A Halo Event observed by Hybrid Experiment at Mt. Chacaltaya

H.Aoki[1], K.Hashimoto[2], K.Honda[3], N.Inoue[4], N.Kawasumi[2], N.Martinic[5], C.Navia O.[6], N. Ochi[7], N.Ohmori[8], A.Ohsawa[9], L.Oliveira C.[1]0, K.Shinozaki[11], M.Tamada[12], R.Ticona[6] and I.Tsushima[2]
(1) Faculty of Science, Soka University, Hachioji, Tokyo, 192-8577, Japan
(2) Faculty of Education, University of Yamanashi, Kofu, 400-8510, Japan
(3) Faculty of Engineering, University of Yamanashi, Kofu, 400-8511, Japan
(4) Faculty of Science, Saitama University, Saitama, 388-8570, Japan
(5) Inst. de Inv. Fisicas, Univ. Mayor de San Andres, La Paz, Bolivia
(6) Dep. de Fisica, Univ. Federal Fluminense, Niteroi, Rio de Janeiro, Brasil
(7) Okayama University of Science, Okayama, 700-0005, Japan
(8) Faculty of Science, Kochi University, Kochi, 780-8520, Japan
(9) Inst. for Cosmic Ray Research, Univ. of Tokyo, Kashiwa, 277-8582, Japan
(10) Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brasil
(11) Max-Planck-Institut für Physik, Föringer Ring 6, 80805 München, Germany
(12) Faculty of Science and Eng., Kinki Univ., Higashi-Osaka, 577-8502, Japan

Abstract

An experiment of an air shower array, hadron calorimeter and an emulsion chamber is under way at Mt. Chacaltaya. One high energy event, having a halo in the center of the family by the emulsion chamber, is analyzed in detail.

1. Experimental setup

We have observed the families in the air shower with emulsion chamber (32 blocks, total area 8 m^2) installed at the center of air shower array at Mt. Chacaltaya(5200 m, Bolivia)[1][2]. We will report a high energy event which is remarkable for a large family with a halo ($\sim$ 1 cm of diameter) on X-ray films of emulsion chamber. A halo is made of large number electrons. The analysis of the halo which bears the information of air shower core, helps us to understand the detailed structure of air shower.

The air shower array covers an area about 50 m radius by 35 plastic scintillation detectors. 5 plastic scintillation detectors are located in the center of array to measure the arrival direction of the air showers. 32 blocks (0.25 m^2 each) of emulsion chambers are installed in the center of air shower array. The emulsion chamber consist of lead plates of 15 cm thick in total and 14 sensitive layers of two sheet of X-ray films which are inserted at every 1 cm lead plate.

pp. 73–76

Table 1. Air shower parameters of the present event

arrival time	20:59 13 Feb. 1985
arrival direction	$\theta = 8.3°$, $\phi = 24.7°$
size	$N_e = 7.03 \times 10^7$
age parameter	$s = 0.59$

Table 2. Halo and high energy particles observed by the emulsion chamber

	No. of showers	Energy sum(TeV)
(Inside the halo)		
Halo	–	$(7.2 \sim 7.5) \times 10^2$
γ-rays (See the text.)	–	8.5×10^2
(Outside the halo)		
γ-rays	176	6.4×10^2
Hadrons	40	2.8×10^2

2. Air shower and halo event

Table 1. and Table 2. show the data of the air shower and high energy particles which are obtained by the air shower array and by the emulsion chamber, respectively.

The present event hits the upper-left corner of one block (50cm $\times$ 50 cm) of the emulsion chamber with arriving angle of $\theta = 8° \pm 10°$ and $\phi = 65° \pm 10°$. Therefore a part of particles fell outside emulsion chamber, and the halo in the center of the event leaves emulsion chamber at large depth (12 cm Pb).

The opacity of the halo on X-ray film is measured by a microphotometer (with the slit of $200 \times 200\mu$ m^2) over the square area of 1 cm $\times$ 1 cm at 500 μm interval. The opacity is converted into the electron density. In this way we obtain the lateral distribution of electron density at every depths in the emulsion chamber. The transition curve of the total electron number in the halo is obtained by integrating the lateral distribution at every depths. We estimate that the total observed energy in the halo is $E_{total} = 720 \sim 750$ TeV from the total track length[3].

We assume that the halo and the γ-ray showers outside the halo are produced by high energy γ-rays in the air shower. And these γ-rays are assumed to have the energy-lateral distribution

$$\frac{\gamma N_0}{\pi}\left(\frac{E}{E_c}\right)^{-\gamma-1} d\left(\frac{E}{E_c}\right)\frac{E^2}{K^2}\theta\left(1-\frac{E^2r^2}{K^2}\right) \qquad (E_c = 1 \text{ TeV}) \qquad (1)$$

where $\theta(x)$ is the step function and K the cosntant to express the lateral spread.

The formula is the approximated of the three dimensional cascade function.

Then the γ-rays with $r \leq R$ ($R:$ the radius of the halo) in eq.(1) produce the halo whose transition curve is calculated as

$$\gamma N_0 \left(\frac{K}{RE_c}\right)^{-\gamma} \frac{1}{2\pi i} \int \frac{ds}{s(\gamma - s)} \left[1 + \frac{\gamma - s}{s + 2 - \gamma}\right] \left(\frac{K}{R\epsilon}\right)^s M(s)\sqrt{s} K_{1,0}(s, -s) e^{\lambda_1(s)t}$$

Comparing the transition curves of the total electron number in the halo by the experiment and the calculation we obtain $\gamma = 1.5$ for the best exponent value.

The γ-rays outside the halo ($r \geq R$) have the following energy spectrum in integral form from eq.(1).

$$N_0 \left(\frac{E}{E_c}\right)^{-\gamma} \left\{ \left[1 - \left(\frac{ER}{K}\right)^{\gamma}\right] - \frac{\gamma}{2 - \gamma} \left[\left(\frac{ER}{K}\right)^{\gamma} - \left(\frac{ER}{K}\right)^{2}\right] \right\}$$

for $E < K/R$ where R is the radius of the halo. The energy spectrum is 0 at $E > K/R$ and converges to $N_0(E/E_c)^{-\gamma}$ at $E \ll K/R$. The values of $\gamma = 1.5$ and $K/R = 10$ (TeV) describe the experimental data.

Using $\gamma = 1.5$, the family energy ($E_{th} = 2$ TeV) is obtained as

$$\sum E_\gamma \equiv \int_{E_{th}}^{\infty} E \, \gamma N_0 \left(\frac{E}{E_c}\right)^{-\gamma - 1} d\left(\frac{E}{E_c}\right) = \frac{\gamma}{\gamma - 1} N_0 E_{th} \left(\frac{E_{th}}{E_c}\right)^{-\gamma} = 1.4 \times 10^3 \text{ TeV}$$

The value is consistent with the sum of the halo energy $E_{halo} = 8.5 \times 10^2$ TeV and γ-ray energy outside the halo $\sum E_\gamma = 6.4 \times 10^2$ TeV.

3. Summary and discussion

(i) We have made a detailed analysis of a high energy event with a halo. The event is the first one in which the air shower and the halo have been observed simultaneously.

The halo and the γ-rays outside the halo are described by the γ-rays in the air shower core, which have the energy spectrum

$$N_0 \left(\frac{E}{E_c}\right)^{-\gamma - 1} d\left(\frac{E}{E_c}\right) \qquad (E_c = 1 \text{ TeV})$$

with $N_0 = 6.7 \times 10^2$, $\gamma = 1.5$ and the lateral spread of them is characterized by the constant $K = 5$ TeV·cm.

(ii) It is interesting to see the position of this event in the diagram of $\sum E_\gamma \; vs. N_e$. The diagram enabled us in our previous paper [1] to point out that nuclear interaction models used widely in simulations of cosmic-ray diffusion in the atmosphere do not describe the experimental data. This argument can be made without any particular assumption regarding the primary cosmic ray intensity.

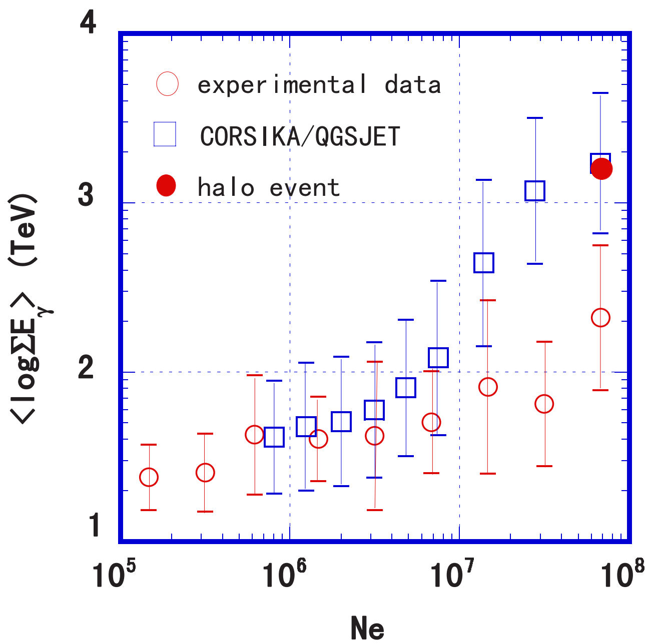

Fig. 1. Average value of $\sum E_\gamma$ in the family and air shower size N_e from the experimental data and the simulated events. The error bars signify the dispersion σ. The average value at $N_e = 7 \times 10^7$ is by 3 events including the present event.

Fig. 1. shows the present event together with other families. One can see that the present event has a higher value of $\sum E_\gamma$ than other events of similar air shower size, and that the average value of the experiment is still appreciably lower than that by the simulation. It indicates that the conclusion in the previous work[1] is valid. That is, the nuclear interaction changes its characteristics in the high energy region in such a way that the incident energy is subdivided more strongly.

4. References

1. N. Kawasumi *et al.*, Phys. Rev. **D53** 3534 (1996); K. Honda *et al.*, Nucl. Phys. B (Proc. Suppl.)**52B**, 528(1996)
2. C. Aguirre *et al.*, Phys. Rev. **D62** 032003 (2000); C. Aguirre *et al.*, Nucl. Phys. B (Proc. Suppl.) **97**, 158 (2001).
3. H. Aoki *et al.* Proccedings of ICRC2001 (Hanburg), **1**, 53 (2001)