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On the penetrating showers observed in Chacaltaya two-storey emulsion chambers(*)

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Summary. — The penetrating nature of the cascade showers observed in the Chacaltaya two-storey chamber is compared with that of simulated (e,γ)- induced and hadron-induced cascade showers. It is shown that around 1/3 of the observed penetrating showers are neither (e,γ)-induced nor hadron-induced ones. A possible explanation is given in connection with "mini-clusters".

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1. – Introduction

The Chacaltaya and Pamir emulsion chamber experiments have shown that there exist unusual phenomena which are not yet observed in the present accelerator experiments from the analysis of high energy cosmic ray families (a bundle of electromagnetic particles and hadrons produced in the nuclear and electromagnetic cascade process in the atmosphere [1]). Those are called "Centauro-species", multiple hadron production without association of π^0-mesons. It is also discussed that the nature of secondary particles is possibly different from that of ordinary hadrons in those unusual phenomena. In ref. [2] we discussed about unusual behaviour of cascade development of the high energy showers in high energy cosmic ray families observed by Chacaltaya two-storey chambers no. 18 and no. 19. We studied in detail how the shape of the transition curve on the spot darkness of the observed showers, which penetrate from the upper chamber down to the lower chamber, deviate from that of standard electromagnetic cascade showers expected in the uniform lead chamber. We found frequent existence of strong penetrating showers which became rejuvenated after passing through the target layer. The results were discussed in connection with "mini-clusters", clusters which consist of extraordinarily correlated γ-rays and hadrons [1,3]. Here we discuss the issue again by comparing the

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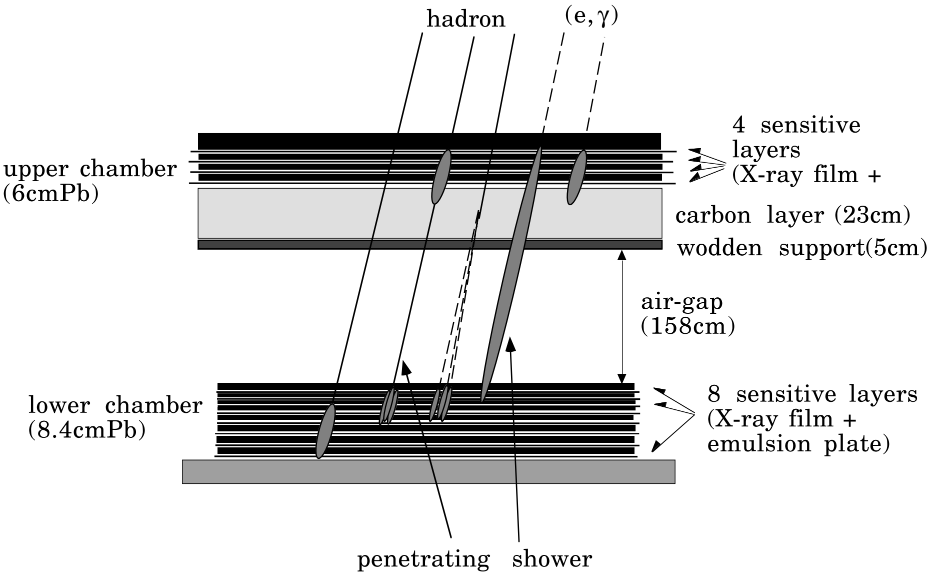

Fig. 1. – Illustration of Chacaltaya two-storey chamber no. 19.

penetrating probability of the cascade showers with those initiated by (e, γ) and also by hadron interaction taking into account the exact structure of the Chacaltaya two-storey chambers no. 18 and no. 19.

2. – Experimental data

2˙1. *The structure of the two-storey chambers.* – Figure 1 shows the basic structure of Chacaltaya two-storey chamber no. 19. The chamber consists of the upper chamber of 6 cmPb, the target layer of 23 cm carbon (petroleum pitch), wooden support of 5 cm thick, the air gap of 158 cm height and the lower chamber of 8.4 cmPb. Four sensitive layers (X-ray film and nuclear emulsion plate) are inserted in the upper chamber and eight sensitive layers in the lower chamber. In the chamber no. 18, the thickness of the upper chamber is 7 cmPb and 5 sensitive layers (composed of only X-ray films) are inserted. The other structure of the chamber no. 18 is just the same as that of the chamber no. 19. Showers detected in the upper chamber are mainly (e, γ)-induced ones with small admixture of hadron-induced ones. Showers detected in the lower chamber, on the other hand, are those initiated by nuclear interactions in the target layer (C-jets) and in the lead plates of the lower chamber itself (Pb-jet-lower).

2˙2. *Selection of the events.* – In the present analysis we pick up showers in the high energy cosmic ray families, observed by the Chacaltaya chamber no. 18 and no. 19, which satisfy the following conditions:

1) the total visible energy is greater than 100 TeV and

2) the event has at least two penetrating showers which are observed both in the upper chamber and in the lower chamber.

The latter condition is necessary to confirm the exact upper-lower correspondence.

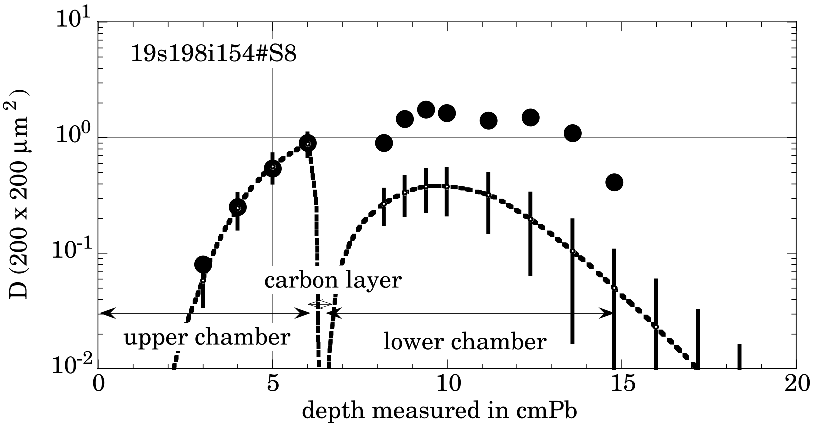

Fig. 2. – An example of the transition curve on spot darkness of the penetrating showers observed in Chacaltaya chamber no. 19. The dotted curve is an expected shower transition curve best fitted to the upper chamber data. Vertical bars are dispersion σ of the standard transition curve.

3. – Penetrating cascade showers

Some of the showers observed in the upper chamber can be followed down into the lower chamber. We define it as a *penetrating shower* when its spot darkness, D, measured by a micro-photometer with square slit of $200 \times 200\ \mu\text{m}^2$ on the the X-ray film, is larger than 0.2 in at least two layers in the upper chamber and at least one layer in the lower chamber. A typical example of the transition curve of the penetrating shower is shown in fig. 2. We summarise in table I the number of showers with visible energy $E(\gamma) \geq 10$ TeV observed in the upper chamber, those which penetrate into the lower chamber among them and those observed only in the lower chamber (C-jets, Pb-jets-lower).

4. – Simulations of cascade showers in the two-storey chambers

4˙1. *Hadron-induced showers.* – We use two different models for hadron-nucleus interactions, one is QGSJET [4] based on the Gribov-Regge theory of multiple Pomeron exchanges and the other is phenomenological UA5 algorithm [5] modified for hadron-nucleus interaction using a geometrical approach. In the nuclear cascade all hadrons, produced in the collisions during passage through the chamber, are followed until their energy falls below 80 GeV or they leave the chamber. The interaction mean free path of hadron-nucleus interactions is assumed to be the same for the above two models and to decrease with increasing interaction energy, *e.g.*, $\Lambda^{\text{p-Pb}}(E) = 15.9$ cm Pb, $\Lambda^{\pi\text{-Pb}}(E) = 17.5$ cm Pb, $\Lambda^{\text{p-C}}(E) = 62.4$ cm C and $\Lambda^{\pi\text{-C}}(E) = 79.4$ cm C at $E = 10^{14}$ eV.

Since the shower-spot formation is mainly determined by high energy γ-rays, we further calculate the three-dimensional electromagnetic cascade development in the chamber for γ-rays of $E_\gamma \geq 1$ GeV, which are mainly decay products of π^0's produced in the collisions, using the Monte Carlo code formulated by M. Okamoto and T. Shibata [6], in which the LPM effect is also taken into account. Electrons and photons are followed until their energies fall below 1 MeV. The electron number density, ρ_e, is converted to the local spot darkness, d, of X-ray film, by using the characteristic relation for the N-type X-ray film, and finally we obtain the transition curve of the spot darkness D, measured by a

TABLE I. – *Number of high energy showers,* $E(\gamma) \geq 10$ TeV*, observed in the chambers no.* 19 *and no.* 18.

	chamber no. 19		chamber no. 18
	Japanese part	all	all
Atmospheric families of $\Sigma E(\gamma) \geq 100$ TeV with at least two penetrating showers	15 events	32 events	14 events
(a) no. of showers observed in the upper chamber	110	188	111
(b) no. of penetrating showers among (a)	47 (61)	83[†] (108)	31 (45)
(c) no. of showers of observed only in the lower chamber (C-jets, Pb-jets-lower)	7	24	18
(d) expected no. of penetrating showers of hadronic origin (see sect. **5** in the text)	2.7 ± 1.0	9.1 ± 1.9	7.5 ± 1.8
(e) no. of (e, γ)-induced showers in the upper chamber (see sect. **5** in the text)	107 ± 10	179 ± 14	104 ± 10
(f) expected no. of penetrating (e, γ)-induced showers [(a)-(d)] (see sect. **5** in the text)	26 ± 2.5	44 ± 3.2	15 ± 1.5
(g) excess of penetrating showers over expectation [(b)-(d)-(f)] (see sect. **5** in the text)	18.3 ± 7.4	30.1 ± 9.8	8.5 ± 6.0

The number in the parenthesis in the raw (b) represents all measured penetrating showers where detection threshold darkness is $D_{\text{th}} \sim 0.1$.
(†) In the Chacaltaya chamber no. 19, full data of spot darkness of the penetrating showers was available at present for a half of the chamber which are measured in Japan. Hence the number of penetrating showers in all events in chamber no. 19 which satisfy the present definition is estimated from the number of all the measured penetrating showers by multiplying a factor 47/61, obtained in the Japanese part data.

200×200 μm^2 slit, *vs.* depth T throughout the chamber. The experimental error of the measurement of spot darkness D is also taken into account by adding noise ΔD in each spot darkness where ΔD is sampled from Gaussian distribution with $\sigma_D = 0.1D$. Protons and pions of $E_h \geq 20$ TeV are sampled from the energy spectrum $I(\geq E_h) \propto E_h^{-1.2}$ and from zenith angular distribution $I(\leq \cos\theta) \propto (\cos\theta)^{-17}$ (¹).

4˙2. *(e, γ)-induced showers.* – We also calculate electromagnetic cascade development in the chamber initiated by γ-rays and electrons using the above-mentioned Monte Carlo

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(¹) The attenuation length of the atmospheric families is usually considered to be $\lambda_{\text{att}} \sim 90$ g/cm². Then the zenith angle distribution of those is given by $I(\leq \cos\theta) \propto (\cos\theta)^{-8}$ at Chacaltaya. Due to the selection condition that the events have at least two penetrating showers, most of the selected events have small zenith angle and the zenith angle distribution of those becomes very steep.

TABLE II. – *Number of hadron-induced showers ($E_h(\gamma) \geq 10$ TeV).*

	chamber no. 19				chamber no. 18	
	QGSJET		modified UA5		QGSJET	
Incident	pion	proton	pion	proton	pion	proton
(a) penetrating	187	195	199	254	228	224
(b) visible only in the lower chamber	609	496	530	546	572	507
Ratio=(a)/(b)	0.31	0.39	0.38	0.46	0.39	0.44

In each set of the calculations, 2000 particles are sampled from the spectra described in subsect. **4**˙1.

code assuming the energy spectrum and zenith angle distribution of the (e, γ) arriving at the chamber as $I(\geq E_\gamma) \propto E_\gamma^{-2}$ and $I(\leq \cos\theta) \propto (\cos\theta)^{-17}$, respectively.

5. – Penetrating showers

Some of the hadrons interact with Pb-nucleus in the upper chamber and those hadron-induced showers can be visible in the upper chamber. According to the simulations, almost all hadron-induced showers in the upper chamber penetrate into the lower chamber. The number ratio of those penetrating hadron-induced showers to the showers visible only in the lower chamber (C-jets and Pb-jets-lower) is given in table II. As is seen in the table, the ratio is around 0.38 in the chamber no. 19 and 0.42 in the chamber no. 18 on the average. Then we can obtain the expected number of hadron-induced penetrating showers (given in (d) of table I) from the number of showers which are observed only in the lower chamber in the experiment (given in (c) of table I). The number of (e, γ)-induced showers in the upper chamber is then given by subtracting the above number of hadron-induced penetrating showers from the number of showers in the upper chamber and the result is shown in (e) in the table. The probability for (e, γ)-induced showers with $E_{e,\gamma} \geq 10$ TeV to penetrate into the lower chamber is summarized in table III. According to the simulations of the atmospheric families using CORSIKA/QGSJET code, the number ratio of γ-rays to $e^{\pm}$ in the families of $\Sigma E(\gamma) \geq 100$ TeV is found to be 2 to 1. Then the average penetrating probability of (e, γ)-induced showers is 0.245 for the chamber no. 19 and 0.145 for the chamber no. 18. The expected number of penetrating showers of (e, γ) origin is calculated using those penetrating probabilities and is shown in (f) of table I, around one half of the observed penetrating showers can be considered to be (e, γ) origin. The excess of the number of penetrating showers over the expectation (shown in (g) of table I) amounts to $\sim 37\%$ of all the penetrating showers in the chamber no. 19 (given in (b) of table I) and $\sim 27\%$ in the chamber no. 18 (given in (b) of table I), though the statistical error is rather large.

6. – Discussions

We have shown that around 37% (27%) of penetrating showers, $\sim 16\%$ ($\sim 8\%$) of all the showers in the upper chamber, observed in the Chacaltaya two-storey chamber no. 19 (no. 18) are neither (e, γ)-induced nor hadron-induced showers. One of the possible

TABLE III. – *Penetrating probability of γ-ray and electron-induced showers ($E_{\gamma,e} \geq 10$ TeV).*

	γ-ray	electron	(e,γ)
Chamber no. 19	0.26	0.23	0.245
Chamber no. 18	0.17	0.12	0.145

In each set of the calculations, 2000 particles are sampled from the spectra described in subsect. **4**˙2. The figure in the last column is obtained assuming the number of γ-rays is two times more than that of $e^{\pm}$ in the atmospheric families.

explanations is to assume the occurrence of extremely collimated pair of a γ-ray and a hadron. That is, if the mutual distance between a γ-ray and a hadron is extremely small, *e.g.*, less than ~ 1 mm, and the γ-ray-induced shower is observed in the upper chamber and the hadron-induced shower is observed in the lower chamber, we would possibly misidentify those two as a penetrating shower. If a γ-ray make electromagnetic interactions in the atmosphere, we can observe collimated several (e,γ)-particles and a hadron as a “mini-cluster” which are often found in the exotic events. Possible existence of hadron-bundles in which the mutual distance of the constituent hadrons is extremely small is also discussed in the analysis of transition curve of high energy hadronic showers observed in the Pamir thick lead chamber [7,8].

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