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III-4-7. On μ-Meson Beams in the Composition of Extensive Air Showers

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During 1960–1961 we have continued studying μ-meson beams in the composition of extensive air showers. The μ-meson detector is consisted of 16 groups of counters, as it is shown on Fig. 1a. The dimensions of each group were $55 \times 72\,\mathrm{cm}^2$. The total sensitive area of the detector was $6.3\,\mathrm{m}^2$. Under each group of counters, as shown on the plane, two groups of counters were arranged (see the section of the detector on Fig. 1b): the middle group was separated from the upper by 10 cm of Pb and 10 cm of Fe, the lower group being separated from the middle by 6 cm of Fe. Counters of the middle group were separated one from another by 2.5 cm of Pb. The entire detector was placed in underground premises at a depth of 40 m of water equivalent.

During registration of extensive air showers of sufficient size, several μ-mesons pass simultaneously through the detector. In this connection, one can determine in each shower the distance D between the points of impact on the detector, of any two μ-mesons of all falling on the detector. For a great sum of showers it is possible to draw the exprimental distribution of distances D. Fig. 3a shows the histogram of distances D for the central region of the shower (the distance from the shower axis to the device's center (Fig. 2) at the earth's surface did not exceed 30 m).

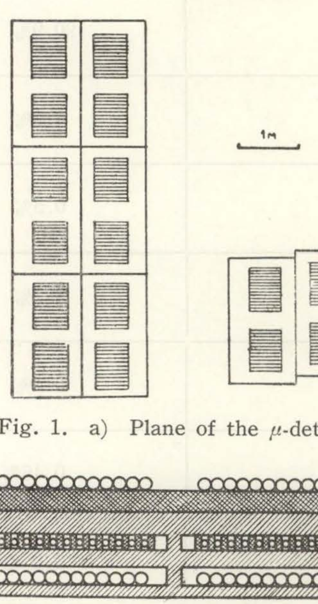


Fig. 1. a) Plane of the μ-detector.

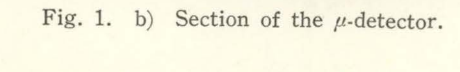


Fig. 1. b) Section of the μ-detector.

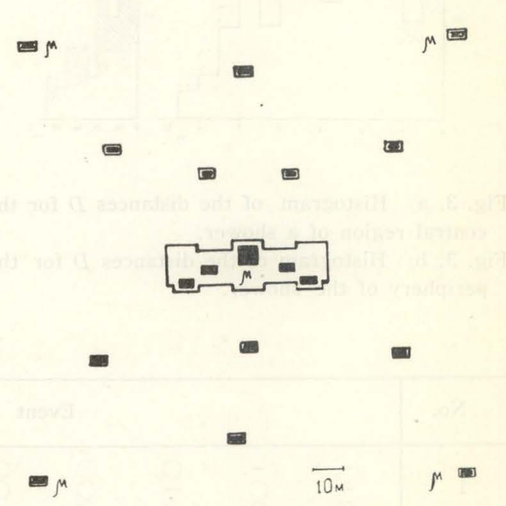


Fig. 2. Plane of the device for determining the total number of particles and the shower-axis position.

Fig. 3b shows the histogram for the shower periphery (the distance mentioned was more than 50 m). On the same pictures a dash-and-dot-line indicates the results of the theoretical calculation by Monte-Carlo's method, carried out under the assumption that μ-meson paths are distributed independently and uniformly on an average, over the μ-detector area.

As one can see, we have good agreement of the experimental and theoretical distributions for the shower periphery. For the central part of a shower, on the contrary, there exists a notable disagreement: the number of experimental events substantially exceeding the number of those theoretically calculated, for the $D<1-2$ m. The same is also observed for the distances $D<0.5$ m. (see Fig. 3c).

It may be assumed that the difference between the experimental and theoretical distributions for the central regions of a shower is connected with the hit of a shower axis within the range of the detector. However, if one takes into consideration the number of shower axis expected on the μ-detector area, during operation of the device, and also if use is made of the known lateral distribution of μ-mesons, extrapolating it to small distances, then the unimportant role of this effect may be shown. Thus, to explain the disagreement observed it is necessary to assume the existence of a genetic connection between μ-mesons in the central regions of the shower.

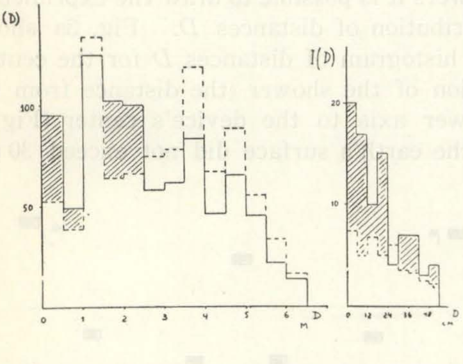


Fig. 3. a) Histogram of the distances D for the central region of a shower.

Fig. 3. b) Histogram of the distances D for the periphery of the shower.

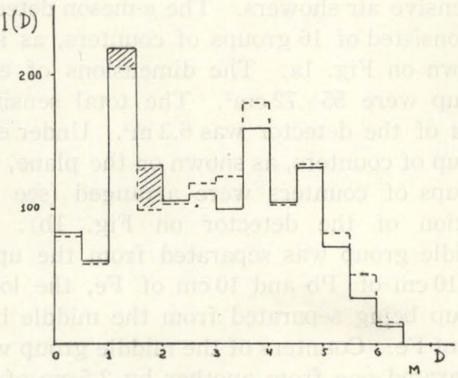
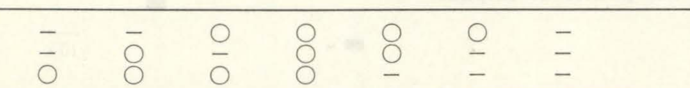
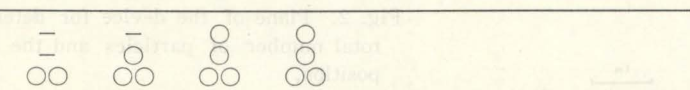
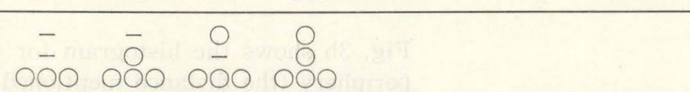
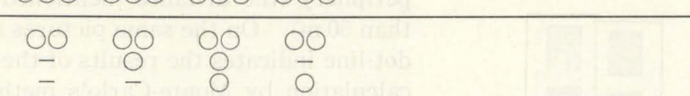
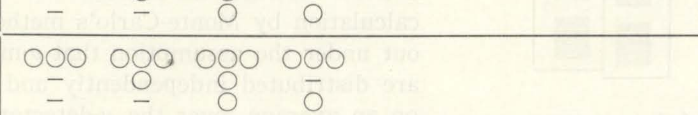
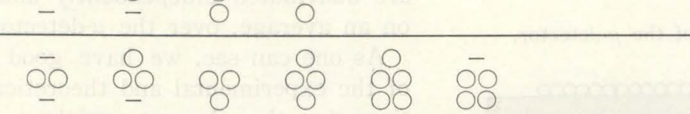
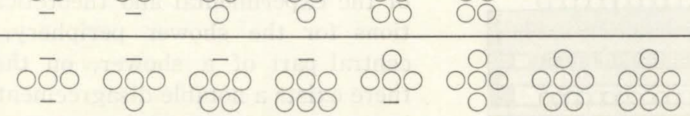


Fig. 3. c) The same as a) for the $D<0.5$ m. A solid lines indicates the experiment; a dash-and-dot-lines are the calculated data.

Table I

No.	Event	Number of events
1		90.9%
2		4.5%
3		0.5%
4		3.2%
5		0.4%
6		0.45%
7		0.05%

Full number of events: 4.10^4 for 2340 hours.

This connection should be sufficiently strong in order to become apparent with D of the order of linear dimensions of the μ-detector.

It is difficult to observe directly in what form this connection becomes apparent for such D, because of the character of the detector's geometry. (Fig. 1a). However, for the distances D less than linear dimensions of the counter groups ($D<0.5$ m) it is possible to observe a direct reflection of this connection in the form of the existence of narrow μ-meson beams. As it was reported at the previous Conference (Moscow, 1959) μ-meson beams were observed in showers with the primary energy of $E_0 \simeq 10^{15}$ ev, these beams consisting of three or more particles. The size of the beams is $d \sim 20$ cm. The types of events observed by means of the μ-detector are given in Tables I and II, the events of the type given in Table II being assumed as beams*).

In the present work, due to the use of the μ-detector with a thick filter and special shielding of middle-tray counters (see Fig. 1b), we found it possible to give reliable evidence of the fact that the phenomena observed are obviously unconnected with local showers from individual μ-mesons which are a part of an extensive air shower. This evidence is based on a comparison between the frequency of events of type 7 (Table I) and those of type 2 (Table II) in extensive air showers, and also on a comparison of the shower accompaniment of these events. Indeed, during approximately 2 500 working hours in showers with size $N>3.10^5$ 20 events were observed of type 7, and 17 events of type 2. Thus, if the events 7 and 2 are caused by local showers from individual μ-mesons, then the energy of these local showers must be approximately equal. At the same time, as is shown in Fig. 4, the events of types 7 and 2 have strongly differing shower accompaniment curves. The probability of these distributions agreeing is $\leq 10^{-4}$. Thus, the events of the type 2 are a special class of events which are not connected local showers.

Table II

No	Event	Number of events ($T=2340$ hr)
1	○○○ ○○○ ○○○ — ○ ○○ ○○○ ○○○ ○○○	9, 22, 10
2	○○ ○○ ○○○ ○○○ ○○○ ○○○ ○○○ ○○○ ○○ ○○○ ○○ ○○○	2, 2, 1, 12

* Details will be given below.

Data on the lateral distribution of narrow μ-meson beams and on their presence in showers with various energy are of considerable interest. For each shower, we determined with the help of the ground device, the total particles number N and the distance r from the axis to the center of device. Because of shower-axis decline, the distance to the μ-detector may differ considerably from r. However, the μ-meson beam has always a notable accompaniment of shower μ-mesons. Since we know the mean function of the lateral distribution of extensive air shower μ-mesons, we can in each individual case determine the actual distance from the axis

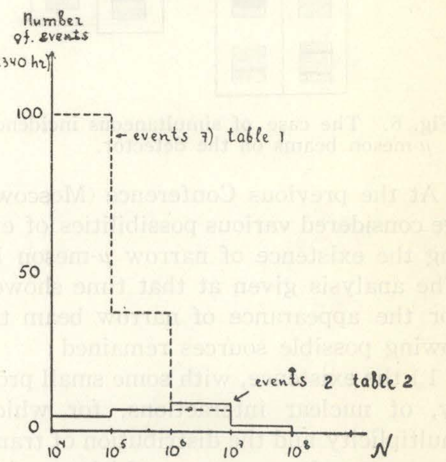


Fig. 4. Comparison of shower accompaniment for the events of the types 7 and 2.

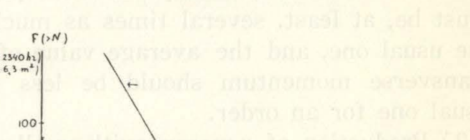


Fig. 5. Shower accompaniment of μ-meson beams. Solid line is a size spectrum of showers.

to the μ-detector. For all 17 events of the type 2 this distance has proved to be $r<10$ m. The total data on shower-accompaniment of μ-mesons beams are shown in Fig. 5.*) From these data it can be concluded that the μ-meson beams number for a shower increases $N^{1.5\pm0.2}$ in the range of variation of $10^5<N<10^7$. According to this dependence several showers were observed in which a few beams (up to 3), fell simultaneously on the μ-detector, being separated from one another by a distance of the order of metres (Fig. 6).

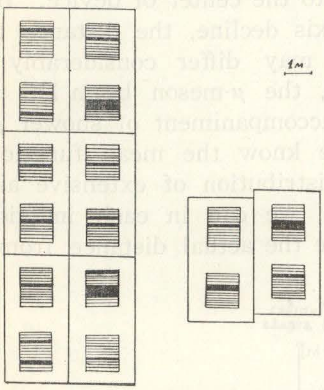


Fig. 6. The case of simultaneous incidence of 3 μ-meson beams on the detector.

At the previous Conference (Moscow, 1959) we considered various possibilities of explaining the existence of narrow μ-meson beams. The analysis given at that time showed that for the appearance of narrow beam the following possible sources remained:

1) the existence, with some small probability, of nuclear interactions, for which the multiplicity and the distribution of transverse momenta of π-mesons, which produce μ-mesons in $\pi-\mu$ decay, differ considerably from the usual ones, namely: the multiplicity must be, at least, several times as much as the usual one, and the average value of the transverse momentum should be less than usual one for an order.

2) Production of μ-mesons with small cross section, in nuclear interactions of high energy, either directly or as a result of the decay of some short-lived particles whose lifetime is scores of times less than that of π or K-mesons.

3) The same, but with a cross section close to the geometrical, and in the nuclear interactions with super high energies of 10^{14}-10^{15} ev.

Let us examine the first of these possibilities. Table III gives the data on the minimum multiplicity, necessary for the creation of narrow μ-meson beams with various values of a mean transverse momentum and the height H of production of π-mesons. It should be noted that μ-mesons gain the momenta of the order of $3\cdot10^7$ ev due to the Coulomb scattering, practically independently of H. For comparison the multiplicity required has been given, in the case of $\bar{p}_\perp=3.10^8$ ev/c. As is seen from the table, such multiplicity is improbable from the viewpoint of the laws of conservation, even if one consider the production of secondary particles by a particle with an energy equal to the total shower energy ($E_0\sim10^{15}-10^{16}$ ev). The energy of a n.a. particle able to produce a narrow μ-meson beam at the altitude H cannot be accurately determined (In Table III following value of $E_{\text{n.a.}}$ presented: $E_{\text{n.a.min}}=n_\pi\cdot E_\pi$). On the hand, it is clear that this energy must be higher than the value given in Table III, for there the production of π-mesons is not taken into account; neither is the production of secondary particles with higher or lower energy, than that required by us. On the other hand, since the decay of π-mesons in a beam occurs accidentally, the minimum number of π-mesons creating the beam of a given number (3 for example) of μ-mesons may be less than $h=3\,w^{-1}$, where w is the probability of $\pi-\mu$ decay (for example, by Poisson's law $P(3)=e^{-\nu}\nu^3/3\,!$ and ν may be less than $3\,w^{-1}$). As further more precise definitions assume that the character of fluctuations is known quantitatively, we shall limit ourselves to the assumption that $E_{\text{n.a.}}=E_{\text{n.a.min}}$ (Table III). On this assumption and proceeding from the experimental data on the energy-spectrum of nuclear-active showers of an EAS and the number of narrow beams for a shower, one may estimate the necessary probability of the production of a narrow π (or K) mesons beam as a result of nuclear interaction. This pro-

* Here the events of type 1 are used (Table II). The events of type 1 have the same shower-accompaniment as type 2 events, and differ greatly from the accompaniment of the type 7 events. The origin of the type 1 events is easily understood, if one takes into account the fact that when μ-beam passes through the detector, in some cases μ-mesons pass through the gaps between the counters of the middle groups.

Table III

	H	100 m	250 m	500 m	10^3m	3.10^3m	5.10^3m	10^4m	$1.7\cdot10^4$m
$\bar{p}_\perp$ due to Colomb scattering	E_π ev	$1.4\cdot10^{10}$	$1.8\cdot10^{10}$	$3.3\cdot10^{10}$	$9.3\cdot10^{10}$	$3.3\cdot10^{11}$	$6.3\cdot10^{11}$	$1.2\cdot10^{12}$	$1.7\cdot10^{12}$
	$n_\pi=3/w$	30	15	20	25	15	100	100	90
	$n_{\pi\ theor.}$	9	8	10	16	25	32	36	40
	$E_{n.a.\ min}$	$2\cdot10^{11}$	$4\cdot10^{11}$	$6.6\cdot10^{11}$	$2.3\cdot10^{12}$	$2.5\cdot10^{13}$	$6.3\cdot10^{13}$	$1.2\cdot10^{14}$	$1.5\cdot10^{14}$
$\bar{p}_\perp=3.10^8$ev/c	E_π ev	$1.2\cdot10^{11}$	$3\cdot10^{11}$	$6\cdot10^{11}$	$1.2\cdot10^{12}$	$3.6\cdot10^{12}$	$6\cdot10^{12}$	$1.2\cdot10^{13}$	2.10^{13}
	$n_\pi=3/w$	260	260	260	300	720	1000	1000	1000
$\bar{p}_\perp\sim10^8$ ev/c	E_μ ev	$4\cdot10^{10}$	10^{11}	$2\cdot10^{11}$	$4\cdot10^{11}$	$1.2\cdot10^{12}$	2.10^{12}	$4\cdot10^{12}$	$6.8\cdot10^{12}$
	$E_{min}=3E_\mu$ev	$1.2\cdot10^{11}$	$3\cdot10^{11}$	$6\cdot10^{11}$	$1.2\cdot10^{12}$	$3.6\cdot10^{12}$	6.10^{12}	$1.2\cdot10^{13}$	$2\cdot10^{13}$

bability proves to be equal to $\alpha\sim3\%$.

Let us consider now a second possibility. In this case it is reasonable to suppose that $\bar{p}_\perp=10^8$ ev/c. The values $E_{n.a.min}$ given in Table III for this case, should be deliberately increased several times because of the production of $\pi^\pm$ and π°-mesons. Thus, it is reasonable to assume α to be the same as for the previous case of the order of 3%.

It should be noted that the given values of α do not contradict numerous experimental data obtained by means of photoemulsions and a cloud chamber, on nuclear interactions in the range of energies of 10^{11}-10^{13} ev.

Case 1) and 2) have some features in common. At first, it is natural in both cases to expect the existence of beams of larger size together with narrow beams ($d\sim0.2$ m). Secondly, the beams of a given size d may appear due to the interaction of nuclear-active particles at various altitudes H, and so the mean energy of particles in a beam may vary from case to case in a wide range (though at the same time $E_\mu\sim d^{-1}$). Herein lies the difference of the cases 1) and 2) from the case 3), in which E must always be higher, and correspond to the shower origin altitude.

Probably cases 1) and 2) must differ in respect of the predicted dependence of the number of μ-meson for a shower, on the size of the beam $d-I(d)$. For the case 1) $I(\leq d)\sim I(E_{n.a.min})$; $E_{n.a.min}=mw^{-1}E$ where m is the number of μ-mesons in a beam; $w(E)$ is the probability of π-μ decay. E is the energy of a π-meson.

In its turn $E\sim d^{-1}$. Thus, $E_{n.a.min}\sim d^{-2}$ Hence, the number of beams with the size of d for a shower, with an integral spectrum of nuclear-active particles $E_{n.a.}^{-1}$ is proportional to d^2. For case 2) $w(E)=1$ and $I(\leq d)\sim d$.

Precise calculation, with due account of beam-production over all altitudes H, confirms this qualitative consideration. Let us now return to Fig. 3a. We have found a notable exceeding of the experimental number of events with $D<2$ m over the theoretical one, which may be explained, from the viewpoint of the case 1) and 2), by existence wide μ-beams, than directly observed.

It is not so difficult to determine with the Monte-Carlo's method the number of beams with greater d for a shower necessary to explain the disagreement between experimental and theoretical data. The results of our calculations show that $I(d)$ corresponds to the dependence $I(d)\sim d$ and contradicts the dependence $I(d)\sim d^2$.

It is evident that to distinguish between posibilities 2) and 3) it is necessary to carry out measurement of the mean energy of μ-mesons in beams—at least.

In conclusion, we should note, that the following, more detailed and direct experiments are necessary for a final choice of the three possibilities mentioned above.

Discussion

Tanaka, Y.: (1) How could you be so accurate in determining the core location on the underground μ-detector, since you noticed substantial difference from statistical expectation within a few metres from the axis?

(2) What is your opinion on the different features between the bundles of particles observed in diffusion chamber and those observed with the underground μ-detector?

Vernov, S. N.: (1) The error in the determination of location of the shower axis is much greater than the spread of bundles.

(2) The condition of the experiment with the diffusion chamber and with the μ-detector are quite different. In case of the diffusion chamber especially narrow bundles are distinguished. The μ-detector can distinguish only bundles of considerable spread.

Clark, G.: Would you comment on the possibility that the μ-meson bundles arise from the decay of π-meson bundles produced at great altitude in nuclear interactions of high Z primaries?

Vernov: If one believes that π-mesons are generated as usual with $P_T=3.10^8$ ev/c, then this possibility may be ruled out. The calculations showed if one considers the probability of π-meson decay, then to account for the bundles observed, it is necessary to assume the production of many hundreds and even a thousand π-mesons, which may not be plausible.

Matano, T.: The fluctuations of density of μ mesons (≥ 5 Bev) in a single EAS are studied by Tokyo air shower group. The apparatus is neon hodoscope with total area 2 m^2. (Fig. 1)

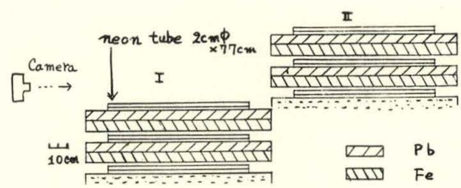


Fig. 1. The side view of underground neon-hodoscope.

In 237 showers ($N \sim 10^5$-10^7) with 5 to 23 μ mesons in 2 m^2, we have found 38 events which contained more than 4 particles in any unit interval which involves 10 tubes on two trays each of which consists of 66 tubes. Figs. 2a, b show the example of such events. We have compared with the frequency of such events and the frequency estimated statistically. In the preliminary results we could not find the significant difference between these values. The more accurate analysis is being continued.

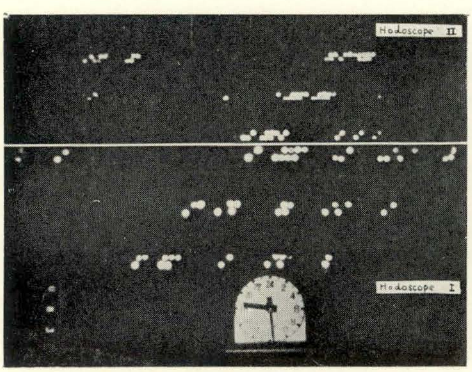


Fig. 2a.

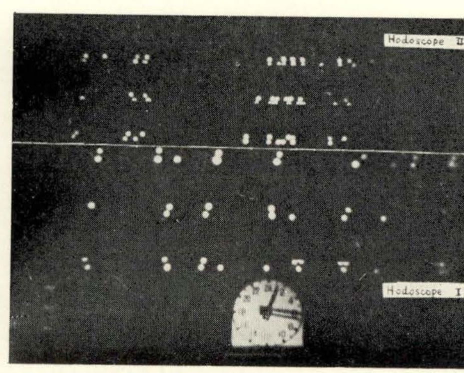


Fig. 2b.