[1] Alekseevskii, Brandt and Kostina, J. Exptl. Theoret. Phys. (U.S.S.R.) **21**, 951 (1951).

[2] Alekseevskii, Brandt and Kostina, Izv. Akad. Nauk SSSR, Ser. Fiz. **16**, 233 (1952).

[3] N. E. Alekseevskii, J. Exptl. Theoret. Phys. (U.S.S.R.) **23**, 484 (1952).

[4] N. E. Alekseevskii, J. Exptl. Theoret. Phys. (U.S.S.R.) **25**, 383 (1953).

[5] Alekseevskii, Zhuravlev and Lifanov, J. Exptl. Theoret. Phys. (U.S.S.R.) **27**, 125 (1954).

[6] Alekseevskii, Zhdanov and Zhuravlev, J. Exptl. Theoret. Phys. (U.S.S.R.) **28**, 237 (1955); Soviet Phys. JETP **1**, 99 (1955).

[7] M. Hansen, *The Structure of Binary Alloys;* Metallurgizdat, M.—L., 1951; p. 317 (J. Springer, Berlin, 1936; p. 324).

[8] E. Zintl and H. Kaiser, Z. anorg. u. allgem. Chem. **211**, 113 (1933).

[9] V. P. Glagoleva and G. S. Zhdanov, J. Exptl. Theoret. Phys. (U.S.S.R.) **25**, 284 (1953).

[10] H. I. Wallbaum, Z. Metallkunde **10**, 200 (1943).

[11] B. T. Matthias, Phys. Rev. **90**, 487 (1953).

[12] N. N. Zhuravlev and G. S. Zhdanov, J. Exptl. Theoret. Phys. (U.S.S.R.) **25**, 485 (1953).

[13] N. N. Zhuravlev and G. S. Zhdanov, J. Exptl. Theoret. Phys. (U.S.S.R.) **28**, 228 (1955); Soviet Physics JETP **1**, 91 (1955).

[14] E. M. Bronshtein-Kupletskaya, *The Determination of the Specific Gravity of Minerals*, U.S.S.R. Acad. Sci. Publ. Hse., 1951, pp. 43—55.

[15] F. Roessler, Z. anorg. u. allgem. Chem. **9**, 68 (1895).

[16] L. M. Kefeli, Author's summary of doctoral dissertation, L. Ia. Karpov Physico-Chemical Institute, 1956.

[17] L. Wöhler and L. Metz, Z. anorg. u. allgem. Chem. **149**, 310 (1925).

Translated by S. D. Elliott
270

SOVIET PHYSICS JETP VOLUME 5, NUMBER 6 DECEMBER 15, 1957

The Penetrating Component of Extensive Cosmic Ray Showers in the Atmosphere

IU. N. VAVILOV, IU. F. EVSTIGNEEV, AND S. I. NIKOL'SKII

P. N. Lebedev Physical Institute, Academy of Sciences, U.S.S.R.

(Submitted to JETP editor January 12, 1957)

J. Exptl. Theoret. Phys. (U.S.S.R.) **32**, 1319-1327 (June, 1957)

We have investigated the spatial distribution of μ mesons arising from extensive air showers initiated by primary particles of various energies. It was found that within experimental errors the spatial distribution function for μ mesons did not depend on the energy of the primary particle. The number of μ mesons produced varied with the energy of the primary particle in such a way as to confirm the supposition, advanced previously, that the manner in which energy is distributed among the secondary particles in an elementary nuclear interaction changes at an energy of about 10^{15} ev.

IT HAS BEEN ESTABLISHED by many experiments[1] that the penetrating component in extensive air showers consists both of particles which react strongly with various nuclei, and those which do not (μ mesons). There are more of the latter (passive) particles than of the former (active) ones. In the following we describe the results of an investigation carried out in the summer and fall of 1954 at an altitude of 3860 m (Pamir) on the passive part of the penetrating component of showers.

1. EXPERIMENTAL SETUP

To study the spatial distribution of charged particles in extensive atmospheric showers, we investigated individual showers, using a large number of counters in a hodoscopic arrangement. For each shower of interest we found where the axis of the shower was, the spatial distribution of charged particles, and the total number of particles in the shower at the plane of observation. Penetrating par-

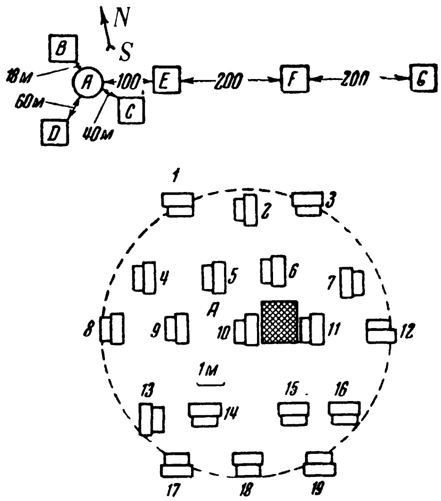

FIG. 1. Experimental arrangement for measuring the particle current density in extensive atmospheric showers whose axes fall near point A. The small arrow near B points north. The crosshatched rectangle near A denotes a detector for penetrating particles.

ticles were also detected at several points.

Figure 1 shows the general experimental setup. Nineteen groups of hodoscopic counters were distributed over a circle of radius 6 m. about the point A. Each group contained 24 counters of area 16 cm², and 24 counters of area 100 cm². The resolving time of the hodoscope channels was $(1-3)\times 10^{-5}$ sec. The axes of extensive air showers which passed near A could be located to within 1 m (taking into account the circular symmetry of the shower).

Figure 1 and table 1 show the number of hodoscope channels, the counter area feeding each channel, and the resolving time of the associated electronics. The number of counters at points B, C, D, as shown in Table 1, was enough to measure the current density of charged particles in showers involving 10^5-10^6 particles. The counter area available at point E was sufficient to determine the current density of charged particles above E only in showers with about 10^6 particles. The charged particle current density in showers with fewer particles was obtained by assuming that showers with the same (total) number of particles have the same spatial distribution functions. Grouping together showers involving the same total number of particles and with the same axes, it is possible to find the probability of recording a particle at a given point, and hence the mean particle current density at a corresponding distance from the shower axis. The average current density of charged particles at points F and G, located 300 and 500 m from the center of the arrangement, was determined in a similar way.

In addition to the hodoscopic groups of counters

TABLE I.

Point	Distance from center, m	Counter area associated with one hodoscope channel, cm²	Number of hodoscope channels	Resolving time of hodoscope, sec
B	18	22 100 330	24 24 24	$\sim 10^{-5}$ $\sim 10^{-5}$ $\sim 10^{-5}$
C	40	22 100 330	24 24 36	$\sim 10^{-5}$ $\sim 10^{-5}$ $\sim 10^{-5}$
D	60	100 330	24 48	$\sim 10^{-5}$ $\sim 10^{-5}$
E	100	22 330	24 48	$1\cdot 10^{-5}$ $1\cdot 10^{-5}$
F	300	22 100 4000	24 24 6	$\sim 10^{-5}$ $\sim 10^{-5}$ $2.5\cdot 16^{-6}$
G	500	3000	8	$2.5\cdot 10^{-6}$

used to measure the total charged particle current density, points A, B, C, E, and G had detectors of penetrating particles. The detectors at points A, B, and C (Fig. 2a) could distinguish between penetrating particles which did not interact strongly with nuclei (μ mesons) and electron showers formed in the material of the detector. The lead and iron absorbers surrounding the hodoscopic counters of the detector practically eliminated the possibility that electrons and photons from the air could reach these counters. Filters between the rows of counters allowed us to distinguish between electron showers and δ-showers produced by μ mesons. In detector A, one row of counters had an area of 0.48 m², the corresponding figures for detectors B and C being 0.36 m² and 0.72 m². The penetrating particle detectors at points E and G were simpler (Fig. 2b), since earlier measurements had shown that at such distances from the shower axis, there were no particles which interacted strongly with nuclei to produce showers. The counter area was 1.8 m² at point E and 2.4 m² at detector G.

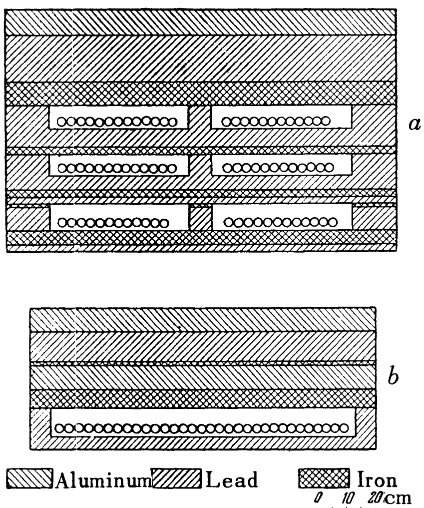

FIG. 2.

The hodoscopic arrangement described above was triggered by coincidences between the four groups of counters at the center of A (Fig. 1). The counter area in each of these groups was 400 cm². About 8000 extensive air showers were recorded in all. In about 1200 of these, the axis of the shower passed near A.

2. SPATIAL DISTRIBUTION OF μ MESONS IN SHOWERS

For the showers we observed, the μ meson current density was not large enough that it could be measured using the penetrating particle detectors described above. The average μ meson current density in showers with a given total number of particles was measured by counting the number of μ mesons passing through the detector in showers whose axes were all the same distance from the detector. The μ meson current density at this given distance from the shower axis can then be written

$$\rho_\mu(r) = (1/S)\ln(1 + m/n).$$

where S is the area covered by one row of detector counters, m is the number of μ mesons recorded, and n is the total number of showers observed in which the counters of the detector did not fire.

We observed events where the μ meson passed through the middle row of counters in Fig. 2a. In such cases, one counter of the middle row was discharged, and in addition a counter registered in at least one other row of the detector. When a μ meson passed through all three rows, the counters which registered were all found to lie on a straight line. When the μ meson passed between counters in the top or bottom rows, or went through the detector at an angle, or was absorbed in the material between the bottom and middle rows, then only two rows of the detector fired. All cases where two or more counters in the same row went off were due to δ-showers, or electron showers originating in the detector and were included neither in the m nor in the n of the above formula. Such showers, which originate in the detector, were excluded from consideration because when a big shower occurs in the detector it is not possible to say reliably whether a μ meson is present or not. Neglecting, then, the μ mesons which initiated δ-showers in the material, and taking electron showers in a detector to be statistically independent of the passage of a μ meson through that detector, we obtained, for each distance from the shower axis and for a given primary energy, the current density of μ mesons with enough energy (≥ 440 Mev) to pass through the absorbers in the detector.

We measured the probabilities of recording δ-showers initiated both by μ mesons from the hard component of cosmic rays and by μ mesons associated with extensive air showers. Measurements were made with a detector of penetrating particles in a shaft whose depth was equivalent to 16 m of water. For all practical purposes, this eliminated that component of cosmic rays which interacts strongly with nuclei. The measurements showed that the probability of observing, in one row of the detector, a δ-shower initiated by a cosmic ray μ meson is $(7 \pm 0.6)\%$ of the total number of mesons passing through the detector. The corresponding probability for δ-showers initiated by μ mesons from extensive atmospheric showers was $(8 \pm 1)\%$. Since the probability of observing a δ-shower in at least one of the three layers of counters in the detector is about three times as large, the number of μ mesons passing through the detector unaccompanied by δ-showers was increased by 25% in calculating the μ meson current density.

In finding the μ meson current density at large distances from the shower axis, it was not necessary to exclude events where showers originated in the detector material. This is because even at 60 m from the shower core the number of particles which interact strongly with nuclei is only a few per cent of the number of μ mesons.[2] Hence at large distances from the shower core, both events where only one counter fired and events where counters in more than one row of the detector fired were taken to mean that a μ meson had passed through the detector. The number of the latter events ($\sim 10\%$) was about the same as the expected number of δ-showers, so that the difference in the criteria for selecting μ mesons did not distort the results.

Analysis of the experimental results leads to Fig. 3, which shows the current density of μ mesons with energy ≥ 440 Mev as a function of distance from the core in extensive atmospheric showers containing

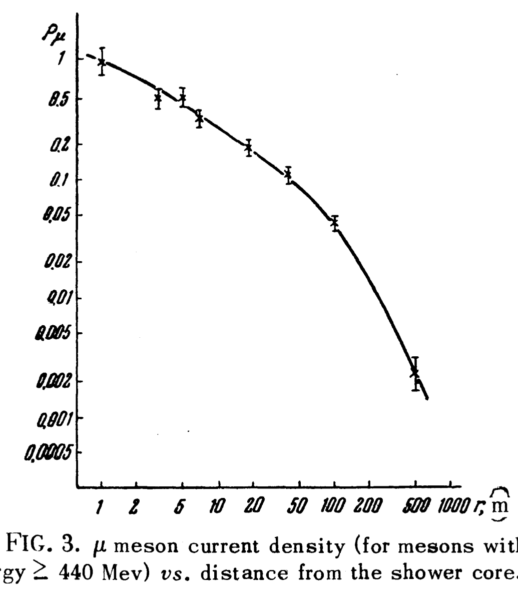

FIG. 3. μ meson current density (for mesons with energy ≥ 440 Mev) *vs.* distance from the shower core.

5×10^4 to 10^6 ($\bar{N} = 2 \times 10^5$) charged particles. In the measurements at 100 and 500 m, μ mesons with energy ≥ 390 Mev were counted, so that the current densities obtained experimentally at these distances were decreased by a factor obtained from the μ meson energy spectrum (at various distances from the core) given in Ref. 3. The correction was less than the statistical error at both 100 m and 500 m. It should also be mentioned that the detector which measured the μ meson current density at small distances from the shower axis was at the center of the setup, thus weighting the results in favor of showers with relatively few charged particles. This decreased the average μ meson current density at small distances from the shower axis.* In order to avoid this effect, the averaging was carried out over such a narrow range in the energy of the primary particle initiating the shower that the average energy in each interval was independent of where the shower axis fell.

As has already been indicated in Ref. 4, the spatial distribution of μ mesons in extensive air showers cannot be completely explained by Coulomb scattering of the μ mesons from the nuclei of air atoms encountered in their progress through the atmosphere. The effect of the angular spread with which the π mesons are emitted in elementary nuclear interactions on the spatial distribution of μ mesons is more marked if one considers μ mesons of a fixed energy. Using the μ meson energy spectrum at various distances from the shower core given in Ref. 3, and the spatial distribution of μ mesons shown in Fig. 3, the mean square radius for the spread of μ mesons with energies 3.5 to 3.9 Bev turns out to be ≥ 300 m. The Coulomb scattering of μ mesons with the above energy and originating at a height of 10 km leads to an rms radius of 50 m, neglecting ionization losses. Ionization losses would only decrease this figure. This difference between the experimental rms radius of the spatial distribution and the rms radius obtained from Coulomb scattering calculations cannot be due to the earth's magnetic field. The expected lateral displacement from the shower axis is about $r \approx h300H'h/2E \approx 50$ m (E is the μ meson energy, H' the horizontal component of the earth's magnetic field, and h the height at which the μ mesons were formed). Finally, taking into account the angles at which the μ mesons from $\pi^{\pm}$ are emitted leads to a similar displacement.

Thus the angle at which π mesons are emitted in

*This effect was neglected in Ref. 5, and consequently the distribution curve obtained there for small distances from the shower axis is distorted.

nucleon–nucleon interactions at high and very high energies must be taken into account to explain the spatial distributions of μ mesons. This is because all the other factors which tend to spread out the μ mesons lead to an rms radius for 3.5–3.9 Bev μ mesons of $\lesssim$ 100 m while experimentally the radius is $\geq$ 300 m.* It should be remembered that, unlike the situation with μ mesons, the spatial distribution of the electron–photon component in extensive atmospheric showers can be explained by Coulomb scattering of the electrons.[4] The angle at which π^0 mesons are emitted in nuclear interactions has no effect on the spatial distribution of electrons in the shower.

There are presumably two reasons for the fact that the angle of emission of π mesons has an appreciable effect on the spatial distributions of the penetrating component of extensive air showers, but not on the soft component. On one hand, μ mesons, the overwhelming majority of which come from $\pi^{\pm}$ mesons, have a considerably longer range than do the electron photon showers. The latter come from the decay of π^0 mesons having the same energy as the $\pi^{\pm}$ mesons leading to the μ meson component of extensive air showers. On the other hand, the shape of the spatial distribution function for electrons near the axis[6] indicates that π^0 mesons with an energy 10^{10} ev play a large role in the formation of the electron–photon component deep in the atmosphere. It is natural that mesons of such energy would be emitted from a nuclear interaction at smaller angles than the mesons producing the general current of μ mesons in the shower.

3. TOTAL NUMBER OF μ MESONS AS A FUNCTION OF ENERGY

If we assume that the spatial distribution of μ mesons does not depend on the energy of the primary particle, then we can compare the number of μ mesons in showers with varying numbers of charged particles. How valid is the above assumption? Figure 3 shows that for distances 0–40 m the spatial distribution varies as r^{-n}. Values of the exponent n for extensive atmospheric showers initiated by primary particles of various energies* are shown in Table 2. From the data in this table it is evident that the spatial distribution of μ mesons near the center of the shower is independent of the energy of the primary particle which started the shower (Fig. 4).

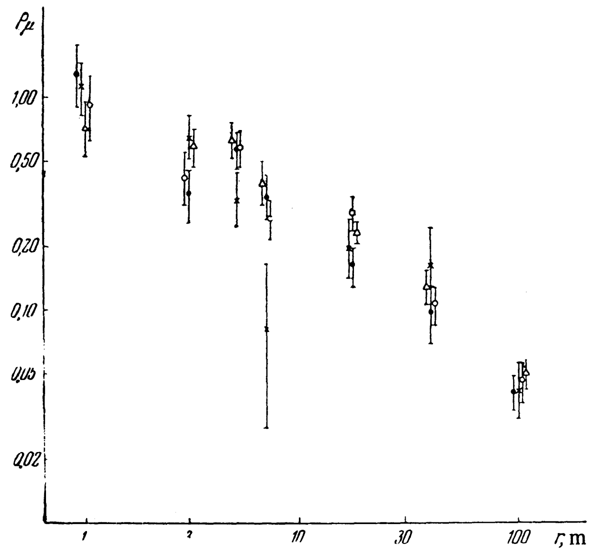

FIG. 4. Spatial distribution of μ mesons with energy more than 440 Mev in extensive showers with various (total) numbers of particles: × – 0.53×10^5; Δ – 1.5×10^5; ○ – 3.2×10^5; ● – 10^6. The μ meson current density is normalized relative to showers with 2×10^5 particles, using the number of μ mesons 100 m from the axis of the shower.

The statistical accuracy of our experimental data is insufficient to give reliable information about changes in the spatial distribution of μ mesons on the periphery of extensive atmospheric showers as the primary energy is varied. At distances of 100–500 m from the center of the shower the normalized spatial distribution of μ mesons is given by the formula $r^{-(1.8\pm0.2)}$ ($E_0 = 6 \times 10^{14}$ ev). This result can be compared with the data of Ref. 4, which were obtained at the same altitude as were our data (3860 m). In Ref. 4 the primary energies considered were more than 10^{17} ev, and the spatial distribution of μ mesons 200–800 m from the shower axis was

---

*Using our experimental data on the spatial distribution of 3.5–3.9 Bev μ mesons, and assuming that the $\pi^{\pm}$ mesons of corresponding energy are formed 2–8 km above the experimental setup, we can estimate the perpendicular momentum received by π mesons in the interaction with nuclei of particles of energy $\geq 10^{11}$ ev. The result is $1-3\mu c$, where μ is the mass of the π meson.

*In an earlier paper,[7] we took the coefficient of proportionality between the number of particles in the shower and the primary energy to be 5×10^{19} ev (at an altitude 3860 m). This estimate was based on calculations with a particular model of the nuclear cascade process. We now use the coefficient given by $E_0 = 2.5 \times 10^9$ N. The new value is based on an analysis of the absorption of extensive showers in the atmosphere.

measured. In complete agreement with our results, this spatial distribution was given by $r^{-(1.8\pm0.2)}$.

Thus the spatial distribution of μ mesons does not change when the energy of the primary particle initiating the shower is increased by a factor of 200. This justifies our supposition that the spatial distribution of μ mesons in extensive atmospheric showers does not depend on the total number of particles.

The experimental data presently available do not give the total number of μ mesons with energy ≥ 440 Mev in an extensive atmospheric shower. This is because, even at the largest distances investigated, the μ meson current density, in the energy range given above, falls off slower than $1/r^2$. μ mesons with energies higher than 1 Bev have a narrower spatial distribution. The total number of such mesons can be obtained from the spatial distribution function in Fig. 3 and the data on the energy spectrum of μ mesons in extensive atmospheric showers (at various distances) given in Ref. 3. Figure 5 shows how the number of μ mesons with energy $\geq$ 1 Bev depends on the primary energy. From this graph it follows that in the energy (of the primary particle) range 10^{14} to 2×10^{15} ev the total number of μ mesons varies as $\sim E_0^{(0.62\pm0.12)}$.

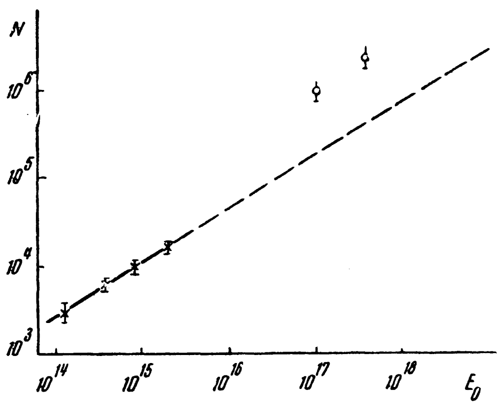

FIG. 5. The number of μ mesons with energy more than 1 Bev occurring in extensive showers initiated by primary particles of various energies. The crosses are experimental data from the present work, the circles are data from Ref. 4.

Our results on the relation between the number of μ mesons in the shower and the energy of the primary particle do not agree with the results of Ref. 9. The latter work was carried on at an altitude of 3260 m above sea level. The number of μ mesons N_μ was obtained as a function of the number of electrons, N_e for extensive atmospheric showers, by

TABLE II

Total number of charged particles in the shower	Energy of primary particle, ev	Meson current density in the total number of particles incident on one m^2 at various distances from the axis of the shower							n
		1 m	3 m	5 m	7 m	18 m	40 m	100 m	
$0.53\cdot10^5$	$1.3\cdot10^{14}$	0.5 ± 0.15	0.31 ± 0.07	0.15 ± 0.06	0.04 ± 0.04	0.08 ± 0.02	0.06 ± 0.02	0.02 ± 0.006	0.61 ± 0.1
$1.5\cdot10^5$	$3.7\cdot10^{14}$	0.6 ± 0.2	0.5 ± 0.09	0.51 ± 0.08	0.35 ± 0.08	0.19 ± 0.03	0.11 ± 0.02	0.043 ± 0.007	0.54 ± 0.12
$3.2\cdot10^5$	$8\cdot10^{14}$	1.2 ± 0.5	0.6 ± 0.18	0.8 ± 0.15	0.35 ± 0.09	0.38 ± 0.09	0.14 ± 0.03	0.062 ± 0.012	0.58 ± 0.12
$7.7\cdot10^5$	$1.9\cdot10^{15}$	3.3 ± 1.4	0.9 ± 0.3	1.5 ± 0.3	0.9 ± 0.2	0.4 ± 0.1	0.23 ± 0.05	0.11 ± 0.02	0.74 ± 0.11

varying the area of unshielded counters. It was found that $N_{\mu} \sim N_e^{0.87}$ in the energy interval 5×10^{14} to 8×10^{16} ev.

Our data pertain to an energy interval $10^{14} - 2 \times 10^{15}$ ev. To compare the two sets of data, we compare the total number of μ mesons with energy ≥ 1 Bev in extensive atmospheric showers, initiated by primary particles of energy $E_0 \approx 10^{15}$ ev with the number of μ mesons in showers initiated by primary particles of energy $E_0 \approx 10^{17}$ ev (Ref. 4). From Fig. 5 we see that in this energy interval the number of μ mesons varies as $E_0^{0.95 \pm 0.05}$ which agrees with Ref. 10. In the method of Ref. 9, the experimental data was averaged over a rather wide range of primary particle energies. The result quoted is thus the average of two different proportionality constants between the number of μ mesons and the number of electrons in the shower ($N_{\mu} \sim N_e^{0.6}$ and $N_{\mu} \sim N_e$).

The change in the relation between the number of μ mesons in the shower and the energy of the primary particle for $E_0 > 10^{15}$ ev agrees with the suggestion we made earlier,[7] on the basis of other data, that there is a change in the nature of the elementary nuclear interaction at an energy $\sim 10^{15}$ ev. Experimental data on the spatial distribution and vertical development of extensive atmospheric showers[11, 12] indicate that in the interaction of nuclei with nucleons of energy $10^{13} - 10^{14}$ ev, a large part of the energy is concentrated on one secondary particle. This is similar to the situation at $10^{10} - 10^{12}$ ev. This secondary particle, presumably a nucleon, maintains its energetically preferred role in the succeeding stages of the nuclear cascade process. This selection, in the first nuclear interaction, of an energetically preferred particle takes place in interactions with primary particles of energy up to $\sim 10^{15}$ ev. At energies higher than 10^{15} ev, the number of secondary particles carrying away most of the energy increases with increasing energy of the primary particle. If secondary nucleons with energy $\leq 10^{15}$ ev keep a large fraction of their energy in succeeding nuclear interactions, then one can regard an extensive atmospheric shower started by a primary particle of energy $> 10^{15}$ ev as approximately equivalent to a sum of showers, each started by particles of energy $> 10^{15}$ ev. In such a situation, the number of μ mesons must be approximately proportional to the energy of the primary particle, which is observed experimentally.

The measurements were made by a large staff at the Pamir Expedition of the Physics Institute, Academy of Sciences, U.S.S.R. The authors express their gratitude to all their comrades, and especially to O. I. Dovzhenko, V. M. Seleznev, and E. I. Tukish. The authors would also like to thank Prof. S. N. Vernov, Prof. N. A. Dobrotin and G. T. Zatsepin for valuable discussion of the results.

---

1 Dobrotin, Zatsepin *et al.*, Uspekhi Fiz. Nauk **49**, 186 (1953).

2 Vavilov, Nikol'skii and Sarantsev, J. Exptl. Theoret. Phys. (U.S.S.R.) **28**, 505 (1955); Soviet Phys. JETP **1**, 399 (1955).

3 Dovzhenko, Nelepo and Nikol'skii, J. Exptl. Theoret. Phys. (U.S.S.R.) **32**, 463 (1957).

4 Antonov, Vavilov, Zatsepin *et al.*, J. Exptl. Theoret. Phys. (U.S.S.R.) **32**, 227 (1957); Soviet Phys. JETP **5**, 172 (1957).

5 Dobrotin, Zatsepin *et al.*, Nuovo cimento Suppl. **3**, 635 (1956).

6 Dobrovol'skii, Nikol'skii *et al.*, J. Exptl. Theoret. Phys. (U.S.S.R.) **31**, 939 (1956); Soviet Phys. JETP **4**, 799 (1957).

7 Nikol'skii, Vavilov, and Batov, Dokl. Akad. Nauk SSSR **111**, 71 (1956).

8 K. Greisen, *Progress in Cosmic Ray Physics*, Vol. III, Amsterdam, 1956.

9 Cocconi, Tongiorgi, and Greisen, Phys. Rev. **75**, 1963 (1949).

10 Zatsepin, Rozental', *et al.*, Dokl. Akad. Nauk SSSR **69**, 341 (1949).

11 Dobrotin, Zatsepin *et al.*, Izv. Akad. Nauk SSSR, Ser. Fiz. **19**, 666 (1955).

12 V. V. Guzhavin and G. T. Zatsepin, J. Exptl. Theoret. Phys. (U.S.S.R.) **32**, 365 (1957); Soviet Phys. JETP **5**, 312 (1957).

Translated by R. Krotkov
271