

## A Halo Event observed by Hybrid Detector at Mt. Chacaltaya

H. Aoki<sup>1</sup>, K. Hashimoto<sup>2</sup>, K. Honda<sup>3</sup>, N. Inoue<sup>4</sup>, N. Kawasumi<sup>2</sup>, N. Martinic<sup>5</sup>, C. Navia O.<sup>6</sup>, N. Ohmori<sup>7</sup>, A. Ohsawa<sup>8</sup>, L. Oliveira C.<sup>9</sup>, K. Shinozaki<sup>4</sup>, M. Tamada<sup>10</sup>, R. Ticona<sup>5</sup>, and I. Tsushima<sup>2</sup>

<sup>1</sup>Faculty of Science, Soka University, Hachioji, Tokyo, 192-8577, Japan

<sup>2</sup>Faculty of Education, Yamanashi University, Kofu, 400-8510, Japan

<sup>3</sup>Faculty of Engineering, Yamanashi University, Kofu, 400-8511, Japan

<sup>4</sup>Faculty of Science, Saitama University, Urawa, 338-8570, Japan

<sup>5</sup>Instituto de Investigaciones Fisicas, Universidad Mayor de San Andres, La Paz, Bolivia

<sup>6</sup>Departamento de Fisica, Universidade Federal Fluminense, Niteroi, Rio de Janeiro, RJ, Brasil

<sup>7</sup>Faculty of Science, Kochi University, Kochi, 780-8520, Japan

<sup>8</sup>Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, 277-8582, Japan

<sup>9</sup>Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, RJ, Brasil

<sup>10</sup>Faculty of Science and Technology, Kinki University, Higashi-Osaka, 577-8502, Japan

**Abstract.** Detailed description is made on a halo event which is obtained by the hybrid detector of an emulsion chamber and an air shower array at Mt. Chacaltaya (5,200 m, Bolivia). Available data for the event are on the halo ( $E_{halo} = 750$  TeV) and on the high energy particles of electron/photon and hadronic components by the emulsion chamber, on low energy hadrons by the hadron calorimeter, and on characteristics of the accompanied air shower ( $N_e = 7.0 \times 10^7$ ,  $s = 0.59$ ) by the air shower array. Structure and origin of the event is discussed based on the observed data of various components.

### 1 Introduction

We have been observing high energy cosmic-ray events — air showers (AS) — by a hybrid apparatus of emulsion chamber (EC), air shower array and hadron calorimeter (HC) at Mt. Chacaltaya (5,200 m, Bolivia)[Kawasumi et al., (96); Aguirre et al., (00)].

We will report a high energy event which is remarkable by a large family with a halo ( $\sim 1.5$  cm of diameter) on X-ray films of EC. A halo is made of a large number of electrons, distributed continuously, which means high concentration of energy. The analysis of the halo which bears the information of air shower core helps us to understand the detailed structure of AS.

*Correspondence to:* Norio Kawasumi  
(n-kawa@edu.yamanashi.ac.jp)

### 2 Description of the event

We will describe the event in relation to the respective detectors.

#### 2.1 Air shower (AS) array

AS array consists of 39 plastic scintillator detectors which are distributed over a circular area of  $\sim 50$  m radius. It can measure the arrival time and arrival direction of AS, together with the lateral distribution of charged particle density from which the age  $s$  and the total size  $N_e$  are estimated by fitting the lateral distribution to NKG function[Kamata and Nishimura, (58); Greisen, (58)]. We obtained  $s = 0.59$  and  $N_e = 7.03 \times 10^7$  for the present event. Hence the primary energy of AS is  $\sim 1.5 \times 10^{17}$  eV approximately.

#### 2.2 Hadron calorimeter (HC)

HC, located in the center of the AS array and placed beneath EC, consists of 32 plastic scintillators ( $0.25$  m<sup>2</sup> each). It measures the arriving time of the event and the lateral distribution of charged particles which arrive at HC. These charged particles are mainly electrons which are produced by the hadrons incident upon EC, because electrons and photons, incident upon EC, are absorbed in EC of 15 cm Pb thick, equivalent to 30 c.u. or to 0.81 collision mean free path of nucleon. Therefore we can estimate the energy distribution of hadrons in AS from the lateral distribution of charged particle density by HC[Aguirre et al., (00)].

That is, the lateral distribution is approximated as

$$n_b(r) = \frac{A}{r_0^2} \left(\frac{r}{r_0}\right)^{-\alpha}$$

$$(r_0 = 1 \text{ m}, A = 4.67 \times 10^5, \alpha = 2.89)$$

from which we can estimate the *differential* energy distribution of hadrons, incident upon EC, as

$$n_h = \left(\frac{dN_h}{dE}\right)_{E=1\text{TeV}} = 3.54 \times 10^3 \quad (1 \text{ TeV})$$

and the power index  $\alpha - 4 = -1.1$  in the energy region  $E = 0.1 \sim 1 \text{ TeV}$ . (See Fig. 5.)

### 2.3 Emulsion chamber (EC)

32 EC's of 15 cm Pb thick and 0.25 m<sup>2</sup> each, placed on HC, have 14 sensitive layers of X-ray films which are inserted at every 1 cm of Pb plate.

The event on the X-ray film consists of several tens of showers, distributed over the area of  $\sim 10 \text{ cm}$  radius, and of a halo of diameter  $\sim 1.5 \text{ cm}$  in the center of the event.

The event hit the upper-left corner of the EC unit No.3 with inclination  $\sim 10^\circ$ . Therefore a part of particles fell outside EC, and the halo in the center of the event leaves EC at large depth (after 12 cm Pb).

In this sense shower detection is biased by the following two reasons.

1. The halo masks the showers.
2. The event hit the upper-left corner of EC unit.

which are called 'the item 1' and 'the item 2' hereafter. The item 1 is discussed in the subsection 3.1, and the item 2 is corrected by sampling the showers only in the third quadrant (*i.e.*  $\varphi = 270^\circ \sim 360^\circ$ ) of the  $xy$  coordinates whose origin is located at the center of the halo, and by multiplying the number by 4.

## 3 Halo and showers by the emulsion chamber

### 3.1 Halo

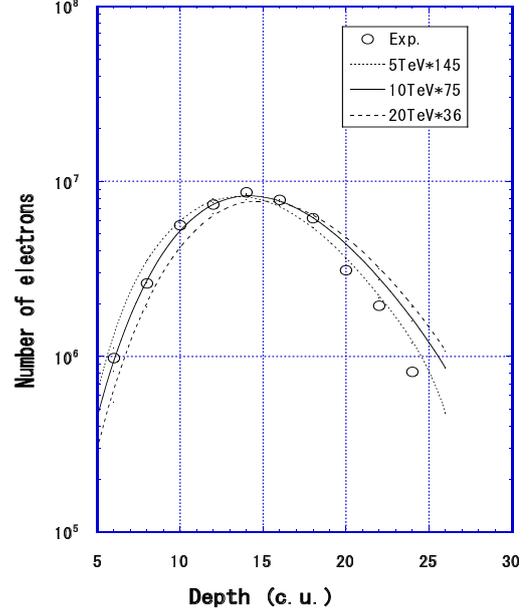
The opacity of the halo on X-ray film is measured by a microphotometer (with the slit of  $200 \times 200 \mu\text{m}^2$ ) over the square area of  $1 \text{ cm} \times 1 \text{ cm}$  at  $500 \mu\text{m}$  interval. The opacity  $D$ , called 'darkness', is converted to electron density  $\rho_e$  using the  $\rho_e - D$  relation, obtained beforehand. In this way we obtain the lateral distribution of electron density  $\rho(r, t)$  at every depth  $t$  in EC.

#### (1) Transition curve of the total electron number

Fig. 1 shows the transition curve of the total electron number in the halo, which is obtained by the integration

$$N_e(t) = \int_0^{r_{th}} \rho(r, t) 2\pi r dr$$

where  $r_{th}$  is the distance at which the darkness is the threshold darkness  $D_{th} = 0.1$ .



**Fig. 1.** Transition curve of the total electron number. The total electron number is obtained by integrating the lateral distribution of the electron density, which is obtained from the local darkness in the halo, at every sensitive layers in EC. The curves are those which are produced by  $N_\gamma$   $\gamma$ -rays with energy  $\langle E \rangle$ , tabulated in Table 1, incident upon EC.

We assume that the halo is produced by a bundle of high energy  $\gamma$ -rays in the air shower.<sup>1</sup> Then, according to the cascade theory[Nishimura, (67)], the maximum depth  $t_{max}$  of the transition curve of the halo is given by

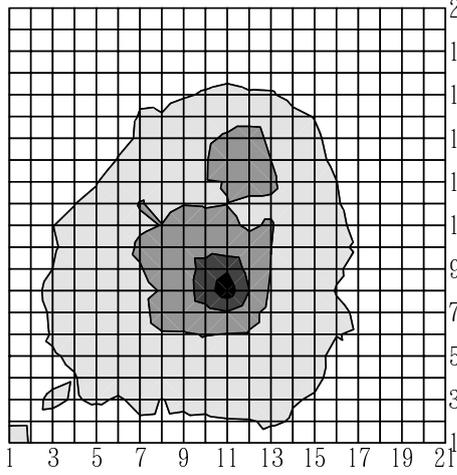
$$\ln \frac{\langle E \rangle}{\epsilon} = \lambda'_1(s) t_{max} \simeq t_{max}$$

where  $\epsilon = 7.4 \text{ MeV}$  is the critical energy of Pb and  $\langle E \rangle$  is the average energy of  $\gamma$ -rays, incident upon EC. Since  $t_{max} \simeq 14 \text{ c.u.}$ , we have  $\langle E \rangle = 8.9 \text{ TeV}$ . Three curves in Fig. 1 are the transition curves of total electron number for the cases in Table 1. Fig. 1 shows that the case of  $\langle E \rangle = 10 \text{ TeV}$  describes the data best among the three, giving the total observed energy 750 TeV in the halo.

<sup>1</sup>Strictly speaking, photons and electrons. We will refer to them as  $\gamma$ -rays, following the EC terminology.

**Table 1.** Energy and number of  $\gamma$ -rays, incident upon EC, to produce the halo.

$\langle E \rangle$ (TeV)	$N_\gamma$	$E_{halo}$ (TeV)
5	145	725
10	75	750
20	36	720



**Fig. 2.** The contour map (1 div. = 500  $\mu\text{m}$ ) of the darkness  $D$  in the halo at the depth 14 c.u., where the total number of electrons attains the maximum development approximately. The steps of the contours are  $D = 0 \sim 1.0, 1.0 \sim 2.0, \dots$

We try to estimate the energy spectrum of  $\gamma$ -rays, incident upon EC, from  $\langle E \rangle = 10$  TeV and  $N_\gamma = 75$  the transition curve of which gives the best-fit to the experimental data. Assuming the energy spectrum as

$$N_0 \gamma \left( \frac{E}{E_{th}} \right)^{-\gamma-1} d \left( \frac{E}{E_{th}} \right), \quad (1)$$

we have

$$\langle E \rangle = \frac{\gamma}{\gamma - 1} E_{th} \quad \text{and} \quad N_\gamma = N_0,$$

where  $N_0$  is the number of  $\gamma$ -rays at  $E = E_{th}$ . That is, if we assume the exponent  $\gamma$ , we can obtain the energy spectrum which is tabulated in Table 2.

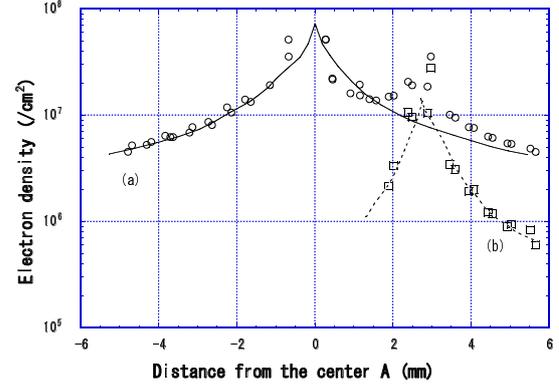
The energy spectra of  $\gamma$ -rays for the cases in Table 2 are shown in Fig. 4, together with experimental data of  $\gamma$ -rays found outside the halo. We consider that the latter spectrum is biased due to the masking by the halo but is not biased seriously in the low energy region. Consequently we have a conclusion in Fig. 4 that the case of  $\gamma = 1.75$  in Table 2 is the best among the three.

## (2) Lateral distribution of the halo

The contour map of the darkness  $D$  in the halo (Fig. 2) shows that the halo contains two high energy cores, A and B

**Table 2.** Energy spectrum of  $\gamma$ -rays to produce the halo

$\gamma$	$E_{th}$ (TeV)	$N_0$
2.0	5.0	75
1.75	4.3	75
1.5	3.3	75



**Fig. 3.** Lateral distribution of electron density along the line to connect the cores A and B. Circles are the experimental data and the squares are after subtraction of the curve (a) which is the best-fit to the data points of the core A.

(with  $A > B$ ). Fig. 3 shows the lateral distribution of the electron density along the line to connect A and B, at the depth of 14 c.u. where the total number of electron attains the maximum development approximately. The curves (a) and (b) in Fig. 3 are the best-fit to the data points, assuming that the distribution is symmetric around the core center. The maximum values of the distribution for A and B are used to estimate the energies of the cores A and B, which are tabulated in Table 3.

It is worthy mentioning that the assumed lateral distributions appear to be wider than that of the electron density in the cascade theory. But quantitative discussion is not easy because the observed region is quite limited, compared with 1 Moliere unit 1.62 cm.

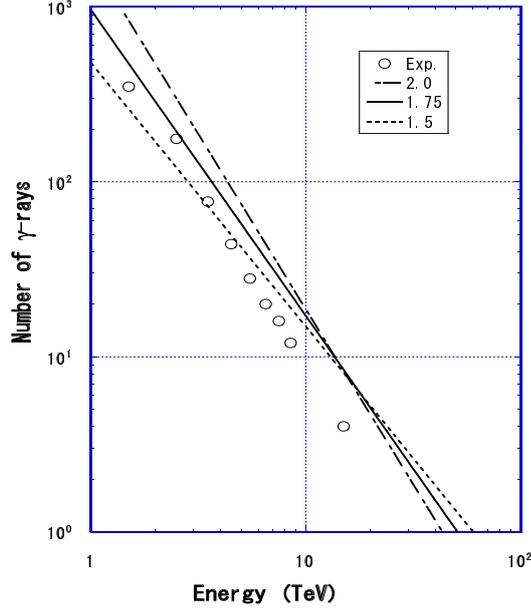
## 3.2 Individual showers

Several tens of  $\gamma$ - and hadron-origin showers are distributed over an area of  $r \sim 10$  cm. Routine process of EC measurement gives shower energies and shower starting points  $\Delta t$  for respective showers. Showers with  $\Delta t > 6$  c.u. are defined as those of hadron-origin and the rest those of  $\gamma$ -origin. By this definition 15 % of the hadron-origin showers are mixed up among  $\gamma$ -origin showers.

Fig. 4 shows the energy spectrum of  $\gamma$ -rays which are found outside the halo (*i.e.*  $r \geq 0.8$  cm). The number of  $\gamma$ -rays is corrected for the item 2, but the spectrum is still biased due to the item 1. The solid line is the estimated one from the

**Table 3.** The estimated energies of the cores in the halo

Core	Electron density at the	
	core center ( $/\text{cm}^2$ )	Energy (TeV)
A	$7.3 \times 10^7$	640
B	$1.3 \times 10^7$	110
Total		750



**Fig. 4.** Energy spectrum of  $\gamma$ -rays which are found outside the halo (corrected for the item 2). The lines are those which are assumed to produce the halo. (See Table 2.)

halo characteristics.

Fig. 5 shows the differential energy spectrum of the hadron-origin showers, which are found outside the halo by EC (the line (4)), together with that which is estimated from the data by HC (the line (5)). Consistency of both spectra may indicate that the event represents the average character of AS development without serious fluctuation.

#### 4 Summary

We analyzed a high energy event with a halo.

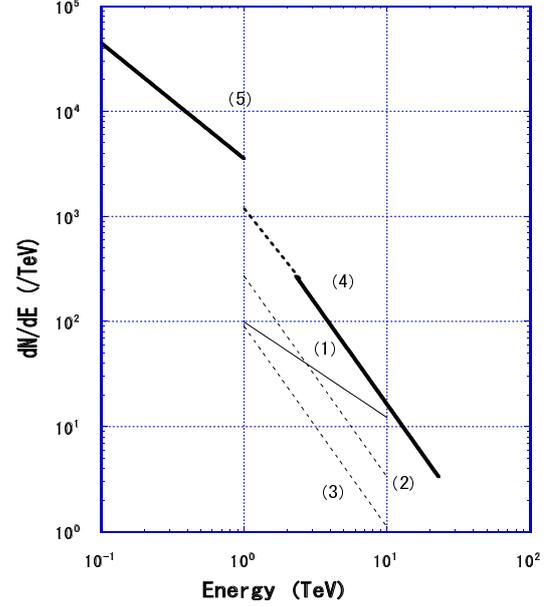
- (1) The accompanying air shower has the age  $s = 0.59$  and the size  $N_e = 7.03 \times 10^7$ .
- (2) The halo is produced by  $\gamma$ -rays with the total energy 750 TeV, which has the energy spectrum of eq.(1) with  $\gamma = 1.75$  and  $N_0 = 75$ . The energy spectrum is consistent with that of  $\gamma$ -rays which are observed outside the halo.
- (3) The two energy spectra of the hadron component in AS, by EC and by HC, are consistent with each other.

Following points will be discussed elsewhere.

- (1) Lateral distributions of  $\gamma$ -rays and hadrons.
- (1) How the events is observed at the sea level ?
- (2) Can a conventional model of hadron interactions produce the event ?

#### References

N. Kawasumi et al., Phys Rev. D, Vol. 53, 3534–3546, 1996.



**Fig. 5.** Differential energy spectrum of hadrons; the line (4) by EC (corrected for the item 1) and the line (5) by HC.

The line (1) is the integral energy spectrum of hadron-induced showers by EC, and the line (2) is the differential. Then corrections are made for the collision probability of hadrons (the line (3)) and for the conversion of observed energy to hadron energy  $k_\gamma$  (the line (4)). That is,  $E_{ob} = k_\gamma E_h$  with  $\langle k_\gamma \rangle = 1/6$ .

- C. Aguirre et al., Phys. Rev. D, Vol. 62, 032003-1–17, 2000.  
 K. Kamata and J. Nishimura, Prog. Theor. Phys. Suppl., 6, 93, 1958.  
 K. Greisen, Progress in Cosmic Ray Physics (North-Holland, Amsterdam), Vol. 3, 1958.  
 J. Nishimura, Handbuch der Physik (Springer, Berlin), Vol. 46/2, 1967.