III-5-22. Hard Showers Produced by High Energy μ-mesons

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The present measurements have been performed from December, 1959 to March, 1961 at a depth of 50 mwe from the top of the atmosphere.

The experimental arrangement is shown schematically in Fig. 1. Two cloud chambers were triggered by five fold coincidences of counter trays A [(I≥1)(II≥1)(III≥2)(IV≥2)(V≥2)] or B [(II≥1)(V≥1)(VI≥2)(VII≥2)(VIII≥2) for hard shower observations. The observing times were 3,394.7 hr. for cl.ch. (Pb) and 3,347.7 hr. for cl.ch. (Fe).

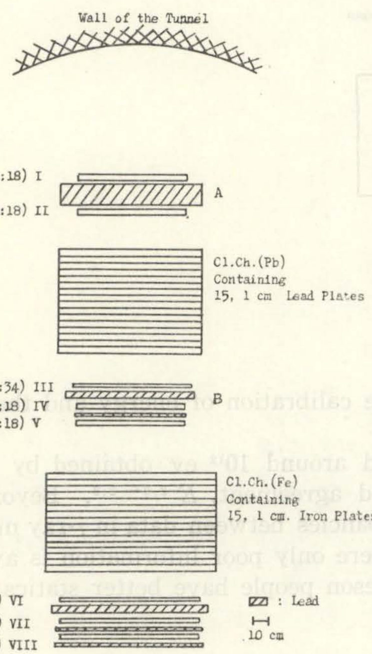

Fig. 1. Experimental arrangement.

The observed hard showers are classified in 7 classes $O_0(W)_{in}, P_0(A), P_i(\mathrm{Pb}), P_0(B), P_i(\mathrm{Fe})$, $S_t(\mathrm{Pb})$ and $S_t(\mathrm{Fe})$ according to the position of occurrence and to the parent of hard showers, as shown in Fig. 2. The showers $O_0(W)_{in}$, $P_0(A)$, $P_i(\mathrm{Pb})$ and $S_t(\mathrm{Pb})$ satisfy the triggering condition A and those $P_i(\mathrm{Fe})$ and $P_0(B)$ satisfy the triggering condition B. The numbers of showers of individual groups are listed in Table I. Table II gives the ratio of the number of secondary showers to that of primary showers, mean multiplicities of secondary penetrating particles and heavily ionizing particles and cross sections of nuclear interactions of μ-mesons. The angular distribution of surviving μ-mesons is shown in Fig. 3 and that of other secondary particles than μ-mesons is shown in Fig. 4 (a), (b). Distributions of "transferred energies" are shown in Fig. 5 (a), (b). The "transferred energies" in the individual showers were evaluated as follows.

A) In the cases, where successive interactions and cascade showers exist,

$$E=\left(\frac{\sum_{i}^{n_i}\varepsilon_i+E_{\rm cas}}{n_i+n_{\pi^0}}\right)\cdot(n_s+n_{\pi^0})\,. \qquad (1)$$

Table I. The numbers of showers of individual groups are listed.

Hard Shower	Notation	No. of events
Occurred in the lead plates (1st-13th) in cl. ch. (Pb).	P_i(Pb)	51
Occurred in the lead producer A.	P_o(A)	26
Occurred in the rock	O_o(W)$_{\rm in}$	13
Occurred in the lead plates in cl. ch. (Pb), its parent is secondary mesons of H.S.	S_t(Pb)	13
Occurred in the iron plates (1st-12th) in cl. ch. (Fe).	P_i(Fe)	23
Occurred in the lead producer B.	P_o(B)	13
Occurred in the iron plates in cl. ch. (Fe), its parent is secondary mesons of H.S.	S_t(Fe)	8

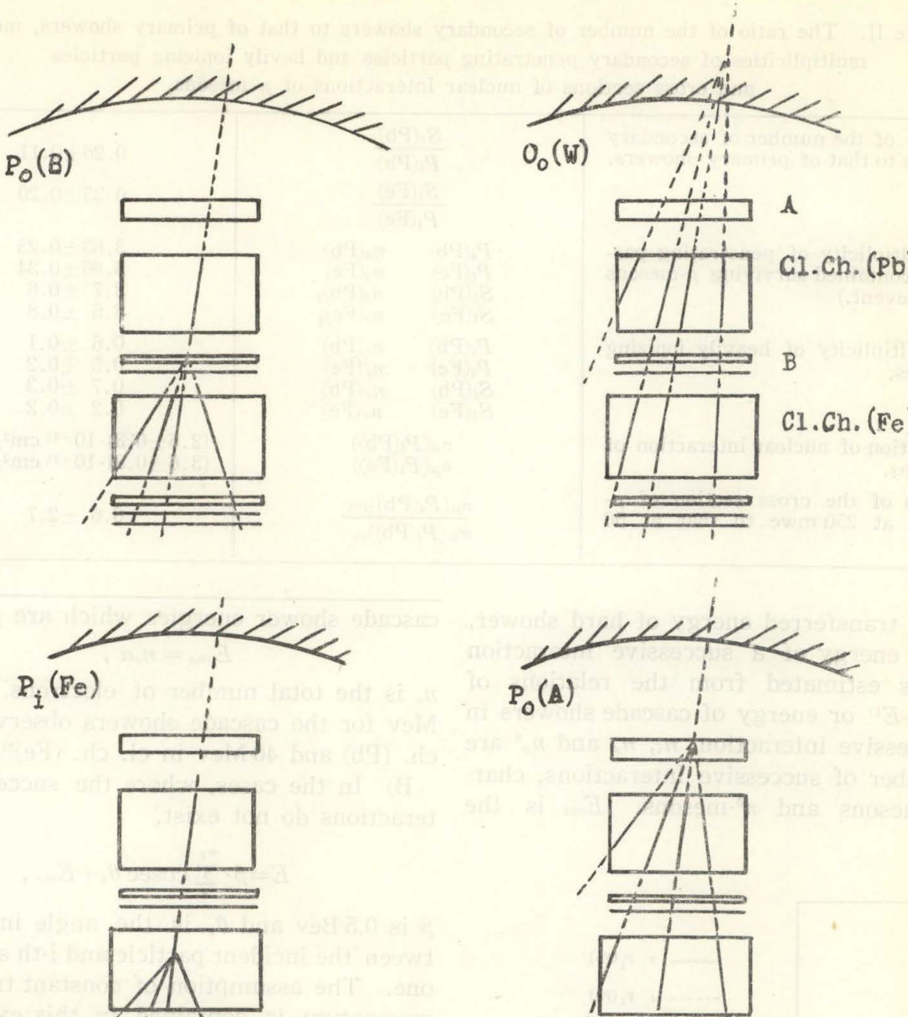

Fig. 2. Schematic illustration of 7 classes of hard showers, $O_o\ (W)_{in}$, $P_o(A)$, $P_i(Pb)$, $P_o(B)$, $P_i(Fe)$, $S_t(Pb)$ and $S_t(Fe)$.

Table II. The ratio of the number of secondary showers to that of primary showers, mean multiplicities of secondary penetrating particles and hevily ionizing particles and cross sections of nuclear interactions of μ-mesons.

The ratio of the number of secondary showers to that of primary showers.	$\frac{S_t(\mathrm{Pb})}{P_i(\mathrm{Pb})}$	0.26 ± 0.11
	$\frac{S_t(\mathrm{Fe})}{P_i(\mathrm{Fe})}$	0.35 ± 0.20
Mean multiplicity of penetrating particles (contained surviving μ-mesons for P_i event.)	$P_i(\mathrm{Pb})$ $n_s(\mathrm{Pb})$	3.63 ± 0.23
	$P_i(\mathrm{Fe})$ $n_s(\mathrm{Fe})$	3.96 ± 0.34
	$S_t(\mathrm{Pb})$ $n_s(\mathrm{Pb})_s$	3.7 ± 0.6
	$S_t(\mathrm{Fe})$ $n_s(\mathrm{Fe})_s$	3.6 ± 0.8
Mean multiplicity of heavily ionizing particles.	$P_i(\mathrm{Pb})$ $n_r(\mathrm{Pb})$	0.6 ± 0.1
	$P_i(\mathrm{Fe})$ $n_r(\mathrm{Fe})$	0.5 ± 0.2
	$S_t(\mathrm{Pb})$ $n_r(\mathrm{Pb})$	0.7 ± 0.3
	$S_t(\mathrm{Fe})$ $n_r(\mathrm{Fe})$	0.2 ± 0.2
Cross section of nuclear interaction of μ-mesons.	$\sigma_\mu(P_i(\mathrm{Pb}))$	$(2.6 \pm 0.3) \cdot 10^{-31}$ cm²/nucleon
	$\sigma_\mu(P_i(\mathrm{Fe}))$	$(3.6 \pm 0.8) \cdot 10^{-31}$ cm²/nucleon
The ratio of the cross section of μ-mesons at 250 mwe to that at 50 mwe.	$\frac{\sigma_\mu(P_i(\mathrm{Pb}))_{250}}{\sigma_\mu(P_i(\mathrm{Pb}))_{50}}$	6.6 ± 2.7

E is the transferred energy of hard shower, ε_i is the energy of a successive interaction which is estimated from the relations of n_s-E, N_g-E[1] or energy of cascade showers in the successive interaction, n_i, n_s and n_{π^0} are the number of successive interactions, charged π-mesons and π^0-mesons. E_{cas} is the

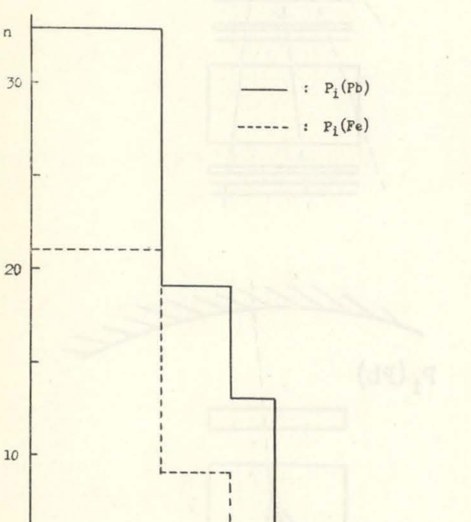

Fig. 3. Angular distribution of secondary particles regarded as surviving μ-meson in L. S.

cascade shower energies which are given by

$$E_{\mathrm{cas}} = n_e \alpha ,$$

n_e is the total number of electrons. α is 20 Mev for the cascade showers observed in cl. ch. (Pb) and 40 Mev in cl. ch. (Fe)[2].

B) In the cases, where the successive interactions do not exist,

$$E = \beta \cdot \sum_i^{n_s} \operatorname{cosec} \theta_i + E_{\mathrm{cas}} , \qquad (2)$$

β is 0.5 Bev and θ_i is the angle in L.S. between the incident particle and i-th secondary one. The assumption of constant transverse momentum is contained in this expression. This assumption would be supported from that each transferred energy obtained by applying the expression (2) and (1) to the same events is in good agreement and the mean value of observed transverse momentum is consistent with 0.5 Bev/c.

The value of $S_t(\mathrm{Pb})/P_i(\mathrm{Pb})$ means the ratio between numbers of showers produced by secondary π-mesons and by μ-mesons. The values of (0.26 ± 0.11) at 50 mwe and (0.69 ± 0.29) at 250 mwe[3] are in agreement with the calculation[4].

The value of $N_h(\mathrm{Pb})/N_h(\mathrm{Fe})$ (heavily ionizing particles ratio produced by μ-mesons) and that of $N_h(\mathrm{Pb})_s/N_h(\mathrm{Pb})$ (the ratio between numbers of heavily ionizing particles produced by secondary π-mesons and by μ-mesons) are estimated to be 1.55 and 1.3 respectively for the same n_s on the assumption that heavily ionizing particles are produced by knock-on process in the nucleus. The observed values of these ratios (1.4 ± 0.7, 0.8 ± 0.5) are not inconsistent with the above estimated ones.

The nuclear interactions of μ-mesons may be accounted for in terms of nuclear interactions of the virtual photon field of μ-mesons with nucleus. Then, the cross section of μ-mesons σ_μ is:

$$\sigma_\mu=\int_{E_{\min}}^{\infty}\sigma_{h\nu}\Phi(x,\varepsilon)d\varepsilon/I(x)$$

where $\Phi(x,\varepsilon)$ is the photon flux of energy between ε and $\varepsilon+d\varepsilon$, $I(x)$ is the μ-meson flux at the depth of x mwe and $\sigma_{h\nu}$ is the photonuclear cross section. Assuming that $\sigma_{h\nu}$ is constant in high energy region, $\Phi(x,\varepsilon)$ is estimated with the aid of the Williams-Weiszäcker expression[5] and the minimum energy of P_i(Pb) showers is to be 5 Bev, the cross section $\sigma_\mu(P_i(\text{Pb}))$ leads to the photonuclear cross section $\sigma_{h\nu}$ of $(2.6\pm0.3)\cdot10^{-28}\,\text{cm}^2$/nucleon. The ratio of $\sigma_\mu(P_i(\text{Pb}))$ at 250 mwe[3] to $\sigma_\mu(P_i(\text{Pb}))$ at 50 mwe is given by

$$\frac{\sigma_\mu(P_i(\text{Pb}))_{250}}{\sigma_\mu(P_i(\text{Pb}))_{50}}=4.2$$

and this value is not inconsistent with the observed one (6.6 ± 2.7).

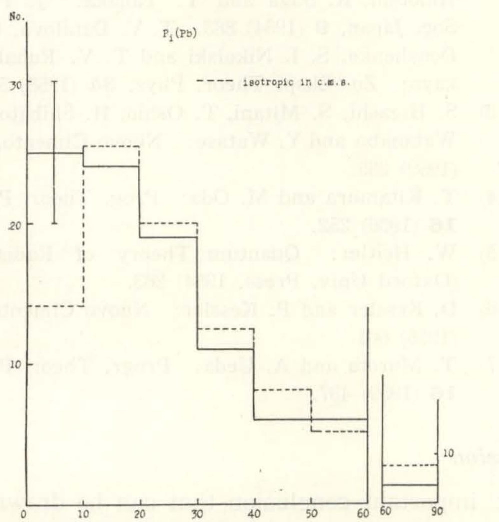

Fig. 4 (a). Angular distribution of other secondary particles than μ-meson in L. S. for $P_i(Pb)$.

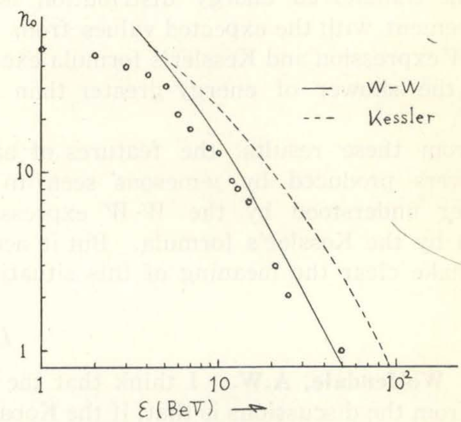

Fig. 5 (a). Energy distribution of hard showers. $P_i(Pb)$.

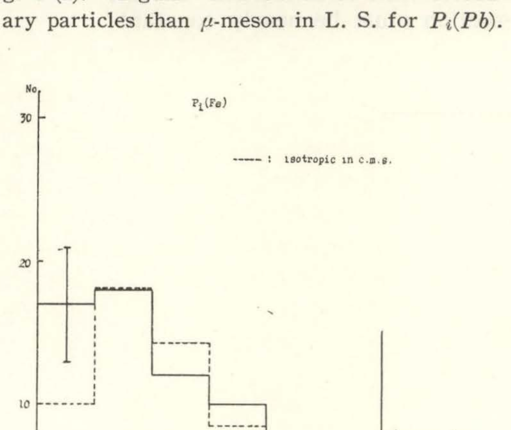

Fig. 4 (b). Angular distribution of other secondary particles than μ-meson in L. S. for $P_i(Fe)$.

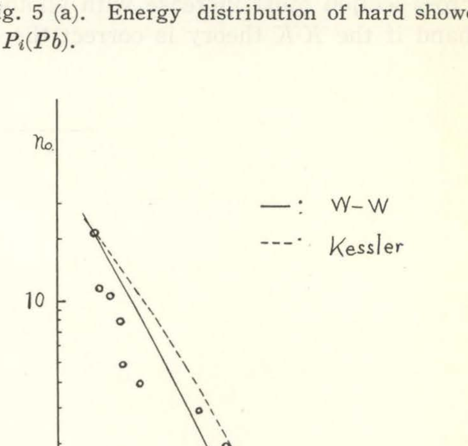

Fig. 5 (b). Energy distribution higher than 15 Bev of hard showers $P_i(Pb)$. $P_o(A)$ and $O_o(W)_{in}$.

On the other hand, if Φ is estimated with the formula given by D. Kessler and P. Kessler[6], $\sigma_{h\nu}$ is found to be $(2.4\pm0.3)\cdot10^{-29}$ cm^2/nucleon and the ratio $\sigma_\mu(P_i(\mathrm{Pb}))_{250}/\sigma_\mu(P_i(\mathrm{Pb}))_{50}$ is to be 2.9. It is, therefore, difficult to understand the nuclear interactions of μ-mesons with photon spectrum of the Kessler's formula.

The integral angular distribution of surviving μ-mesons turned out to be $1n\theta$ and is not inconsistent with the feature expected by the W-W method[6][7].

The angular distribution of other secondary particles than μ-mesons is in agreement with that evaluated by the isotropic distribution in c.m.s. of photon nucleon system, except a few part in 0-10 degree region.

The transferred energy distribution is in agreement with the expected values from the W-W expression and Kessler's formula except for the shower of energy greater than 300 BeV.

From these results, the features of hard showers produced by μ-mesons seem to be better understood by the W-W expression than by the Kessler's formula. But it needs to make clear the meaning of this situation. So, it is very important to investigate the transferred four momentum, transferred energy and μ-meson energy dependences of the features of the hard showers, in order to reveal the mechanisms of meson productions induced by μ-mesons.

The theoretical investigation of the hard showers will be reported by Dr. Murota.

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Discussion

Wolfendale, A.W.: I think that the most important conclusion that can be drawn from the discussions is that, if the Kobayakawa *et al* theory is correct, the photo nuclear cross-section must increase with photon energy in the range 1-100 Gev. On the other hand if the *K-K* theory is correct the cross-section must be nearly constant.