Notas de Física - Volume XII - Nº 14

NUCLEAR INTERACTIONS PRODUCED IN THE EMULSION CHAMBER

M. Akashi, Z. Watanabe
Hirosaki University

J. Nishimura, K. Niu, T. Taira
Institute for Nuclear Study

N. Ogita
Institute of Phys. and Chem. Research

K. Ogata, Y. Tsuneoka, K. Shirai
Kwansei Gakuin University

A. Misaki, I. Mito, K. Sishikawa, Y. Oyama, S. Hazama
Konan University

A. Nishio
Kyoto University

I. Ota, S. Dake, K. Yokoi, M. Sakata, T. Yuda, K. Mizutani
Nagoya University

Y. Fujimoto, S. Hasegawa, A. Osawa, T. Shibata, T. Suzuki
Waseda University

C. M. G. Lattes, C. Q. Orsini, I. G. Pacca,
M. T. Cruz, E. Okuno, T. Borello, M. Kawabata,
S. Hasegawa*, J. Nishimura*
Universidade de São Paulo

and A. M. Endler
Centro Brasileiro de Pesquisas Físicas

(Received January 19, 1967)

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[*] **Staying in São Paulo at the first stage of the analysis.**

ABSTRACT:

Large emulsion chamber (6 m^2 in area, 29 cm Pb thick) were exposed at Mt. Chacaltaya (5200 m) for about 10 months with a collaboration of Japanese and Brazilian emulsion groups.

Several hundred γ rays incident upon and nuclear events produced in the chamber with energy higher than 2.10^{12} eV are observed and the results are reported. The results of observation at Mt. Norikura (2800 m) carried out by Japanese group are also included.

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Since 1962, the collaboration work [1] on the observation of high energy cosmic ray events at Mt. Chacaltaya (5200 m, 550 gr/cm^2) with huge emulsion chamber has been carried out by the Japanese and Brazilian emulsion group. Similar observations have also been carried out by Japanese group at Mt. Norikura since 1958. [2]

The chambers which have been exposed are shown in Table 1 and Fig. 1.

Table 1

List of Exposures

Norikura

	Area	Area × Time	Total Thickness
1959	3.0 m^2	1.2 m^2 year	4 cm Pb
1960-I	7.2	6.0	4
1960-II	1.6	0.2	10
1961	5.4	2.7	5
1962	14.0	14.6	6
Total	31.2	24.8	

Chacaltaya

	Area	Area × Time	Total Thickness
1962-I	0.4	0.05	6
1962-II	1.2	0.3	6
1962-III	6.0	1.2	6
1963	5.6	2.8	10
1964	6.0	5.25	29
Total	19.2	9.6	

Here the report is made about the results observed in the chambers of 6 m^2 area, 29 cm Pb thick exposed at Mt. Chacaltaya for 319 days during 1964. The thickness of the chamber is about 2 nuclear interaction mean free path. Therefore we have enough chance to observe the high energy nuclear interactions as well as high energy γ rays incident upon the chamber.

The observation of nuclear active components in the γ ray families enables us to make more detailed analysis of extremely high energy nuclear interactions, results of which are reported in a separate paper [3] in this proceeding.

Design of the Chamber

As shown in Fig. 1, the chamber consists of 20 layers of lead plates, and in each layer 3 sheets of N type films and one ET7A (50μ thickness) are inserted. In the upper part of the chamber the photographic plates were placed in every 1 cm Pb separation, and in the lower part of the chamber they were placed with the separation of 2 cm Pb.

Scan and Energy Determination of γ Rays and Nuclear Events Produced in the Chamber

High energy electron showers developed in the chamber are registered by a dark spot on N type films. The naked eye scanning to find these dark spots was made over the area of 5.2 m^2 out of 6 m^2. Corresponding to the place of dark spot, one find the shower tracks on the emulsion plate placed just under N type film. The counting of the shower tracks within a certain circle was made under the microscope, and by comparing with the theoretical curve,[4] the energy of the shower was determined. The opacity measurements were also made for the dark spot registered on N type films with a slit of a circle of radius 150 μ, and the energy was determined by the comparison of the theoretically expected value.[5]

The energy determined by the photo-metric method agree fairly well with that obtained by the counting method as shown in Fig. 2. The details of the photometric energy determination will be published in else where.[6]

Absolute Flux and the Energy Spectrum of γ Rays and Jets Produced in the Chamber

γ rays incident upon the chamber developed into cascade shower at the upper layers of the chambers, while the starting depths of nuclear events were distributed over the wide regions as shown in Fig. 3.

Thus the each event can be separated in a statistical way.

First we classified as jets those of observed starting place is below 6 cm Pb, and as a γ ray if the starting depth is observed less than 5 cm Pb. The possible contaminations of jets in γ rays in this classification are subtracted to get a reliable γ ray flux value.

a) γ rays

688 γ rays with energy higher than 2.10^{12} eV were observed in the thick chamber. Considering the possible detection biases near around 2.10^{12} eV, the energy spectrum of γ rays is shown for the energy region higher than 3.10^{12} eV. The results are illustrated in Fig. 4, together with the data [8] reported at the time of Jaipur conference.

The importance of the fluctuation on the γ ray flux due to the effect of the occurrence of the big families was pointed out already. [1]

In order to eliminate this effect, γ rays are separately treated whether they belong to the families or not, and the corresponding spectrum are defined as $F_{2\gamma}$ and $S_{2\gamma}$ respectively.

Here the families are defined as the events having at least two correlated γ rays.

As it was proved [1] the flux of $S_{2\gamma}$ is almost the same as $F_{2\gamma}$, the most probable value of the γ ray flux [9] and the exponent of the spectrum with energy higher than 3.10^{12} eV are

$$I_\gamma = 2\,S_{2\gamma} = (2.2 \pm 0.2) \times 10^{-10}/\mathrm{cm}^2 \text{ sec sterad.},$$

$$\gamma = 2.2 \pm 0.2 \;.$$

b) Jets produced in the chamber

The separation of the events are made as in the case of γ rays, whether it belongs to the families or not. 301 events with energy higher than 3 TeV are observed. After the corrections for probability of the penetration through the chamber, or for the **missinterpretation as** γ rays, one get the absolute flux of these nuclear active component as shown in Fig. 5 together with the data obtained from the analysis of the families observed at Mt. Norikura.

The absolute flux and exponent of the nuclear active component are shown to be

$$S_J = (2.75 \pm 0.3) \times 10^{-10}/\mathrm{cm}^2 \text{ sec sterad.},$$

$$I_J = (3.95 \pm 0.4) \times 10^{-10}/\mathrm{cm}^2 \text{ sec sterad.},$$

$$\Upsilon = 2.0,$$

where S_J and I_J are the non correlated and total flux of nuclear active component respectively.

Jets Produced in the Chamber

a) Nuclear interaction mean free path

From the distribution of the observed starting depth of the jets one can derive the nuclear interaction mean free path of the high energy nuclear active component in lead.

The results are shown in Fig. 6, and

$$L = (202 \pm 20)\ \mathrm{gr/cm^2\ Pb} > 3\ \mathrm{TeV}$$

$$L = (182 \pm 28)\ \mathrm{gr/cm^2\ Pb} > 4\ \mathrm{TeV}\ .$$

In this case, the **correction** is made for the effect of inclination of the direction of the particles and for the effect of the thickness of the emulsions and their bases.

b) Successive interactions

Since our chamber is as deep as about 2 nuclear mean free path, some events make a successive interactions in the chamber as shown in Fig. 7. The residual nucleon **in** a family is some time observed. The liberated energy in the form of γ rays in the first act is called as E_1, and the second as E_2. Then, the frequency distribution with respect to E_2/E_1, can be compared with those calculated under the certain assumptions on the distributions of inelasticity coefficient in each nuclear event. The analysis of those events are shown in appendix 1 and as a result, the inelasticity of those nuclear events is about 0.5.

Discussions

The observations of the flux of high energy γ rays and nuclear active component observed in the chamber enable us to discuss the proportion of $\pi^{\pm}$ mesons in the nuclear active component at extremely high energy region. From the observed flux of γ rays, one can estimate the production rate of π^0 mesons in the atmosphere, thus giving us the information on the production rate of $\pi^{\pm}$ mesons. The estimation can also be made by using the observed results of the production spectrum [2] of $\pi^{\pm}$ mesons and nucleon in a family. Some details of those analysis are shown in appendix II.

Both results giving us the contribution of $\pi^{\pm}$ mesons to the jets produced in a chamber is about 30 ± 10 %, and others is mainly attributed by nucleons.

Thus the consistencies among those observed data are quite satisfactory.

As to the absolute flux of the nuclear active component here observed will be discussed in a separate paper in connection with high energy cosmic ray spectrum. [10]

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APPENDIX I

Analysis of Successive Interactions

The Monte Carlo calculation were made about the successive interaction to see the dependence of inelasticity in a collision on the frequency distribution with respect to E_2/E_1.

The calculations were made by assuming following several models.

a) Inelasticity is always constant

i) $K = 0.2$, ii) $K = 0.3$, iii) $K = 0.5$, iv) $K = 0.7$.

b) Inelasticity is uniformly distributed

  i) from 0.3 to 0.7.

  ii) from 0 to 1.0.

In every case an assumption was made that the part of liberated energy going to π^0 mesons is given by chance with the uniform distribution from 0 to 1 - K.

The spectrum of incident nuclear active particles is assumed $dE/E^{\gamma+1}$, where we took two cases of $\gamma = 2.0$ and 2.3. In each combined cases, calculation was continued to get 2000 events having at least one of E_1 or E_2 is larger than a threshold value.

Comparison with the observed data [11] is shown in Figs. A1a and A1b, and from this the nice fits are observed for the cases,

$K = 0.3$ and 0.5, if one assume $K =$ const.

$K = 0.3 - 0.7$ if one assume K have some distributions.

Similar argument can also be applied to the families having survival nucleons interacted in our chamber, and the distribution of E_2/E_1 is quite similar to those of the successive events observed in our chamber.

APPENDIX II

Estimate of the Contribution of $\pi^\pm$ Mesons to the Jets Produced in a Chamber

Assuming the production spectrum of π^0 mesons at a certain depth X' gr/cm^2 be

$$A \frac{E}{E^{\gamma+1}} e^{-X'} \Lambda \, dX' \ ,$$

the flux of γ rays and $\pi^{\pm}$ mesons at depth X can be calculated with the help of the electron shower theory and by assuming the interaction mean free path of $\pi^{\pm}$ mesons: L.

Table 2 shows the ratio of flux of $\pi^{\pm}$ mesons and γ-rays thus expected at Mt. Chacaltaya.

Table 2

Ratio of flux of $\pi^{\pm}$ mesons and γ rays at Mt. Chacaltaya

$R_1 = \pi^{\pm}/\gamma$ at the same energy of $\pi^{\pm}$ and γ rays
$R_2 = \pi^{\pm}/\gamma$ at the same energy of E_{Pb} and E_{γ}

	R_1		R_2	
L	80 gr cm^{-2}	90 gr cm^{-2}	80 gr cm^{-2}	90 gr cm^{-2}
$\gamma = 2$	2.85	3.72	0.25 - 0.71	0.33 - 0.93
$\gamma = 3$	3.25	4.25	0.08 - 0.41	0.12 - 0.53

The attenuation length Λ **is assumed** to be 110 gr/cm^2. ^{2}

For the evaluation of R_2, k_{γ} is assumed to be 0.4 ± 0.1.

Those values should directly be compared with the ratio of observed flux value listed in this paper,

$$\frac{I_J}{I_{\gamma}} = \frac{3.95}{2.2} = 1.79 \pm 0.25 \ .$$

From the inspection of Table 2, one may put the contribution of $\pi^{\pm}$ mesons to the jets between 15% and 50%. Others may mainly be attributed to nucleons.

From the production spectrum of nucleon and π mesons in a jet, which is presented in the reference 2, onde can estimate the ratio of contribution of $\pi^{\pm}$ mesons and nucleons.

In this case, the evaluation can made without referring to inelastic coefficient as can easily be understood. The ratio of the jets due to $\pi^{\pm}$ mesons to that of nucleons are estimated as 45 ± 20%, the results is quite consistent [12] with that derived from the analysis of the observed ratio of flux of nuclear active component to that of γ rays.

* * *

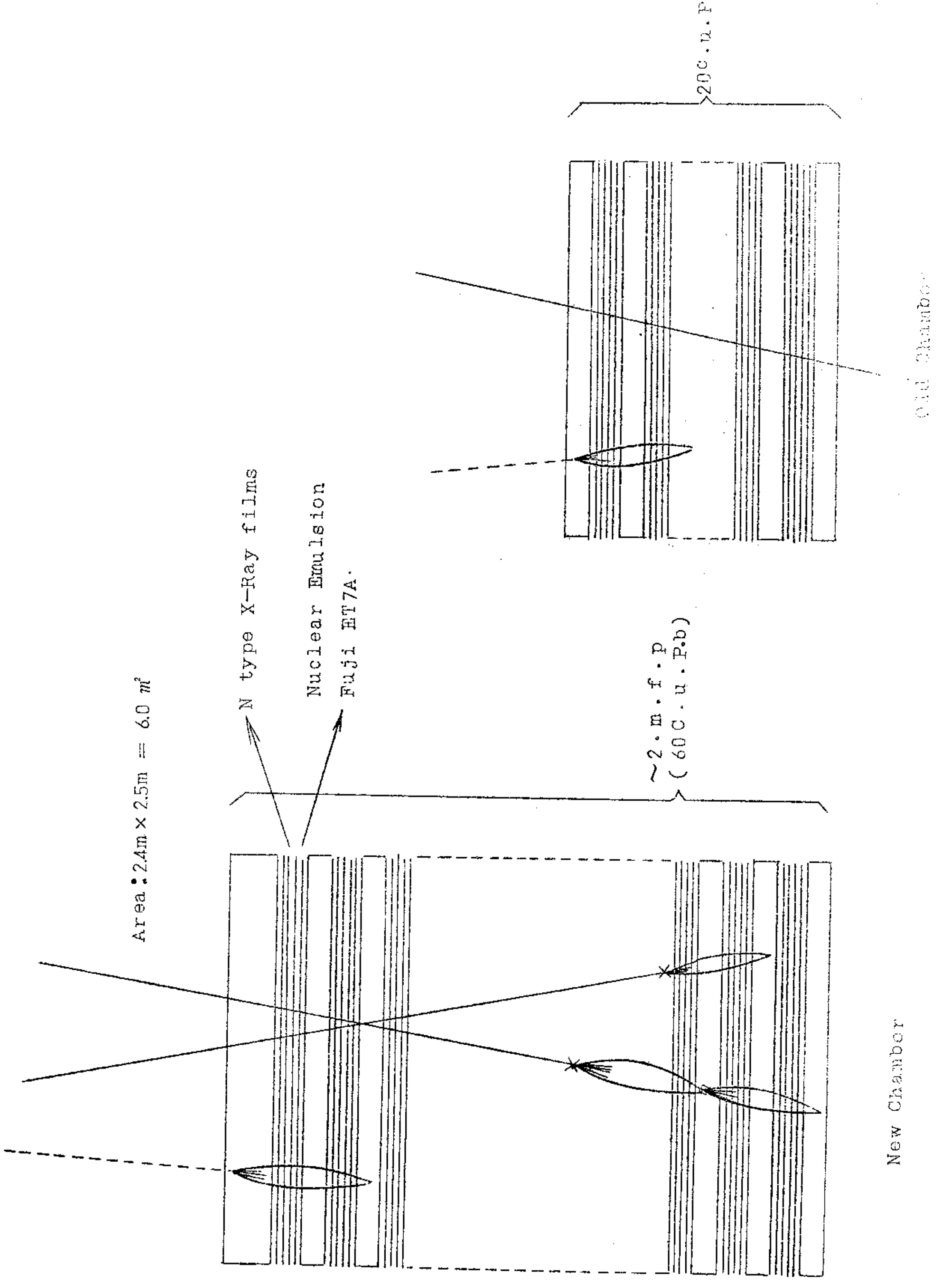

Fig. 1 - Design of the chamber

Nuclear groups.

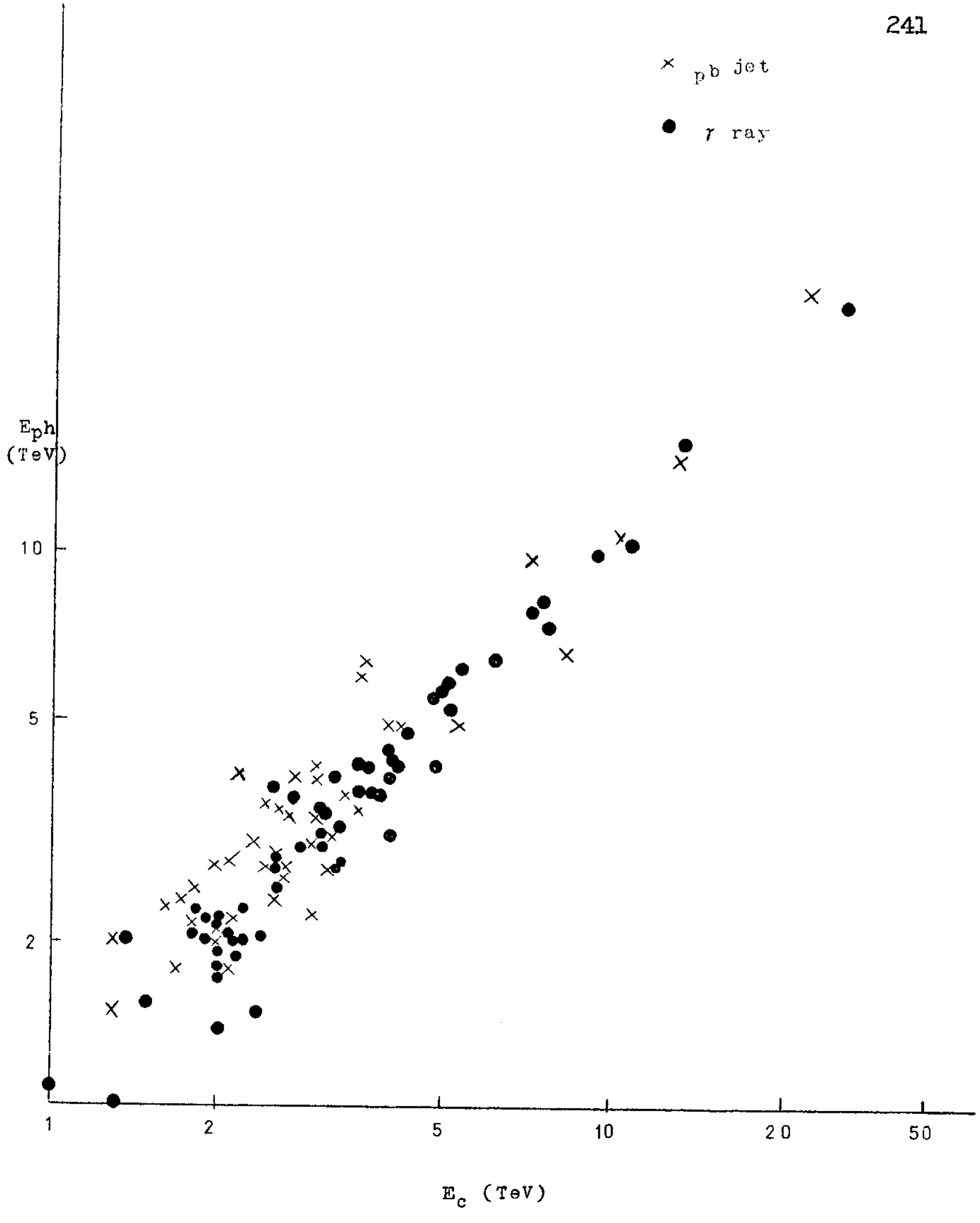

Fig. 2 - Correlation of E_{ph} and E_c

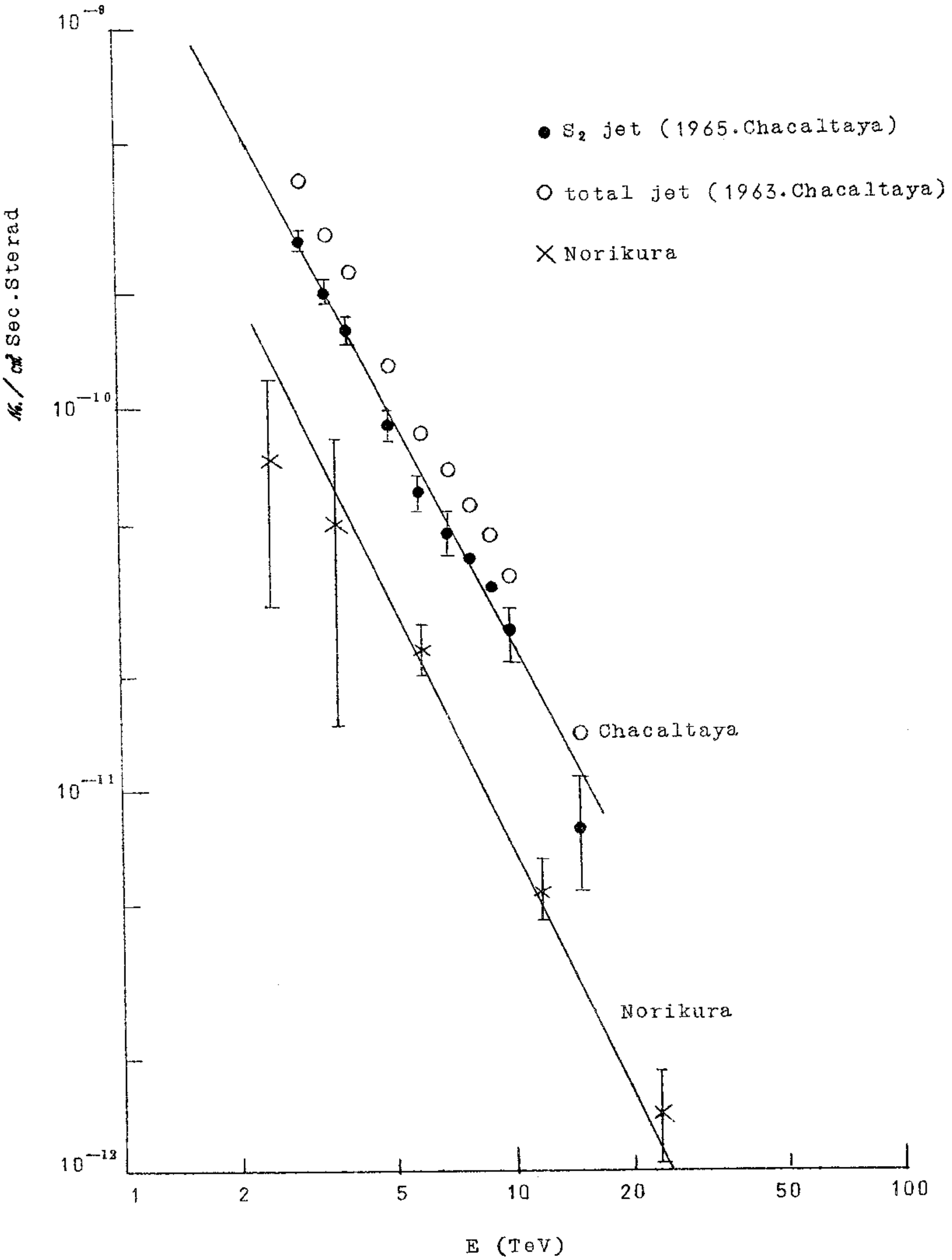

Fig. 5 - Energy spectrum of Nuclear active components

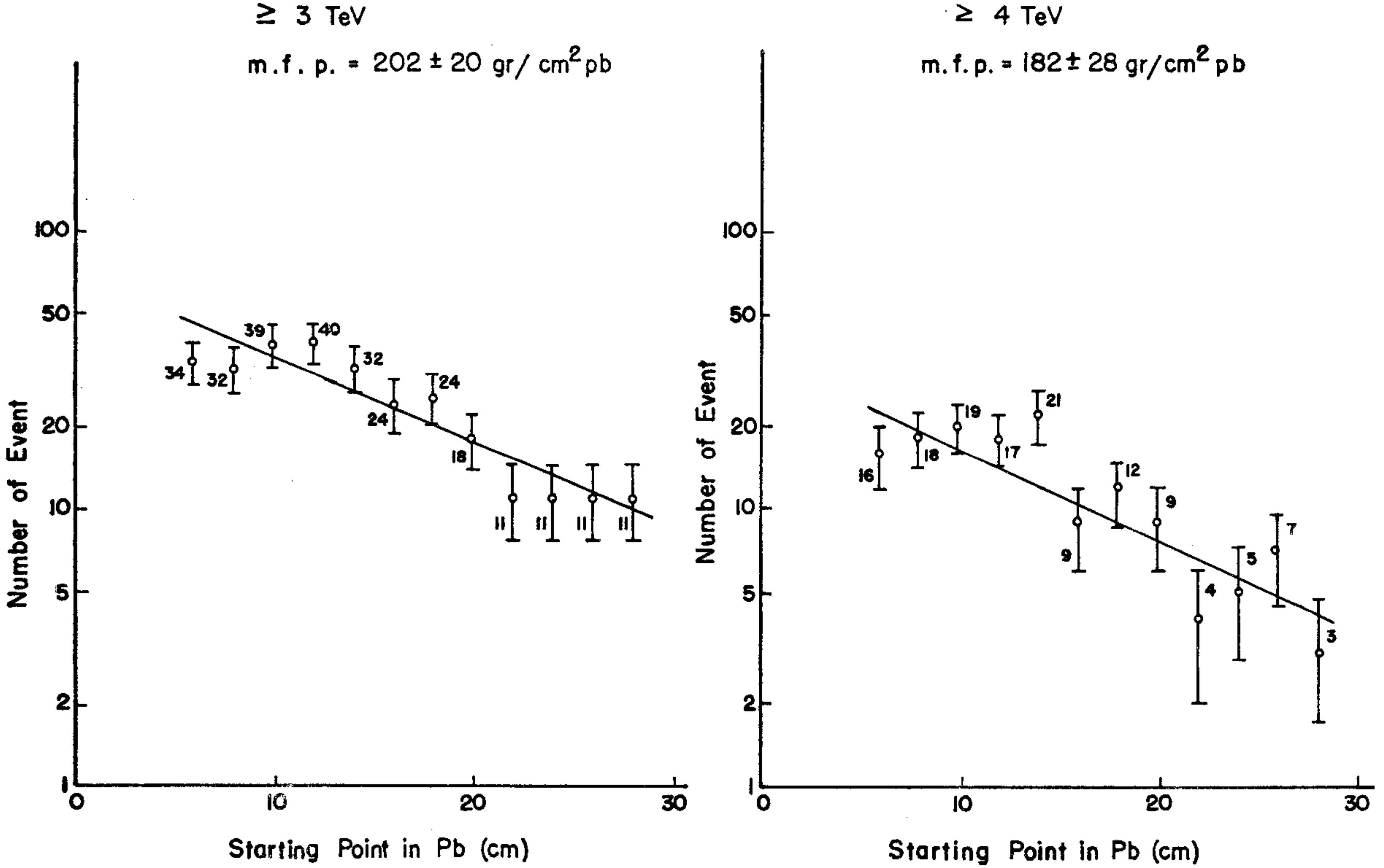

Fig. 6-Nuclear Interaction M.F.P.

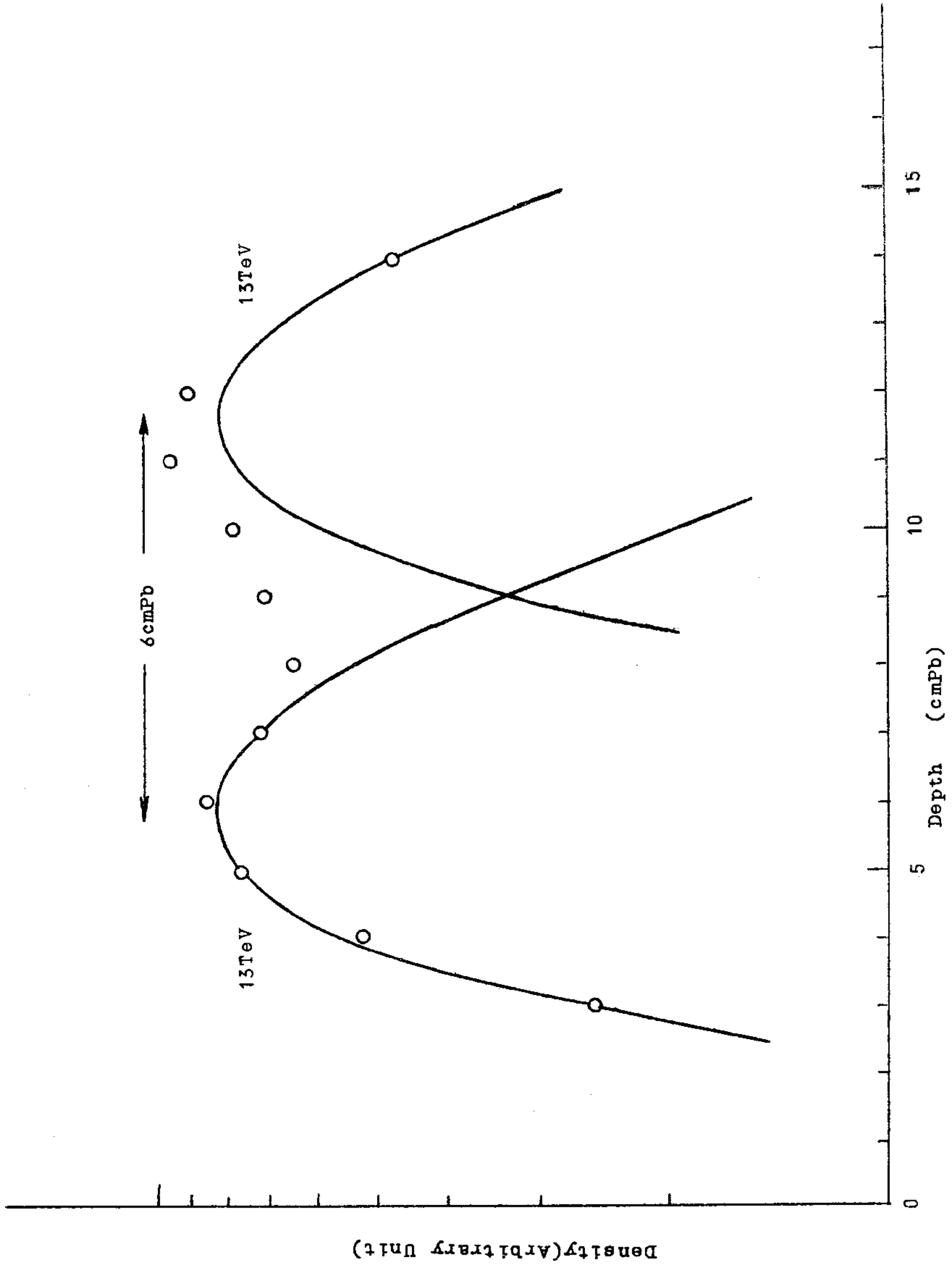

Fig. 7a - Successive Interaction (1)

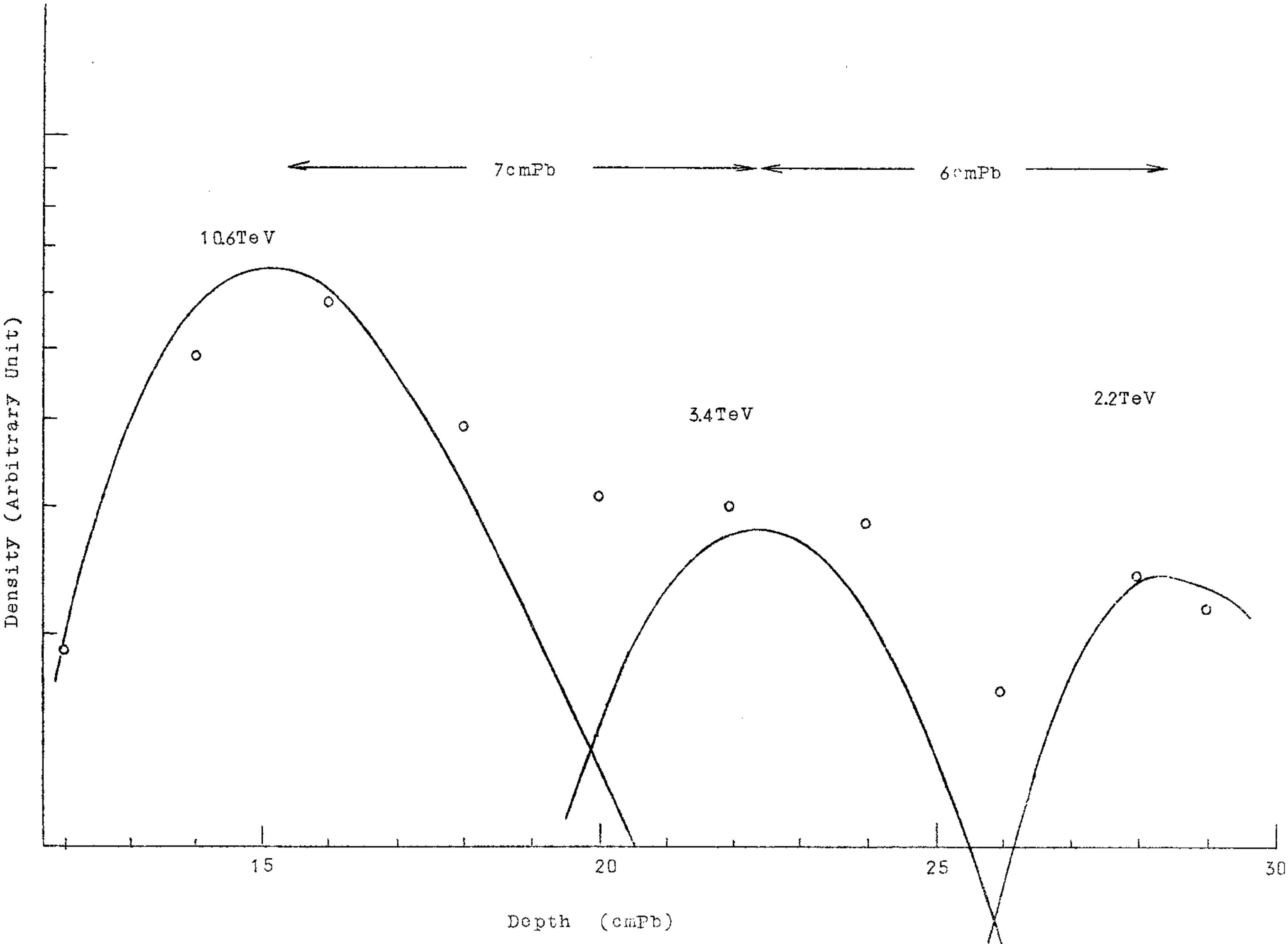

Fig. 7b - Example of the transition curve of successive interaction and the estimation of energy

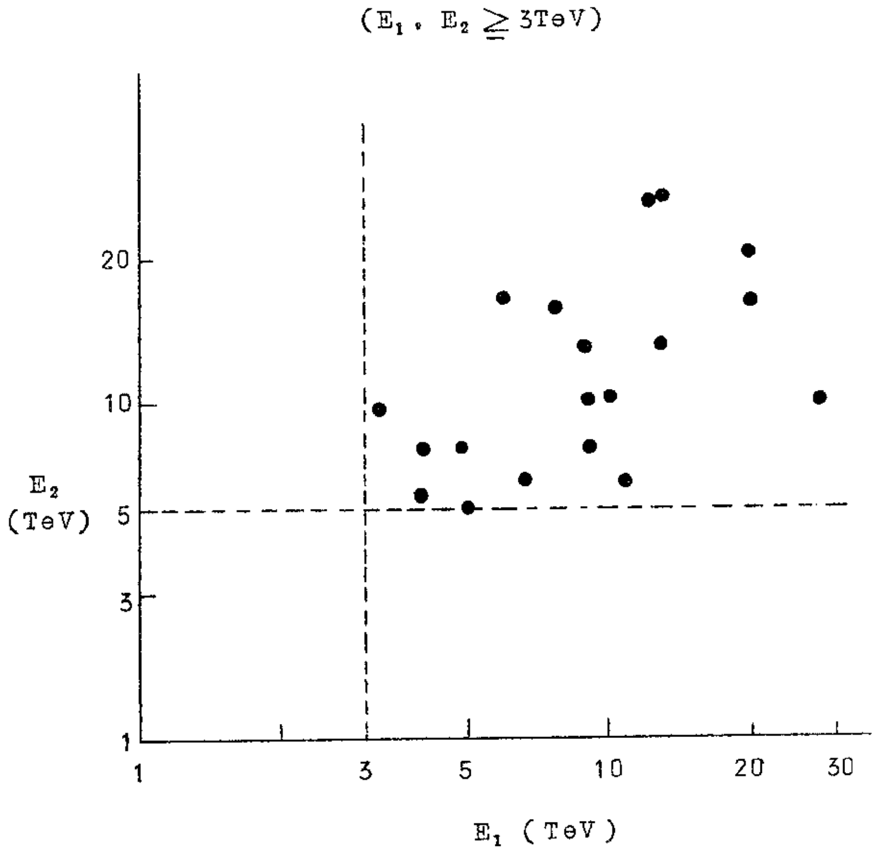

Fig. A1a-Diagram of E_1 vs E_2 in successive interaction

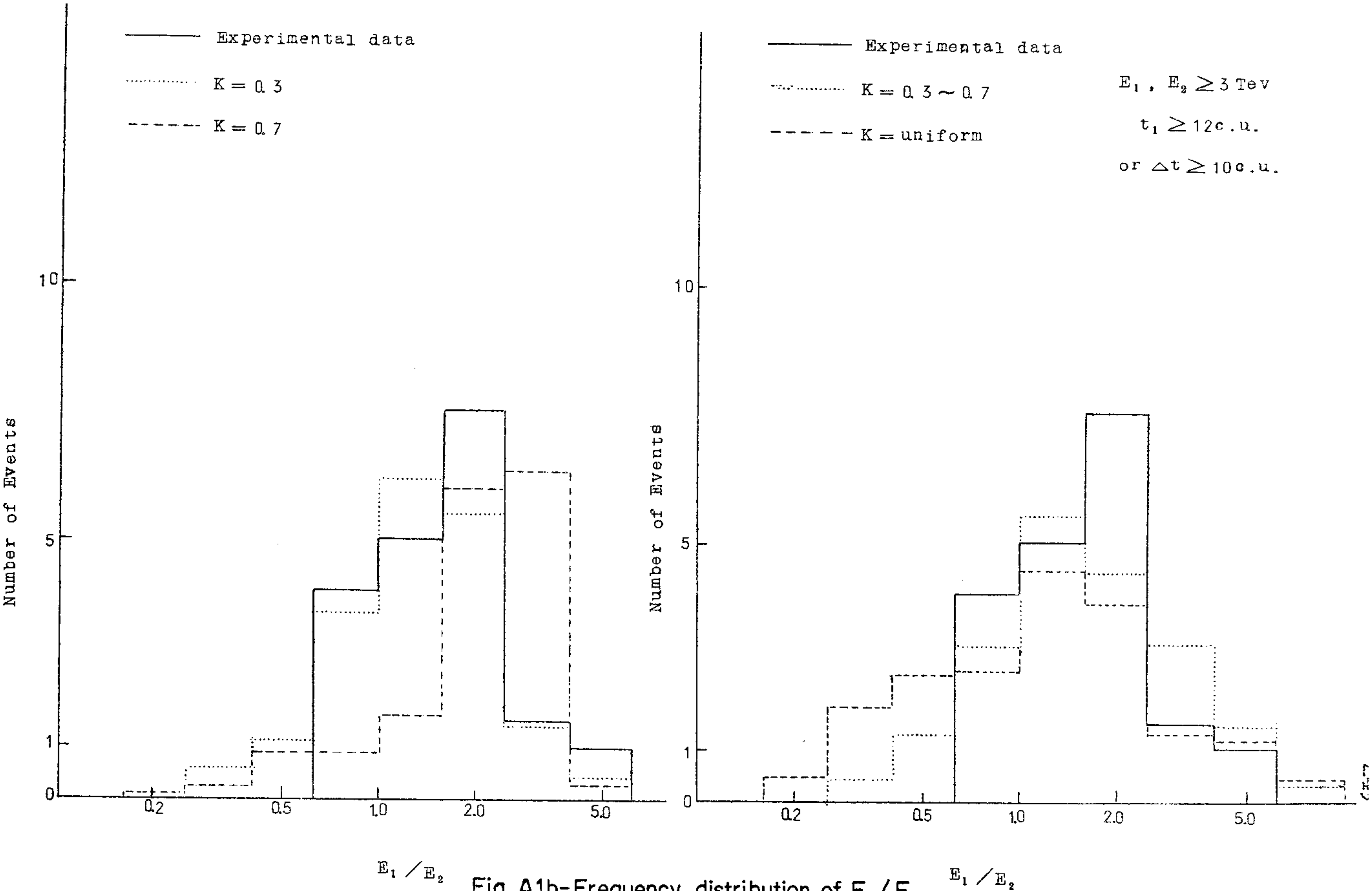

Fig. A1b-Frequency distribution of E_1/E_2

CAPTIONS OF FIGURES

Fig. 1 - Design of the chamber.

Fig. 2 - Correlation of E_{ph} and E_c.

Fig. 3 - Distribution of starting points of γ-rays and Pb jets.

Fig. 4 - Energy spectrum of γ-rays at Mt. Chacaltaya and Mt. Norikura.

Fig. 5 - Energy spectrum of Nuclear active components.

Fig. 6 - Interaction mean free path of nuclear active particles.

Fig. 7a - Example of the transition curve of successive interaction and the estimation of energy.

Fig. 7b - Example of the transition curve of successive interaction and the estimation of energy.

Fig. A1a - Diagram of E_1 vs. E_2 in successive interaction.

Fig. A1b - Distribution of E_1/E_2 of experimental data compared with the calculation by means of Monte Carlo method with various inelasticity.

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REFERENCES

1. M. AKASHI et al., Proc. Jaipur Conf. 5, 326 (1963).
2. M. AKASHI et al., Prog. Theor. Phys. Suppl., Nº 32 (to be published).
3. M. AKASHI et al., in this issue.
4. J. NISHIMURA, Prog. Theor. Phys. Suppl. Nº 32 (to be published).
5. For the determination of the liberated energy in a nuclear event, the energy was first determined by using the same theoretical curve as a single γ ray.
6. E_{ph} of the nuclear events is slightly bigger than E_c in a systematic way. Detailed analysis of the effect on the opacity due to the energy and angular distributions of produced π^0 mesons in a jet using the data of I.C.E.F. 7), and of E.C.C. 1 were made, and it was shown the correct value is expected in the middle of E_{ph} and E_c. The details will be published in elsewhere.

7. I. C. E. F. Collaboration, Nuovo Cimento Suppl. **1**, 1 (1964).
8. The theoretical curve of cascade shower was improved after the Jaipur Conference, by taking the accurate value of the cascade unit in lead. As the results, the energy reported at the time of Jaipur Conference should be increased about 15%.
9. At the time of Jaipur Conference, corresponding value of the γ ray flux is $I_{\gamma} = (2.1 \pm 0.2) \times 10^{-10}/\mathrm{cm}^2$ sec sterad.
   $\gamma = 2.2 \pm 0.2$.
10. M. AKASHI et al., in this issue.
11. The data stands 17 events with both E_1 and E_2 are larger than $3. 10^{12}$ eV, and the starting point is deeper than 6 cm Pb or the separation is larger than 5 cm Pb.
12. One is necessary to mention that the charge to neutral ratio is quite low if those figures are adopted. This is due to the reason that we compared the charged and neutral particles which can give the same liberated energy of γ rays in a collision, and did not compare at the same energy of the particles.
    The difference of inelasticity coefficients between nucleon and π mesons gives us quite different values of charge to neutral ratio.

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