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III-4-27. The Structure of Extensive Air Showers at the Sea-Level

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A large device for the complex study of extensive air showers has been in operation for the last three years at the Moscow State University. A description of this device was, in the main, given in proceedings of the previous International Conference. In the present paper it would be appropriate to repeat its principal features. The device occupies an area of four hectares. In this area are placed detectors of charged particles, detectors of μ-mesons, and detector of nuclear-active particles. The general plan of the device is shown on Fig. 1. The detectors of charged particles are a set of Geiger counters of various areas, each switched on a hodoscope. Their total area is over 110 m². The μ-meson detectors consist of two or three counter trays shielded with deep-bed filter (of lead and iron), and also switched on the hodoscope. Their total area is over 12 m², some of the detectors with a total areas of 6.3 m² being located underground at a depth of 40 m of water equivalent. (see Figs. 2a and 2b). To penetrate such a ground layer, μ-mesons at the earth's surface must have an energy of $E \geq 10^{10}$ ev. The detector of nuclear-active particles is a system of 128 ionization

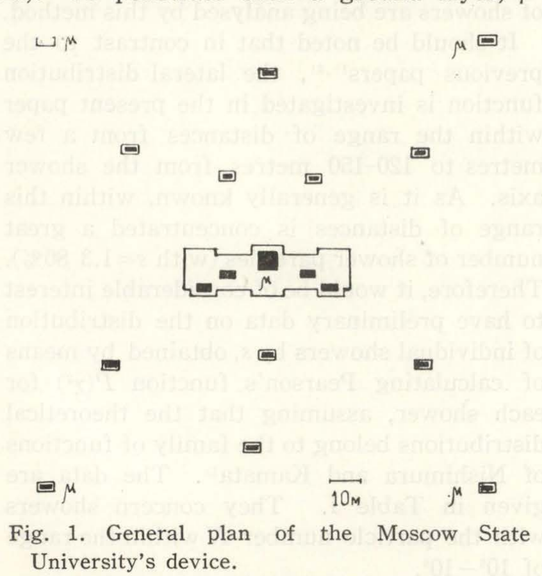
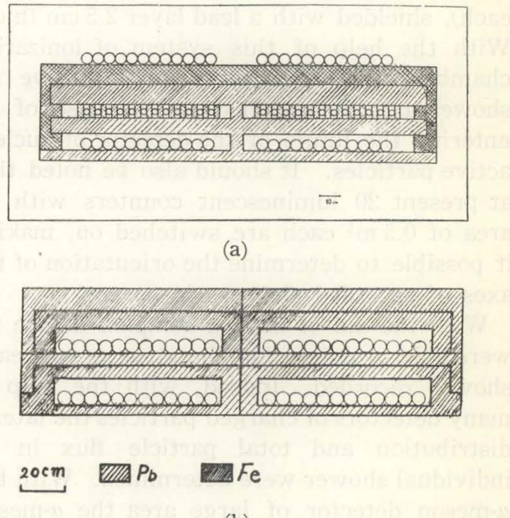


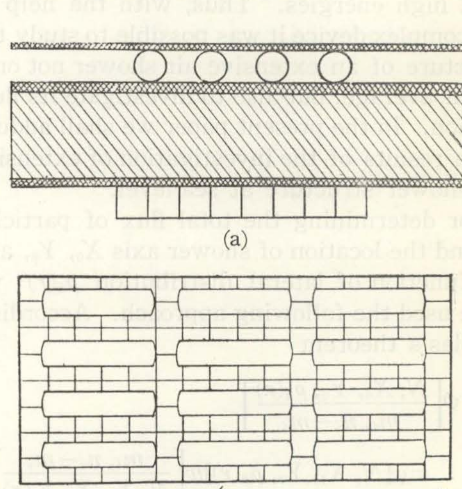
Fig. 1. General plan of the Moscow State University's device.



(a)

(b)

Fig. 2. Section of μ-meson detector.
a) section of underground detector.
b) section of ground detector.



(a)

(b)

Fig. 3. Section (a), plan (b) of the detector of nuclear-active particles.

* This paper was presented by L. I. Sarycheva.

chambers with a total area of $8\,m^2$, shielded with a graphite and lead filter (Fig. 3a and 3b). In graphite the energy of the nuclear-active component converts into the energy of the electron-photon component. In lead the development of an electron-photon cascade takes place up to the maximum. Therefore, while determining the particle number in the cascade with the help of ionization chambers, we can obtain data on the energy of nuclear-active particles. Directly above the detector of nuclear-active particles there are evenly placed 12 chambers (with an area of $0.25\,m^2$ each), shielded with a lead layer 2.5 cm thick. With the help of this system of ionization chambers the location of an extensive air shower axis is specified in the case of its entering the limits of the detector of nuclear active particles. It should also be noted that at present 20 luminescent counters with an area of $0.5\,m^2$ each are switched on, making it possible to determine the orientation of the axes of recorded showers in space.

With the aid of such a complex device we were able to determine the structure of each shower recorded. Indeed, with the help of many detectors of charged particles the lateral distribution and total particle flux in an individual shower were determined. With the μ-meson detector of large area the μ-meson flux in a given shower was determined; with the detector of nuclear-active particles we determined the flux of nuclear-active particles with high energies. Thus, with the help of our complex device it was possible to study the structure of an extensive air shower not only on an average, but also to investigate its fluctuation. In the present paper we shall adduce some results of the investigation of extensive air shower structure at sea-level.

For determining the total flux of particles N, and the location of shower axis X_0, Y_0, and the function of lateral distribution $\rho_S(r)$* we have used the following approach. According to Bias's theorem

$$\Phi\left[\frac{N,\, X_0,\, Y_0,\, \rho_S(r)}{m_i,\, n_i-m_i}\right] =\varphi[N,\, X_0,\, Y_0,\, \rho_S(r)]w\left[\frac{m_i,\, n_i-m_i}{N,\, X_0,\, Y_0,\, \rho_S(r)}\right]$$

where m_i, n_i-m_i are numbers of the counters, with the area of σ_i which discharged and did not discharge during the passage of an extensive air shower.

Φ is the probability of observation of N, X_0, Y_0, with given realization of a set of numbers m_i, n_i-m_i in the charged-particles detectors, φ is the *a priori* probability of observing N, X_0, Y_0, S, and w is the probability of observing m_i, n_i-m_i, with given realization of N, X_0, Y_0, $\rho_S(r)$. The function w may be represented as

$$\Pi_i C_{n_i}^{m_i}[1-\exp\{-\rho_S(r_i)\sigma_i N\}]^{m_i} \exp[-(n_i-m_i)\rho_S(r_i)\sigma_i N]$$

The appearance of φ does not practically influence the appearance of ϕ, ϕ is a distribution function of four incidental values N, X_0, Y_0 and S with the given numbers m_i, n_i-m_i. Therefore, from ϕ one can obtain, for example the distribution of possible values of S, calculating $\int\phi(N, X_0, Y_0, S)\, dN dx_0 dy_0$ or analogously to N and X_0, Y_0. Thus, by means of the function ϕ it is possible to obtain not only the most probable values of N, X_0, Y_0, S, corresponding to the maximum, of ϕ, but also inaccuracies in their determination. The method described seems to us the most universal and accurate in comparison with those formerly used[1),2)] though it is rather labour-consuming. By means of the fast- electoronic-computor of our University, a few hundred of showers are being analysed by this method.

It should be noted that in contrast to the previous papers[1),2)], the lateral distribution function is investigated in the present paper within the range of distances from a few metres to 120-150 metres from the shower axis. As it is generally known, within this range of distances is concentrated a great number of shower particles (with $s=1.3$ 80%). Therefore, it would be of considerable interest to have preliminary data on the distribution of individual showers by s, obtained by means of calculating Pearson's function $P(\chi^2)$ for each shower, assuming that the theoretical distributions belong to the family of functions of Nishimura and Kamata[1)]. The data are given in Table I. They concern showers with the particle number N within the range of 10^5-10^6.

All the showers observed have proved to

* We suppose that the family of the function $\rho_s(r)$ corresponds to the functions of Nishimura and Kamata.

Table I. Probabilities $P(\chi^2)$ of correspondence between the experimental and theoretical distributions of densities of charged particle flux.

No of a shower	$N \times 10^{-5}$	S 0.9	1.0	1.1	1.2	1.3	1.4
1.	2.6	<0.01	0.31	<0.01			
2.	2.0	<0.01	0.61	<0.01			
3.	2.0		<0.01	0.63	<0.01		
4.	2.2		<0.01	0.13	<0.01		
5.	4.5		<0.01	0.11	<0.01		
6.	5.3		<0.01	0.16	0.05		
7.	3.5		<0.01	0.65	<0.01		
8.	4.8		0.02	0.14	0.04		
9.	16.		0.05	0.55	0.07		
10.	1.7		<0.01	0.31	0.17	<0.01	
11.	4.6		0.07	0.6	0.72	0.14	
12.	10.		<0.01	0.18	0.17	<0.01	
13.	3.2			0.09	0.81	0.05	
14.	2.3			<0.01	0.12	<0.01	
15.	2.2			0.02	0.81	<0.01	
16.	4.1			<0.01	0.44	<0.01	
17.	1.9		<0.01	0.02	0.25	<0.01	
18.	1.8			0.025	0.12	<0.01	
19.	3.0			<0.01	0.11	<0.01	
20.	9.4			<0.01	0.04	<0.01	
21.	1.9			<0.01	0.19	0.15	<0.01
22.	3.2			<0.01	0.14	0.11	<0.01
23.	1.9			0.01	0.33	0.57	<0.01
24.	2.7				<0.01	0.37	<0.01
25.	5.8				<0.01	0.56	<0.01
26.	3.6				<0.01	0.14	<0.01

be with s within the range of 1—1.3. The density of particle flux in the showers with N in the range of 10^5-10^6 at distances 100 m from the axis is not high enough to distinguish (in the range of accuracy given by hodoscope points) between $s=1$ and $s=1.3$ at these distances. Therefore, the functions of $P(\chi^2)$ are apparently more sensitive to shorter distances from the shower axis. However, for the cases with $s<1$ Pearson's function $P(\chi^2)$ would be sensitive to $r \sim 100$ m as well. According to previously published data, for the range of distances from 1 m to 30 m, we have obtained $0.8<s<1.4$, approximately the same number of showers being analysed. The probability of the distribution in Table I and that obtained before[1] corresponding to each other, is 5%. Thus, the statistical guarantee of the data is insufficient for the final conclusion about the decrease of parameter s fluctuations for the range of the distances r from the shower axis from 1 m to 100 m.

Let us now consider the data on the structure of the μ-meson component of the extensive air shower. We could investigate μ-meson fluxes with the energy $E \geq 3.10^8$ ev, by means of the ground detector (Fig. 2b), and μ-meson fluxes with the energy $E \geq 10^{10}$ ev, by means of the underground detector (Fig. 2a). It was found that in showers with the given particle number N the lateral distribution of μ-meson fluxes on average may be shown as follows:

$$\rho_\mu(N, r) = kN^\alpha r^{-n} \exp[-r^2/r_0^2]$$

$n=0.7\pm0.1 \quad \alpha=0.85\pm0.1$

$k=5.8\cdot10^{-5} \quad r_0=195\pm15\text{ m} \quad \text{for } E\geq5.10^9\text{ ev}$

$k=4.1\cdot10^{-5} \quad r_0=155\pm15\text{ m} \quad \text{for } E\geq10^{10}\text{ ev}$

Table II.

n_μ \ $I(n_\mu)$	a		b		c		d		e	
	1	2	1	2	1	2	1	2	1	2
0	47	42	6	5	11	5	24	17	20	4
1	42	51	9	8	19	9	27	28	28	12
2	44	34	8	9	10	15	23	28	19	20
3	12	18	8	8	12	15	17	19	22	25
4	8	8	5	6	10	12	12	13	12	27
5	2	2	8	5	4	10	5	7	10	24
6	2	1	6	4	3	5	7	4	12	18
7	1	1	—	2	—	4	1	2	3	12
8		1	1	1	4	2	2	2	5	7
9			1	1	5	2	—	1	4	4
10				1	1	1	3	1	2	2
11				1	1	1	1	1	4	1
12							—		3	1
13							—		2	
14							1		2	
15									1	
16					1				1	
17										
18										
19										
20										
21									1	
22									1	
23										
24					1					
25									1	
26										
27										
28										
29										
30										
Number of events	158	158	52	52	82	82	123	123	156	156
P/χ^2	15%		50%		0.3%		20%		0.01%	

n_μ the number of μ-mesons which fell on the detectors.

a) $E_\mu \geq 3.10^8$ ev, $N=(2\sim 5)\cdot 10^6$
b) $E_\mu \geq 3.10^8$ ev, $N=(5\sim 10)\cdot 10^6$
c) $E_\mu \geq 5.10^9$ ev, $N=(2\sim 4)\cdot 10^6$
d) $E_\mu \geq 10^{10}$ ev, $N=(1\sim 2)\cdot 10^6$
e) $E_\mu \geq 10^{10}$ ev, $N=(2\sim 4)\cdot 10^6$
1) Experimental number of events.
2) Number of events predicted by Poission's fluctuations.

Use of large-area μ-detectors made it possible to obtain in showers with sufficient particle number $N \geq 10^6$ data on the μ-meson fluxes in each individual case. On the basis of these data, and also the data on the $\rho_\mu(N, r)$, distributions have been obtained, which are shown in Table II and Fig. 4. As is obvious from the table and figure, the fluctuations of the μ-meson fluxes with the energy $E \geq 3.10^8$ ev do not exceed the usual Poisson fluctuations. For the μ-mesons with the energy $E \geq 10^{10}$ ev the fluctuations considerably exceed those of Poisson. The agreement probability of the experimental and the Poisson distribution is $\sim 10^{-4}$, according to Pearson. It is also confirmed in another way. We have estimated the correlation coefficient g between the numbers of the μ-mesons falling on two halves of the underground detector identical in the area. It appeared that $g = 0.6 \pm 0.15$.

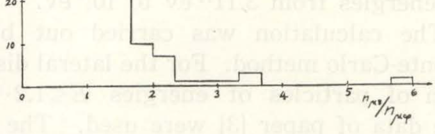


Fig. 4. Histogram of distribution of $N\mu/\overline{N}\mu$.

Note that with the number of events used by us (n. 109), the formally determined correlation coefficient of two independent accidental values could account for 0.45 with the probability of only 10^{-3}. Let us further consider the experimental data on the nuclear-active component of extensive air showers. The increase in the area of the nuclear-active-particle detector in comparison with [3] made it possible to carry out a study of the showers with the total particle number N from 3.10^5 to 3.10^6.

We have carried out measurement of the energy carried by the nuclear-active particles of high energy in a circle with a radius $R = 6$ m, with the centre in the shower axis. The method of the obtaining of the experimental data processing was the same as [3]. The determination of the flux energy was carried out in two ways: a) by the energy-spectrum of particles obtained in the circle mentioned, and b) by the obtained function of the lateral distribution of the energy-flux of the nuclear-active component. The values of the energy obtained are given in Table III for 2 groups of N.

Table III.

Range N	$\overline{N}$	$E_{n.a.}$ ev (a)	$E_{n.a.}$ ev (b)
$3.10^5 \sim 10^6$	$4.8.10^5$	$(5.5 \pm 0.3)10^{13}$	$(4.5 \pm 0.3)10^{13}$
$10^6 \sim 5.10^6$	2.10^6	$(3.1 \pm 0.5)10^{14}$	$(2.5 \pm 0.5)10^{14}$

The presence of a great number of counters switched on in the hodoscope (including ones of the small area $\sigma = 20$ cm^2), and ionization chambers placed under a thin layer of lead made it possible to determine the cases of the passage of the extensive air shower axis with the particle number $N \geq 3.10^5$ through the detector of nuclear-active particles. During this, the value of the energy flux of nuclear-active particles recorded by the device varied considerably from one shower to another. Among 34 cases of shower axis penetration through the detector, the energy-flux deflection from

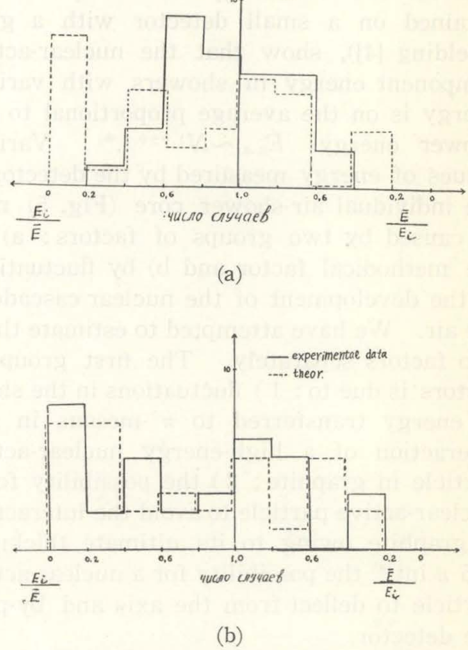


Fig. 5. Histograms of distribution of relations of energy flux of the nuclear-active component in the detector area, in the individual shower (E_i) to the mean flux ($\overline{E}$), in the same area.
a) experimental and theoretical histograms with due account of fluctuations in the share of energy transfferred, to π^0-meson during the interaction.
b) experimental and theoretical histograms with due account of both fluctuations and a) probability of particles escaping the device because of lateral distribution.

average exceeded the tenfold $(0.05<(E_i/E)<0.1)$ in 3 cases.

Fig. 5 shows the histogram of energy relations in the individual case E_i to the average E. The data are normalized to one and the same N. The data presented in Table III on an energy-flux for the shower with $N=4.8.10^5$ are somewhat smaller than those given for this group before [3]. This fact is linked with a poor shielding of the edge chambers of the lower layer which made possible the penetration of the electron-photon component through the edge of the detector's filter in [3]. In the present paper this effect is completely excluded. The data for the showers with $N=2.10^6$ show that in the showers with such energy at sea-level the nuclear-active component carries an energy approximately equal to the electron-photon component. The data obtained for the high-energy showers and the data for the low-energy showers (previously obtained on a small detector with a good shielding [4]), show that the nuclear-active component energy in showers with various energy is on the average proportional to the shower energy $E_{n.a.}\sim N^{1.0\pm0.1}$.*) Various values of energy measured by the detector in the individual air-shower core (Fig. 5) may be caused by two groups of factors: a) by the methodical factor and b) by fluctuations in the development of the nuclear cascade in the air. We have attempted to estimate these two factors separately. The first group of factors is due to: 1) fluctuations in the share of energy transferred to π°-mesons in the interaction of a high-energy nuclear-active particle in graphite; 2) the possibility for a nuclear-active particle to avoid the interaction in graphite owing to its ultimate thickness (1.5 n int)[3] the possibility for a nuclear-active particle to deflect from the axis and by-pass the detector.

It is most reasonable to study the fluctuations in the nuclear-active fluxes near the powerful shower axis, where most of the energy is carried by high energy, nuclear-active particles of which lateral distribution is sufficiently narrow. It allows the assumption that particles always pass the detector, when the shower axis passes it. However, in such showers, in the axis region, there are also particles of lower energies, the lateral divergence of which should not be neglected[3]. To ascertain the role of the factors mentioned above we have calculated the energy distribution, transferred to the π°-mesons in graphite detector for the following simple case. The "standard" flux of shower particles passes through the detector and this flux is ascertained in the following way:

1) Energy-spectrum of particles is $E^{-r}dE$;

2) Number of particles of energy $E\geq10^{12}$ ev is equal to experimental number of particles of the same energy, measured by us near the shower axis, at a distance of $R\leq6$ m;

3) The spectrum is limited by particles of energies from 3.11^{11} ev to 10^{13} ev.

The calculation was carried out by the Monte-Carlo method. For the lateral distribution of particles of energies $E\leq1.2\cdot10^{12}$ ev the data of paper [3] were used. The deviation from the shower axis of particles of energy $E>1.2\cdot10^{12}$ was neglected. The values of probability of energy transfer to π°-mesons was taken from paper [6], which deals with the energy-region observed.

Several series of calculations with 34 showers in each were drawn (by the number of axes experimentally recorded). In each, the following facts were drawn successively:

a) the incidence of each particle upon the detector (or its passing-by);

b) the presence in the given shower of the particles with high energy, the average appearance frequency of which is below one;

c) the interaction of each particle in the detector (or its passage without interaction);

d) the share of energy of each interacting particle, transferred to π°-mesons.

The results of the calculations made it possible to obtain the distribution of the energy transferred to π°-mesons in the detector during the fall of 34 showers on it. These distributions were found much the same for various series. The width and shape of the distributions obtained in this way, do not differ from the experimental distribution, with regard for statistical accuracy (Fig. 5). We should note that the same calculation, but carried without regard

* The strong dependence of $E_{n.a.}\sim N^{1.4\pm0.2}$, obtained in the [5] is connected with the fact mentioned above of the penetration of electron-photon component through the filter in powerful showers having apparently a large flux of electrons and photons with high energy.

for the probability of deviation of particles with $E \leq 1.2 \cdot 10^{12}$ ev from the axis, leads to distributions which are considerably narrower than the experimental.

Thus, the conclusion may be drawn that for an explanation of particles energy flux fluctuations in the shower axis with $N \geq 3.10^5$, it is unnecessary to assume the presence of such fluctuations which would cause a substantial decrese in the energy flux of nuclear-active particles, in comparison with the mean flux.

In order to explain our experimental data it is sufficient to take into account only the Poisson fluctuations in the appearance of high-energy particles, the average quantity of which is less than one.

References

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Discussion

Sreekantan, B. V.: Since nearly 90% of the μ-mesons are supposed to have the energy above 10 Bev, why should there be a difference in behavior of the fluctuation for the cases of μ-meson energy below 10 Bev and above 10 Bev?

Sarycheva, L. I.: Authors have not made any attempt to explain the fluctuation in behavior of μ-meson yet, but they have only established the existence of the fluctuation.

Oda, M.: Have you seen any evidence of unusual energy spectrum of N-particles which indicates the existence of exceptionally high energy N-particle.

Sarycheva: They did not measure the energy spectrum of N-particles. Rather they made a calculation from the point of view that there are particles whose energy is greater than the other particles.

Zatsepin, G. T.: I think that from presented data one can only say, that apparatus fluctuations were so big that actual fluctuation could not be measured. But this does not mean that actual fluctuation does not exist.