment in integral form.

Appendix I. Hadron energy and the particle number

The charged particles on the top of the burst detector consist of the electrons and charged pions which are produced by the hadrons, incident upon the emulsion chamber, through the nuclear and electromagnetic cascade processes in Pb of the emulsion chamber. We calculate number of charged pions and electrons at the depth $T = 15$ (cm Pb) in the emulsion chamber in the case when a single pion of the energy E_0 hits the chamber.

A. Pion-Pb collisions

A pion of the energy E_0 collides with Pb nucleus to cause multiple particles production. We assume that the final state of multiple particle production consists of one surviving pion and a number of produced pions.

Figure 5. The distribution of n_h by the simulation in integral form, for the case of proton showers. The figures attached to the curves are the number of events.

The surviving pions is one of π^+ , π^- , and π^0 . That is, there is a charge exchange process of the incident charged pion into π^0 , whose probability is assumed to be $b = 1/3$ tentatively. All the produced particles are assumed to be pions with equal provability $c = 1/3$ for three charge state, for the sake of simplicity.

The inelastic mean free path of pion-Pb collisions is assumed to be the same as that of nucleon-Pb collision ($\lambda = 18.5$ cm Pb), because the size difference between pion and nucleon affects the cross section slightly due to the large size of the target.

B. Number of pions at the depth t in Pb

To calculate the number of pions of $E > 0$, one has to take into account the energy losses of the pion through the multiple particle production and through the ionization loss. The diffusion of

pions in Pb is expressed by

$$\begin{aligned} \frac{\partial F_\pi}{\partial z} = & -F_\pi(E, z) \\ & + \int_0^1 g(K) dK \int_E^\infty \varphi_\pi(E', E, K) F_\pi(E', z) dE' \\ & + \epsilon_\pi \frac{\partial F_\pi}{\partial z} \end{aligned} \quad (5)$$

where $F_\pi(E, z)dE$ is the number of pions with energy E at the depth $z = t/\lambda$. $\varphi_\pi(E_0, E, K)dE$ is the energy spectrum of the produced pions, and $g(K)dK$ is the distribution of the inelasticity K . The average value of the inelasticity is assumed to be $\langle K \rangle = 0.63$.

The equation has the same structure as that of the electromagnetic cascade theory under Approximation B. We have an approximate solution

$$\begin{aligned} F_\pi(E, z) = & \frac{1}{(2\pi i)^2} \int ds dq \left(\frac{E_0}{E}\right)^2 \frac{1}{E} \left(\frac{\epsilon_\pi}{E}\right)^q \\ & \times \Gamma(-q) A(s, q) e^{\mu_\pi(s)z} \end{aligned} \quad (6)$$

where $\epsilon_\pi = 0.24$ GeV is the energy loss of pion per collision mean free path.

Number of pions at the depth T in Pb is given by

$$I_\pi(0, T) = \int_0^\infty F_\pi(E', T) dE' \quad (7)$$

C. Number of electrons

The number of π^0 's of energy E , which are produced by pion-Pb collision at the depth t in Pb, is given by

$$\begin{aligned} P_{\pi^0}(E, t) dE dt = & \int_0^1 g(K) dK \\ & \times \int_E^\infty \varphi_{\pi^0}(E', E, K) dE \frac{dt}{\lambda} F_\pi(E', t) dE' \end{aligned} \quad (8)$$

The production spectrum of γ -rays, which are produced from π^0 's through $\pi^0 \rightarrow 2\gamma$, is given by

$$P_\gamma(E, t) dE dt = \int_E^\infty \frac{2dE'}{E'} P_{\pi^0}(E', t) dE' dt \quad (9)$$

The number of electrons which are produced by γ rays and are to be observed at the depth T is given by

$$\begin{aligned} N_e(T) = & \int_0^T dt' \int_0^\infty dE' \\ & \times \Pi(E', 0, T - t') P_\gamma(E', t') \end{aligned} \quad (10)$$

where $\Pi(E_0, E, t)$ is the number of electrons at the depth t .

D. Number of charged particles

The sum of Eqs.(7) and (10) gives the number of charged particles, incident upon the burst detector, which are produced in Pb by a single pion of the energy E_0 . The numerical calculation of Eqs.(7) and (10) shows that the particle number is approximated by

$$\begin{aligned} N_{hc}(E_0) = & (E_0/E_c)^\beta \\ & (E_c = 0.56 \text{ GeV}, \beta = 1.0) \end{aligned} \quad (11)$$

Appendix II. Energy spectrum of pions and charged particle density

We assume the energy-lateral distribution of hadrons, incident upon the emulsion chamber, as

$$\begin{aligned} F(E, r) dE = & \frac{N_0}{\pi} \left(\frac{dE}{E_c}\right)^{-\gamma-1} \frac{dE}{E_c} \\ & \times \frac{1}{\left(\frac{K}{E}\right)^2 - \left(\frac{K}{E_2}\right)^2} \theta(K - Er) \end{aligned} \quad (12)$$

where $K \simeq 0.6$ TeV·m is a constant to express the lateral spread of the particles. The energies of hadrons are distributed between E_1 and E_2 .

Because the relation between the energy of the pion, incident upon the chamber, and the number of charged particles is given by Eq.(11), the particle density distribution is

$$\begin{aligned} n_b(r) = & \int_{\max(E_1, E_c)}^{E_2} N_{hc}(E') F(E', r) dE' \\ \simeq & \frac{N_0}{\pi(\beta - \gamma + 2)} \left(\frac{E_c}{K}\right)^2 \left(\frac{K}{E_c r}\right)^{\beta - \gamma + 2} \end{aligned} \quad (13)$$

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