OBSERVATION OF A HIGH-ENERGY COSMIC-RAY FAMILY CAUSED BY A CENTAURO-TYPE NUCLEAR INTERACTION IN THE JOINT EMULSION CHAMBER EXPERIMENT AT THE PAMIRS

Pamir Collaboration and Chacaltaya Collaboration

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0370-2693/87/$ 03.50 © Elsevier Science Publishers B.V. (North-Holland Physics Publishing Division)

Received 20 January 1987

An exotic cosmic-ray family event is observed in the large emulsion chamber exposed by the joint experiment at the Pamirs (4360 m above sea level). The family is composed of 120 γ-ray-induced showers and 37 hadron-induced showers with individual visible energy exceeding 1 TeV. The decisive feature of the event is the hadron dominance: $\sum E_\gamma$, $\sum E_h^{(\gamma)}$, $\langle E_\gamma \rangle$, $\langle E_h^{(\gamma)} \rangle$, $\langle E_\gamma \cdot R_\gamma \rangle$ and $\langle E_h^{(\gamma)} \cdot R_h \rangle$ being 298 TeV, 476 TeV, 2.5 TeV, 12.9 TeV, 28.6 GeV m and 173 GeV m, respectively. Most probably the event is due to a Centauro interaction, which occurred in the atmosphere at ~700 m above the chamber. The event will constitute the second beautiful candidate for a Centauro observed at the Pamirs.

Pamir joint emulsion chamber experiment. An exotic cosmic-ray family with visible energy ~770 TeV was found in a large emulsion chamber from the USSR–Japan joint exposure at the Pamirs (4360 m above sea level).

The joint experiment was planned and agreed on at the First International Symposium on Super-high energy cosmic-ray particle interactions, held at Nakhodka in October, 1980 [1]; both the USSR and Japanese sides were to contribute their own X-ray films and nuclear plates, the USSR side was to contribute the lead plates and the carbon blocks and was to take charge of the construction and recovery of the chambers. After recovery, both sides were to develop, in their respective countries, those respective parts of the films and plates they had contributed. Since that time, after several small-scale tests, four series of joint exposures have been carried out, in full accordance with the agreement.

The joint exposure was motivated by the need of an interface between the super-high energy cosmic-ray family data given by the Brazil–Japan Chacaltaya Collaboration and those given by the USSR–Poland Pamir Collaboration, the special aim being a further study of exotic nuclear phenomena, e.g., those belonging to the "Centauro species" [2], and of the halo phenomena associated with "super families" (see, e.g., ref [3]).

The chamber which recorded the present event, Chamber P-3′, is of the standard Pamir type as shown

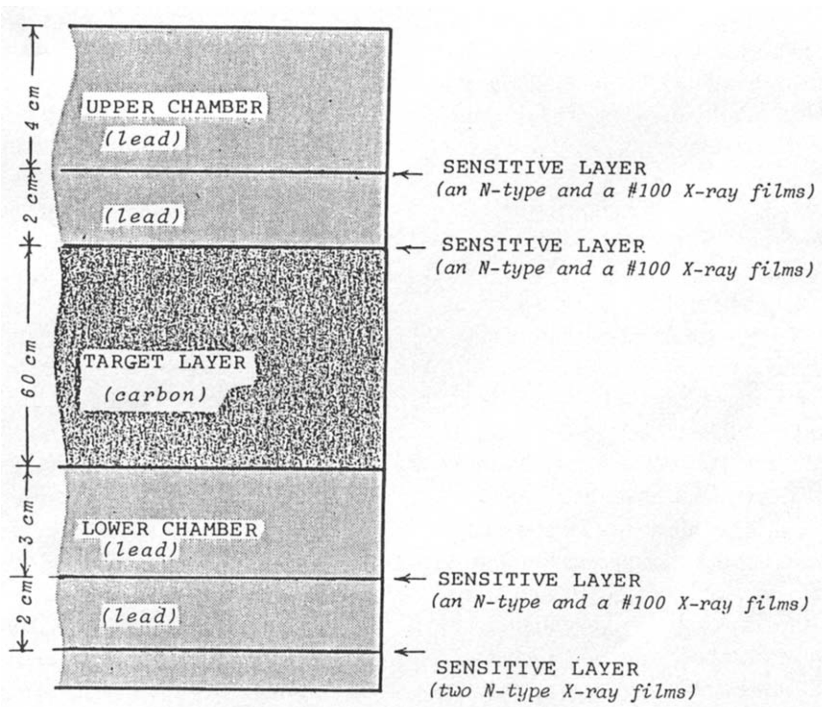

Fig. 1. Structure of the Pamir joint emulsion chamber P-3′.

in fig. 1. It consists of the upper detector (Γ-block) and the lower detector (H-block), with a carbon target layer in between. The showers recorded in the Γ-block are mainly due to γ-rays and electrons of atmospheric origin, with a small admixture of showers due to local hadronic interactions inside the Γ-block itself. The H-block detects the showers due to local hadronic interactions in the carbon target or in the H-block itself. Some Γ-block showers continue into the H-block, and they are, sometimes, of great importance.

In our third series of joint exposures, it happened that the preparation of some part of the Japanese materials was not completed in time for regular expedition to the Pamirs, so that the USSR group made two expeditions, a regular one in the summer to construct Chamber P-3, and an extra one in the autumn especially to construct an additional chamber, Chamber P-3′, with the Japanese materials which arrived late. For this reason, the photosensitive layers in Chamber P-3′ consist only of Japanese films and plates. The total area of the chamber is 170 m^2 and it was exposed for ~20 months beginning in October, 1983.

In the course of a quick survey for cosmic-ray family events, two amazing events have been found. One is a super family with a huge halo in its center, whose size and energy are comparable to those of the Chacaltaya event "Andromeda" [2]. The other is an extremely hadron-rich family of Centauro type, and it is the purpose of the present report to give a short account of the latter event.

Description of the event P3′-C2-B178. The present event happened to fall in "Chamber #2" of P-3′. The "X-ray films" consisted of two sheets of high-signal Konishiroku N-type films and one sheet of fine-grain Fuji #100 film.

The event was first found in the H-block, Block No. 178 of "Chamber #2" in P-3′, in the form of a family [2] composed of a big bundle of hadron-induced showers. Tracing back into the Γ-block, a family consisting of a large number of electromagnetic showers of rather modest energy was found just in the geometrical upstream of the former. The shower spots are clean, showing only very slight contamination due to atmospheric cascade processes. Continuation of the four Γ-block showers, starting near the bottom of the block, are identified also in the H-block family of showers, which confirms the consanguinity of the Γ-block showers and the H-block showers.

A glance at the films would suffice ro recognize the exoticity of the event, which shows every feature of a Centauro. Fig. 2 gives the photographs of the event on the X-ray films: (a) under 5 cm Pb of the H-block, (b) under 3 cm Pb of the H-block, (c) under 6 cm Pb of the Γ-block and (d) under 4 cm Pb of the Γ-block, respectively.

By a careful naked-eye scanning for dark spots on the films, 30 H-block showers and 127 Γ-block showers are found whose visible energies exceed 1 TeV. Shower energies are measured by applying microphotometry on individual shower spots.

An electron shower satisfying either or both of the following criteria is identified as of a hadronic origin:

(i) It is observable only under 6 cm Pb and below.

(ii) The change with depth of its film spot darkness deviates significantly from that of a pure electron–photon cascade shower.

30 H-block showers and 7 Γ-block showers are identified as hadron-induced according to the above criteria. Fig. 3 shows some examples of the showers satisfying criterion (ii). If they were to be pure electron–photon cascade showers, we should have to assign to them fantastically large energy values.

Fig. 4 gives the lateral distributions of (a) the hadron-induced showers and (b) the γ-ray-induced showers, with respect to the "family axis", i.e., the visible-energy-flow axis of the whole observed family. As is seen in the figure, most γ-ray-induced showers are concentrated within a circle of a few mm radius, while the hadron-induced showers are distributed wider.

Table 1 gives some main results of the measurement. In the table, the quantities pertaining to the showers of energy exceeding 4 TeV are shown in parentheses.

Peculiarities of the event as seen from the table are as follows. (i) Energy is mainly released into the hadron-induced showers. (ii) The average shower energy, $\langle E_{vis} \rangle$, is much higher for the hadron-induced showers than for the γ-ray-induced ones. (iii) The average lateral visible-energy spread, $\langle E_{vis} \cdot R \rangle$, where R is the distance of a shower from the "family axis", is much higher for the hadron-

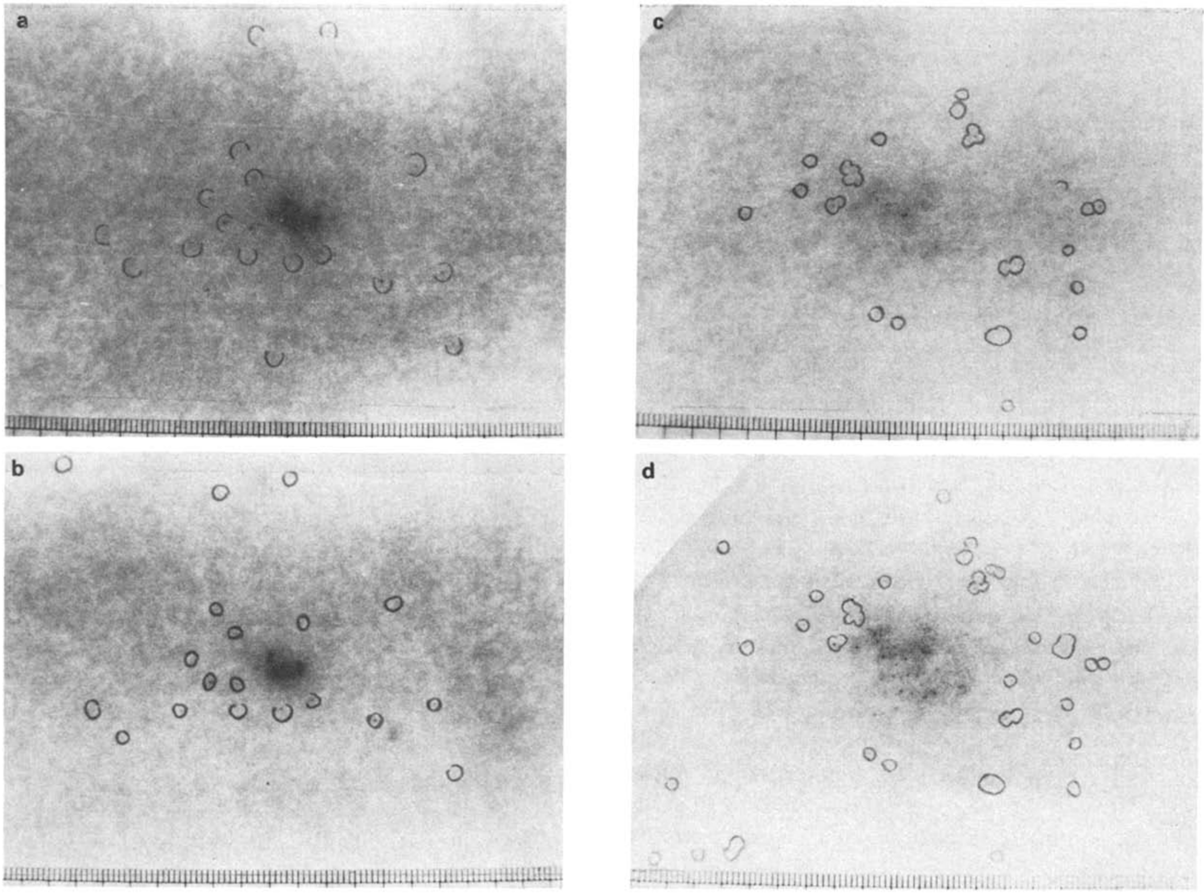

Fig. 2. Photographs of event P3′-C2-B178 as recorded on X-ray films: (a) under 5 cm Pb in the H-block, (b) under 3 cm Pb in the H-block, (c) under 6 cm Pb in the Γ-block and (d) under 4 cm Pb in the Γ-block. One unit of the accompanying scale equals 1 mm. The films used are Sakura N-type for (a), (b) and (d), and Fuji #100 for (c).

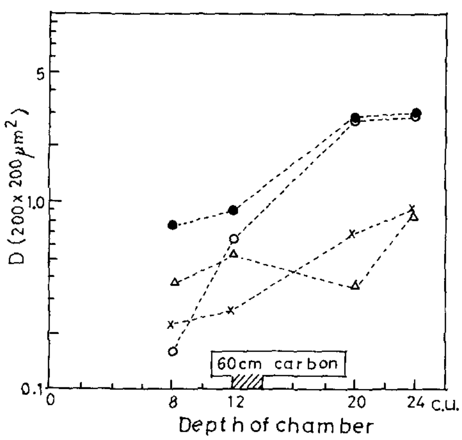

Fig. 3. Examples of highest-energy hadron-induced showers starting early in the Γ-block.

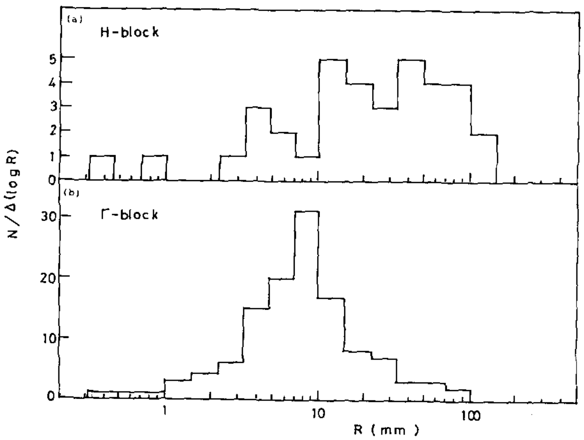

Fig. 4. Lateral distributions of the showers, where R stands for the distance of a shower from the "family axis": (a) hadron-induced showers and (b) γ-ray-induced showers.

Table 1
Some details of the family P3'-C2-B178. Incident zenith angle: $\theta = \arccos(0.86)$.

Shower inducing particle	Number of showers	Total visible energy (TeV)	Total visible energy (%)	Average visible energy (TeV)	Average lateral visible energy spread (GeV)
γ-ray	120 (15)	297.6 (95.2)	38 (18)	2.48 (6.34)	28.6 (67.0)
hadron	37 (22)	475.8 (443.7)	62 (82)	12.9 (20.2)	173.0 (244.2)

induced showers than for the γ-ray-induced ones. As a more specific presentation, fig. 5 shows the fractional visible-energy spectra, and fig. 6 the lateral visible-energy spread spectra, of the hadron-induced showers (●) and the γ-ray-induced showers (○), respectively. In both figures, a large difference is clearly observed between the distributions for the γ-ray-induced showers. The latter are concentrated within the regions of much smaller numerical values than the former. For the hadron-induced showers, both spectra can be well reproduced by exponential forms with the average values given in table 1. In fig. 5, the expected distribution for the γ-ray-induced showers, calculated on the basis of the theoretical distribution derived by Tamada for Centauro-type events [4] is also shown by a solid curve. (A more detailed account of the "expected distribution" shall be given in the next section.) The agreement between theory and observation seems satisfactory, especially so if we take into account the possible degradation due to atmospheric cascade processes. These features are no less than the signals indicative of a Centauro-type character of the event.

In order to show it more clearly, fig. 7 gives a scatter plot of the hadron multiplicity, N_h, against

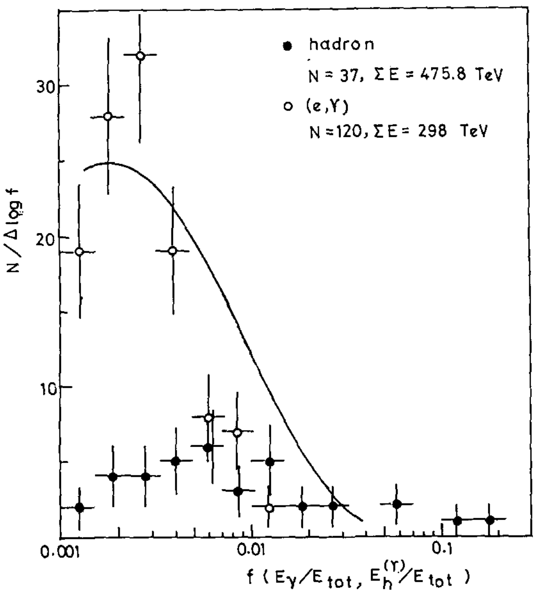

Fig. 5. Fractional visible-energy spectra of the hadron-induced showers (●) and the γ-ray-induced showers (○). Expected spectrum for the latter is shown by a solid curve. For details, see text.

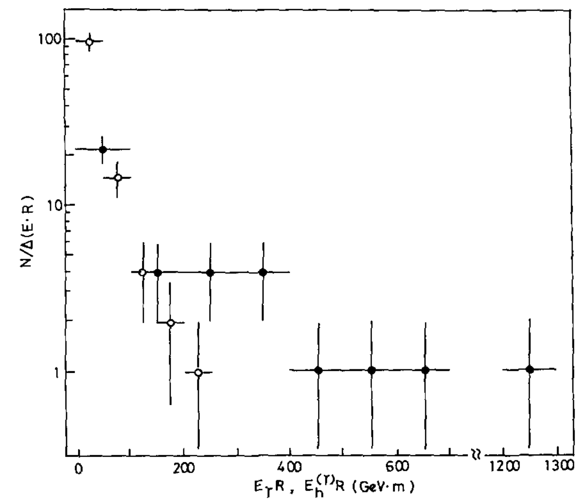

Fig. 6. Lateral visible-energy spread spectra of the hadron-induced showers (●) and the γ-ray-induced showers (○).

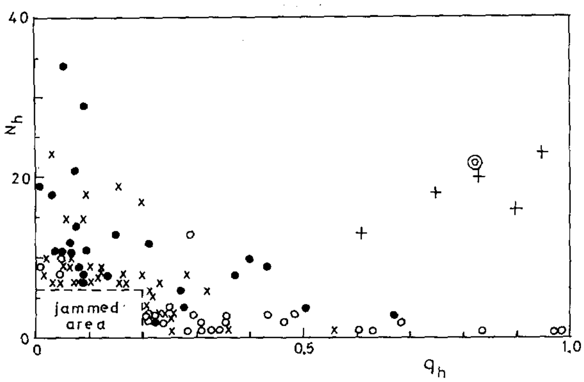

Fig. 7. N_h versus q_h scatter plot of event P3'-C2-B178 (◎) and Chacaltaya Centauro events (+), where N_h is the observed multiplicity of hadron-induced showers of visible energy not less than 4 TeV, and q_h is the hadron visible-energy fraction: $q_h = \Sigma E_h^{(\gamma)} / (\Sigma E_h^{(\gamma)} + \Sigma E_\gamma)$, where $\Sigma E_h^{(\gamma)}$ and ΣE_γ are the visible-energy sums of the hadron-induced and the γ-ray-induced showers, respectively, of visible energy not less than 4 TeV. Also shown, for comparison, is the simulation result by Shibata [5] for "nonexotic" families: ○ × and ● stand for a family originated by a primary proton, a primary nucleus with $2 \leqslant Z \leqslant 8$ and a primary nucleus with $10 \leqslant Z \leqslant 26$, respectively. In the figure, the area with $q_h \leqslant 0.1$ and $N_h \leqslant 6$, designated as "jammed area", contains 615 simulation family events.

the hadron visible-energy fraction, $\Sigma E_h^{(\gamma)} / (\Sigma E_h^{(\gamma)} + \Sigma E_\gamma)$, for the present event (◎) and for the Centauro's and Centauro candidates observed on Chacaltaya (+). The visible-energy threshold is set to be 4 TeV. In spite of some difference in structure between the Pamir and Chacaltaya chambers, the similarity of the events is clear.

As a reference, the simulation result by Shibata [5] is also presented in the figure. The simulation is designed in such a way as to fit the present experimental condition at the Pamirs, the total amount of exposure being set equal to 1000 m^2 yr, and assumes (i) ordinary type multiple meson production for nucleon–nucleon collisions [6], (ii) energy-dependent p–air–nucleus collision mean free path (see, e.g., ref. [7]) and (iii) normal chemical composition for the primary cosmic rays [8]. "Observed" showers in a simulated family are defined to be those contained, on the X-ray films, within an area of dimension 40 cm × 50 cm around the "family axis", which is now defined as the visible-energy-flow axis of the "observed" part of the family. Simulation family events satisfying the following criteria are accepted. (a) For both the "observed" γ-ray-induced showers and the "observed" hadron-induced showers, both the multiplicities and the visible-energy sums should exceed 3/4 of the total multiplicities and the total visible-energy sums. (b) The total "observed" visible energy of the family, $\Sigma E_h^{(\gamma)} + \Sigma E_\gamma$, should exceed 300 TeV. (c) Neither the average lateral visible-energy spread, with respect to the "family axis", of the hadron-induced showers, $\langle E_h^{(\gamma)} \cdot R_h \rangle$, nor that of the γ-ray-induced showers, $\langle E_\gamma \cdot R_\gamma \rangle$, should exceed 300 GeV m.

As will be seen in the figure, the present event falls right inside the "Centauro-type region", where no ordinary event can gain access even in its extreme fluctuation tail.

Reconstruction of the original interaction. The peculiar characteristics of the present family shown above induce us to study the event under the hypothesis of a Centauro interaction which should have happened close above the chamber.

The occurrence height of the main interaction in the present event, H, is estimated to be

$$H = (700 \pm 100)\ \mathrm{m}\,,$$

from the mean lateral visible-energy spread, (240 ± 30) GeV m, of hadrons with $\Sigma E_h^{(\gamma)} \geqslant 4$ TeV, with use of the $\langle p_{th}^{(\gamma)} \rangle$ value, 0.35 GeV/c, obtained from the Chacaltaya event Centauro I.

Fig. 8 shows the fractional visible energy spectra of the hadron-induced and the γ-ray-induced showers for the four Chacaltaya Centauro events. Fig. 8a shows the cases of Centauro I and II, which have occurred ~50 m and ~80 m, respectively, above the chamber. One sees that in these events γ-rays are practically absent. Fig. 8b shows the cases of Centauro IV and V, which have been interpreted as to have occurred ~500 m and ~400 m above the chamber. Comparing figs. 8a, 8b and 5, one will visualize how the γ-ray energy spectra get enhanced at the expense of the original hadron spectra, in passing through 400 – 700 m of atmosphere. At the same time, in figs. 5 and 8b, one recognizes the similarity in the manner how the spectra of the two types of showers differ. The difference is most pronounced in the present Pamir event, as (i) it has occurred at a little larger height above the chamber, (ii) it has

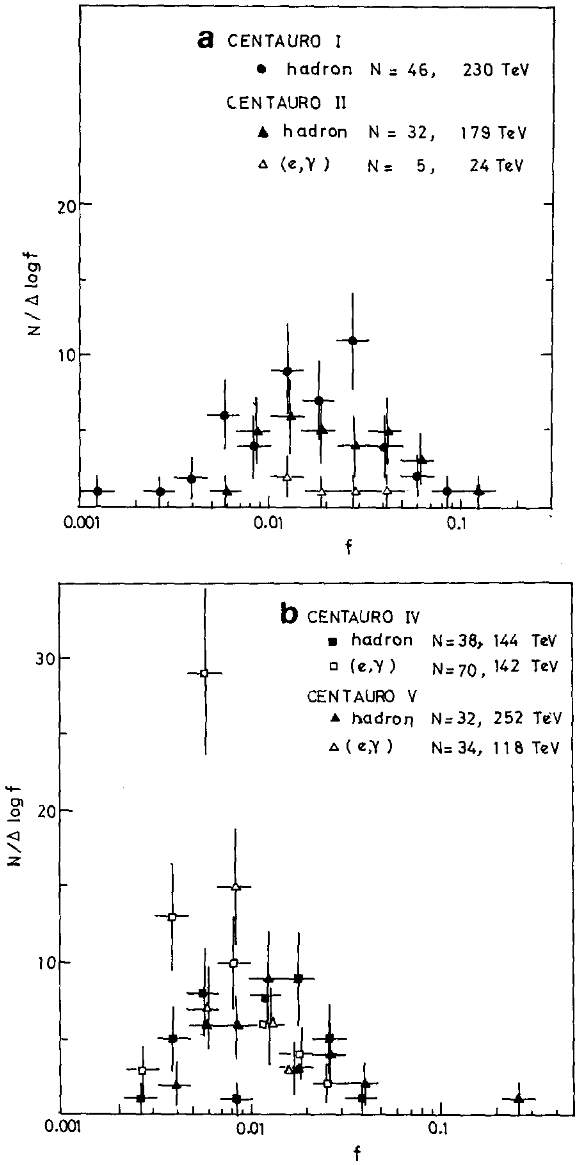

Fig. 8. Fractional visible-energy spectra of the showers in the Chacaltaya Centauro eveents. Full symbols: hadron-induced showers, open symbols: γ-ray-induced showers. (a) Centauro I: ●, ○; Centauro II: ▲, △; (b) Centauro IV: ■, □, Centauro V: ▲, △.

greater visible energy and (iii) the Pamir chamber has a higher detection efficiency for hadrons.

Now let us estimate the number of hadrons originally produced in the main interaction, in such a way as to compare the present event with Centauro IV [4], which has a similar production height. In Centauro IV, the bias-less detection threshold for shower energy is 1 TeV and the energy sum of all the showers with energy $\geqslant 1$ TeV is 284.3 TeV. In the present event, the energy sum of all the showers with energy $\geqslant 2.3$ TeV is 642.4 TeV, 2.3 times that of Centauro IV. Therefore we are allowed to seek for a parallelism between the two events, if we look at the showers with energy $\geqslant 2.3$ TeV. The number of observed target-layer-originated hadron-induced showers with $E_h^{(\gamma)} \geqslant 2.3$ TeV is 22, which falls right on the exponential extrapolation of the energy spectrum of the showers with $E_h^{(\gamma)} \geqslant 4$ TeV. From this, the numbers of hadron-induced showers starting in various other parts of the chamber can be estimated. 85 g/cm^2, 89 g/cm^2 and 186 g/cm^2 are adopted as the nucleonic interaction lengths in carbon, air and lead, respectively [2]. 60 cm carbon in the Pamir chamber amounts to 69 g/cm^2. A shower due to a nuclear collision at a depth <5 cm Pb in the Γ-block is classified as a "Γ-block shower", and sometimes defies distinction from the γ-ray-induced showers. On the other hand, a shower due to a collision at a depth >3 cm Pb in the H-block escapes detection. A shower due to a collision in between is classified as a "H-block shower". Table 2 gives the numbers estimated in this way. The correction for the track inclination due to the incident zenith angle of the event (arccos 0.86) has been taken into acount.

Now the 700 m thick atmosphere equals 0.54 λ_{int} at the Pamirs, so that one arrives at a hadron multiplicity at the original interaction of

$$N = 77 \pm 16 ,$$

Table 2
Estimated number of hadron-induced showers with $E_h^{(\gamma)} \geqslant 2.3$ TeV starting in various parts of the chamber.

	Thickness in γ_{int}	Number of hadrons
Γ-block	0.35	13 ± 3
carbon and H-block	1.2	22 ± 4.7
escape	–	10 ± 2
total sum	1.55	45 ± 12

which is to be compared with the corresponding multiplicity, 90, of Centauro IV.

On the basis of these numerical figures, the following picture of the present event is constructed. About 75 hadrons are produced at the original interaction. During the passage through 700 m of atmosphere, ~ 30 hadrons make secondary nuclear interactions, giving rise to a number of γ-rays, out of which ~ 120 are observed in the Γ-block. The remaining ~ 45 hadrons arrive at the chamber, out of which ~ 13 and ~ 22 make nuclear collisions within the lead of the Γ-block and within the carbon target layer and the lead in the H-block, respectively, leaving ~ 10 which traverse the whole chamber without making any observable interactions.

The picture presented above seems to be supported by the following fact. If one looks at the showers with visible energy exceeding 1 TeV, the average visible energies are 12.9 TeV and 2.5 TeV for the hadron-induced showers and the γ-ray-induced showers, respectively. This indicates that the average γ-ray multiplicity at the atmospheric secondary nuclear interactions with $\sum E_\gamma \sim 13$ TeV is ~ 5, which is consistent both with the number of atmospheric secondary interactions estimated above, and with the Chacaltaya C-jet data in the same energy region. If one wants to express it in a more sophisticated way, one looks at the fractional energy spectrum of the γ-ray-induced showers. The "expected distribution" in fig. 5 is the one calculated from the theoretical fractional energy distribution [4]

$$F(>E_\gamma) = \boldsymbol{a} \cdot \sqrt{4\boldsymbol{ax}} \cdot K_1(\sqrt{4\boldsymbol{ax}}) ,$$

with $\boldsymbol{x}$ and $\boldsymbol{a}$ reduced to $E_\gamma / \sum\sum E_\gamma$ and $N_{\mathrm{atm}} \cdot N_\gamma$, respectively, where N_γ is the average number of γ-rays with energy $>E_\gamma$ produced per interaction, N_{atm} is the number of hadrons which have made secondary interactions with γ-ray energy sum$>E_\gamma$, and $\sum\sum E_\gamma$ is the total observed energy sum of the showers induced by γ-rays of energies $>E_\gamma$. K_1 is the modified Bessel function of order 1. The curve in fig. 5 corresponds to the case where $\boldsymbol{a}=270$. N_{atm} for γ-ray energy sum >1 TeV is obtained as 47 by extrapolation from the value 32 estimated above for γ-ray energy sum >2.3 TeV. This gives us $N_\gamma \sim 6$, again consistent with the Chacaltaya C-jet data.

The joint experiment at the Pamirs is financially supported in part by a Grant-in-Aid for Scientific Research of the Ministry of Education, Japan.

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