Structure of Super-Families

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I. Introduction.

At present study of nuclear interactions induced by cosmic rays is the unique source of information on the nuclear interactions in the energy region above 10^{15} eV. The phenomena in this energy region are observed by air shower array or emulsion chamber installed at high mountain. Emulsion chamber is the pile of lead plates and photo-sensitive layers (nuclear emulsion plate and/or X-ray films) to detect electron showers. High spatial resolution of photographic material used in the emulsion chamber enables us to observe the phenomena in detail, and recently experiments of emulsion chamber with large area are being carried out at high mountains by several groups in the world [1].

They are to observe the mixture of high energy hadronic and e.m. (= electromagnetic) particles produced through the nuclear and e.m. cascade process in the atmosphere, induced by high energy primary cosmic rays. The phenomenon observed by the emulsion chamber is called family, and that with high energy (say, $\Sigma E_\gamma > 10^{15}$ eV) is called super-family.

All the super-families, observed so far, consist of, on N-type X-ray films of high sensitivity, the black core and halo of radius 1 $\sim$ 3 cm in the center (called halo) and several hundreds of shower spots scattering over $\sim$ 30 cm around the center. It is found by the microscopic observation in the nuclear emulsion plates that the halo is made of numerous number of electrons distributed densely and continuously, and that there exist many high energy shower spots even inside the halo.

Super-families carry the information of high energy nuclear interaction. However, since the events are very complicated, it is most important, we think, at first to make clear the whole structure of the events from the observed data. In other words the first step is to make clear how is the behaviour of the showers incident upon the chamber, and the second is what can produce such behaviour of the showers on the chamber. For the purpose of the first step we assume an appropriate function of energy-lateral distribution for the particles produced through the cascade process, and examine the inter-relation between the halo and detected high energy showers.

The five events analysed here are those with the energy above 10^{15} eV, observed by the series of emulsion chamber experiment at Mt. Chacaltaya (5,200 m, Bolivia), carried out by Brazil-Japan collaboration. Those are among 14 events, observed so far, and the rest are under measurement and analysis. Full description of the events is made elsewhere [2]. Table 1 gives a summary of the events.

II. Energy-Lateral Distribution of Showers

We here approximate the energy-lateral distribution of high energy showers incident upon the chamber, $F(E,r)\,dE\,2\pi r\,dr$, to be,

$$F(E,r) = AC\, r^{s-1} \exp\left[-\frac{1}{\sigma^2}\left(\ln\frac{Er}{a}\right)^2\right] \qquad (1)$$

The distribution, Eq.(1), has the following nature which is fundamental for the particles produced through the cascade process.

(1) The relation, $Er \sim a$, holds with the dispersion σ around $Er = a$ in log-scale.

(2) Integration with respect to r gives the energy spectrum of, $2\pi A(E/a)^{-s}/E$.

The parameters in Eq.(1) are four; A relating to the absolute number of showers, s to the power index of the energy spectrum, a to the lateral spread and σ to the dispersion around the average of the lateral spread. And we determine the four parameters by comparing the energy spectrum and Er-distribution, obtained from the Eq.(1), with the experimental data.

The parameter values determined are tabulated in Table 2 for e.m. and hadronic particles. As to Urça Maior, only several showers have large Er-values and it is difficult to fit the distribution by one set of values.

(a) Lateral distribution of high energy showers.

Fig.1 shows how the lateral distribution, Eq.(1), of high energy e.m. showers, with the parameter values in Table 2, can reproduce the experimental data in case of Andromeda. The expected distribution can reproduce the experimental data in case of shower energy > 5 TeV and > 10 TeV, while the experimental data is short in number for E > 3 TeV. And the agreement becomes good if we adopt the observed number of showers at 3 TeV (the chain line in the figure) instead of the one extrapolated from the energy spec-

Table 1.

	Andromeda	Urça Maior	M.A. I	M.A. II	M.A. III
Halo	$\times10^{16}$	$\times10^{14}$	$\times10^{15}$	$\times10^{15}$	$\times10^{15}$
Total energy (eV)	(2.1±0.5)	(9.8±0.2)	(3.2±0.2)	(1.3±0.2)	(5.1±0.5)
e.m. (eV)	1.6×10^{16}				4.4×10^{15}
hadronic (eV)	5.3×10^{15}				6.6×10^{14}
High Energy Showers					
(1) Central region					
Observed number					
e.m.	288	113	96	24	264
hadronic	45	14(22)	11(73)	-	60(101)
Total obs. energy					
e.m. (TeV)	3,585	582	958	437	1,566
hadronic (eV)	1,401(3,417)	281(439)	143(953)	-	516(875)
(2) Outer region					
Observed number					
e.m.	322	108	50	89	227
hadronic	75(183)	25(39)	2(13)	-	92(166)
Total obs. energy					
e.m.	833	355	212	520	782
hadronic	317(773)	267(417)	8(53)	-	622(1,054)

[Numbers in the parenthese are the corrected ones due to the detection efficiency for hadrons.]

trum. The agreement is good for M.A. I, II and III.

Fig.2 is that for the hadrons in the case of Andromeda. Deviation of expected distribution from the experimental data, suggests the hadron distribution is rather of exponential type.

(b) Comparison with halo data.

In this paragraph we examine whether the energy-lateral distribution, Eq. (1), with the parameter values in Table 2, can reproduce the behaviour of the halo. It is to see the behaviour of low energy showers, incident upon the chamber and not to be observed individually.

Energy cut, E_{th}, at the low energy side is necessary to be introduced to reproduce the transition curve of the total electron number in the halo. The values of E_{th} for the events are listed in Table 2. One can see the values for four events except Andromeda are similar to the value of detection threshold of high energy showers of $E_d \sim 3$ TeV. It indicates the observed high energy showers are sufficient to produce the halo in the chamber. In the case of Andromeda the behaviour of the transition curve necessitates a number of low energy showers with the average energy of ~ 0.4 TeV. However, if we assume those showers follow the distribution of Eq. (1), those showers should fall around $r = z_{max} / E = 25$ cm, far from the central region.

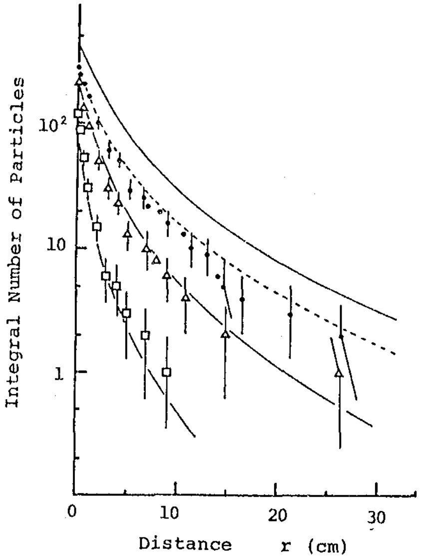

Fig.1. Lateral distribution of e.m. particles in integral form (Andromeda). The marks are for different energy thresholds; ● for E > 3 TeV, Δ for E > 5 TeV, and □ for E > 10 TeV. The curves are the expected ones from the assumed energy-lateral distribution with parameter values given in Table 2. The chain line is the case when we adopt the observed number of showers instead of the one expected from the parameter values listed in Table 2.

Table 4

Event	$A(\mathrm{cm}^{-s})$	s	a(TeV·cm)	σ	E_{th} (TeV)	z_{max} (TeV·cm)
(e.m. particles)						
Andromeda	7.8×10^2	1.36	6.7×10^{-1}	1.5	0.1	10.4
Urca Maior	-	1.87	-	-	2.0	-
M.A. I	9.8×10^6	1.94	7.5×10^{-3}	2.0	1.3	3.0
M.A. II	8.3×10^2	1.17	1.0×10^{-1}	2.0	1.0	8.2
M.A. III	5.6×10^5	1.85	2.1×10^{-2}	2.0	2.0	5.7
(hadrons)						
Andromeda	1.9×10	0.97	2.0	1.5		5.0
Urca Maior	-	0.94	-	-		-
M.A. III	8.6×10^2	1.25	2.6×10^{-1}	2.0		38.0

[z_{max} is the value of Er where Er-distribution becomes the maximum.]

The fact that those showers exist inside the halo to contribute to the transition curve, indicates that they have smaller lateral spread. If these particles have the lateral spread characterized by the e.m. cascade process, their spread is, $r = z_{max}(e.m.)/\ E = 1.5$ cm, which is consistent with the size of the halo.

It means Andromeda consists of two different kind of showers; one is characterized by $z_{max} = 10$ TeV·cm and the other by $z_{max} = 0.6$ TeV·cm. The former value may be due to nuclear cascade process and the latter due to pure e.m. cascade process.

The lateral distribution of the halo in Andromeda, in terms of track length density, is also consistent with the conclusion of two component of showers, stated above.

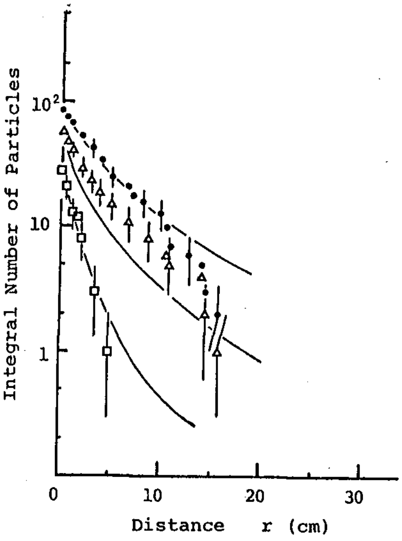

Fig.2 Lateral distribution of hadrons in integral form (Andromeda). See the caption of Fig.1 for the explanation of marks and curves.

III. Conclusion.

We analysed five highest energy events, $\Sigma E_\gamma > 10^{15}$ eV, observed by Chacaltaya emulsion chamber experiment. The results are;

(1) We tried to approximate the behaviour of high energy showers, e.m. and hadronic, by the function Eq.(1). The behaviour of e.m. particles can be described well by Eq.(1), both longitudinally and laterally, while hadrons have the lateral distribution of rather exponential type.

(2) We examined whether the halo can be explained by extrapolating the shower energy to lower energy side in Eq.(1). The four events except Andromeda can be explained by the behaviour of the observed high energy showers, while, as to Andromeda, low energy showers with average energy ∿ 0.4 TeV contribute significantly. And these showers has the spread consistent with that of pure e.m. cascade showers.

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