EXPERIMENTAL INVESTIGATION OF THE ENERGY SPECTRUM OF THE PENETRATING COMPONENT OF EXTENSIVE AIR SHOWERS

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The energy spectrum of the μ-meson component of extensive air showers was measured in the range from 0.4 to 37 Bev. The investigations were carried out for three groups of showers with mean number of particles equal to 1.4×10^4, 7×10^4, and 2.9×10^5. The energy spectrum has been plotted for the three shower groups at a mean distance of ~ 28 m from the axis. The energy spectrum of the shower as a whole has also been determined. For all three shower groups, the power exponent of this spectrum is approximately equal to one.

AN investigation of the energy spectrum of the penetrating component of extensive air showers (EAS) was carried out by measuring the absorption of μ mesons in EAS at various depths underground. The measurements were carried out in several mines situated at an altitude of 400 m above sea level in various parts of the city of Tbilisi. Because of the need of transporting the array from place to place, the geometry of the setup that was used was not optimal from the point of view of statistics and of the accuracy of shower size determination and axis location. However, the setup corresponded to the best that could be attained under the conditions prevailing at each place.

The block diagram of the array is shown in Fig. 1. Triple coincidences between closely placed groups of Geiger-Müller counters, shown in Fig. 1 by the small circles, were used for the selection of EAS. The area of each group amounted to ~ 0.0257 m^2. The counters were placed in the vertices of a right-angle triangle, for which the radius of the circumscribing circle was equal to 1 m. These counter groups triggered four trays of hodoscope counters I — IV. The distance between the groups I, II and I, III was equal to ~ 10 m, while that between the groups I and IV was ~ 20 m. In each group of the hodoscope counters, counters of three different dimensions were used with a total sensitive area of 0.3 m^2. This ensured measurement of the density of the soft component in the range from 2 to 400 particles/m^2 with an average accuracy of $\pm 40\%$.

The underground part of the array consisted of two Geiger-Müller counter trays. All the Geiger counters in each tray were connected in parallel. The total area of the tray amounted to

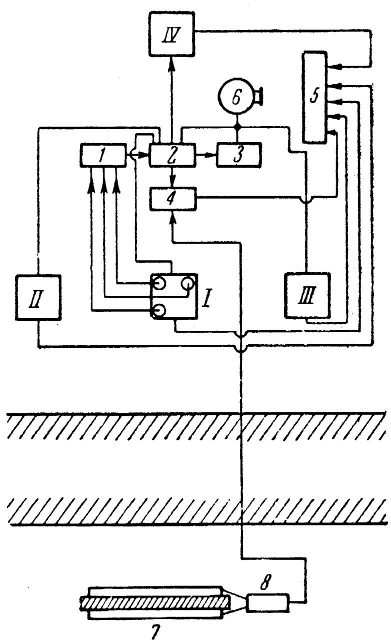

FIG. 1. Block diagram of the array: I, II, III, and IV – hodoscope trays, o – counters of the selection system, 1 – triple coincidence circuit, 2 – master-pulse shaping circuit, 3 – camera control circuit, 4 – master-pulse underground detector coincidence circuit, 5 – neon lamp panel, 6 – cine camera, 7 – underground counter trays, 8 – double coincidence circuit.

~ 1 m^2. The trays were placed one above the other and connected to a double-coincidence circuit. A lead absorber 8 cm thick was placed between the trays, and prevented the detection by the array of accidental background coincidences. The signals from the underground detector, as can be seen from Fig. 1, were fed to the circuit which selected their coincidences with the master pulse.

The master pulse, formed as the result of triple coincidences of the selection-system count-

Depth, m w.e.	$\bar{N}\cdot 10^{-4}$	n	n_μ	ρ_μ	$\sqrt{\overline{r^2}}$, m
3.2	1.4	562	59	0.44±0.06	10
	7	311	62	0.86±0.13	10
	29	222	71	1.48±0.25	10
61	1.4	257	32	0.13±0.03	13
	7	156	26	0.18±0.04	15
	29	217	82	0.48±0.08	16
127	1.4	348	19	0.058±0.014	27
	7	278	32	0.12±0.024	27
	29	302	63	0.23±0.04	27
162	1.4	1095	50	0.049±0.007	29
	7	737	60	0.086±0.012	29
	29	658	91	0.148±0.018	29

ers, was fed also to the hodoscope and to the circuit controlling the operation of a cine-camera which recorded the panel with the neon lamps. The resolving times of the systems were as follows: selection system — 2.5×10^{-6} sec, underground double coincidences — 2.5×10^{-6} sec, and hodoscope — 4×10^{-5} sec. These resolving times were sufficient to justify neglecting chance coincidences.

In a different series of experiments, the underground group of hodoscope counters was placed at depths of 162, 127, and 61 m water equivalent (w.e.). In one series of measurements, the penetrating-particle detector was placed on the surface of the earth under a layer of lead with a thickness of 3.2 m w.e. In the latter case, the detector consisted of three trays of hodoscope counters of the type GC-60 separated by lead layers. Each tray consisted of eight counters with a total area of 0.26 m^2. This detector made it possible to distinguish between the passage of μ mesons and the tracks of the nuclear-active component, according to the following criteria: an event was considered to be a μ meson if:

a) a single counter was discharged in each of the trays, so that one could reconstruct the particle track; and

b) if two or three adjoining counters in one of the trays were discharged together with single counter discharges in the remaining trays. In such a way, the δ-ray-producing μ mesons were also taken into account.

For the chosen selection system, 90% of all EAS detected by the array fell inside a circle 50 m in radius, the center of which coincided with the center of the selection system. Under these conditions, it was possible to determine the coordinates of the point of intersection of the shower axis with the plane of observation with an average error of ±50% from the information on the density of charged shower particles at the position of the hodoscope trays, and using the Nishimura-Kamata formula for the lateral distribution.[1] From these data, the shower size was determined with an error of +100%, −30%. It should be noted that we used the analytical expression for the Nishimura-Kamata distribution given by Greisen,[2] assuming that the age parameter $s = 1.25$.

All EAS detected by the array were divided into groups of various sizes. The groups contained showers with number of particles N from 7×10^3 to 4.5×10^5. Such a choice was made because of the fact that the size of showers smaller than 7×10^3 cannot be determined using the chosen array geometry (less than three hodoscopic trays are struck), and showers with $N > 4.5 \times 10^5$ were not considered because of poor statistics. According to the accuracy of shower size determination, the division into the three groups was as follows: $7 \times 10^3 - 2.8 \times 10^4$, $2.8 \times 10^4 - 1.1 \times 10^5$, and $1.1 \times 10^5 - 4.5 \times 10^5$, which correspond to mean weighted values of shower size 1.4×10^4, 7×10^4, and 2.9×10^5 respectively.

The results obtained in different series of measurements are collected in the table which presents, among other data, the average density of penetrating particles, and the mean square distance from the axis to which this density corresponds, for each shower group. The mean density ρ_μ of the μ-meson flux was determined from the expression

$$\rho_\mu = \frac{1}{\sigma} \ln \frac{n}{n - n_\mu}, \tag{1}$$

where σ is the area of one tray of the detector, n is the number of detected showers of a given group, and n_μ is the number of showers of the given group with μ-meson accompaniment.

In spite of the fact that, in all series of measurements, the penetrating-particle detector was placed near the vertical passing through the center of the selection system (at a distance of 0 — 10 m), it can be seen from the table that the actual distance between the axis and the detector increases with depth. If the detector is placed at a depth h, and if the point of intersection of the vertical passing through it with the surface of the earth is taken as the origin of the coordinate system, then the distance r between the detector and the shower axis at the depth h is given by the formula

$$r^2 = R^2 \sin^2 \varphi + (R \cos \varphi \cos \vartheta - h \sin \vartheta)^2, \qquad (2)$$

where R is the distance from the shower axis trace on the earth's surface to the origin of coordinates, and φ and ϑ are the azimuth and zenith angles of the axis.

In order to obtain the required root-mean-square distance $(\overline{r^2})^{1/2}$, one should assume specific statistical distributions of the quantities entering into the right-hand side of Eq. (2). For φ we shall, obviously, take a uniform distribution. The angle ϑ, according to Greisen,[2] has a distribution of the form $J_\vartheta = J_0 \cos^{8.3} \vartheta$, while the distribution of A has been calculated by us from direct hodoscope measurements. The values of $(\overline{r^2})^{1/2}$ found in such a way are given in the table.

In order to construct the energy spectrum at a given distance from the shower axis, the numbers given in the table were recalculated for one average distance of 28 m from the axis. An analysis of the data given in the table shows that, in choosing the distance of 28 m, it is necessary to recalculate the μ-meson flux density only for the depths of 61 and 3.2 m w.e., for which the lateral distribution of the μ-meson flux in EAS is sufficiently well known.[3,4]

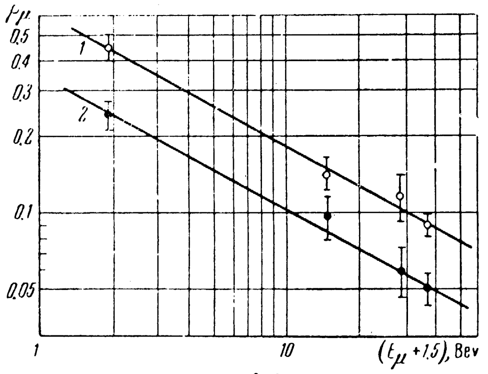

FIG. 2. Energy spectrum of the μ-meson component at a mean distance of 28 m from the axis of EAS: 1 – for $\overline{N} = 7 \times 10^4$, 2 – for $\overline{N} = 1.4 \times 10^4$. The x axis represents the energy of μ mesons increased by 1.5 Bev taking into account the average energy losses in the passage of the μ mesons through the atmosphere (corresponding to an average production height of μ mesons equal to 10 km). The y axis represents the μ-meson flux density at the distance of 28 m from the EAS axis, in terms of number of particles per m^2.

The shape of the energy spectrum, characteristic for the smaller of the investigated showers, is shown in Fig. 2. It can be seen that, for showers of 1.4×10^4 and 7×10^4 particles, the spectrum can be well represented by a straight line on log-log coordinates, with a slope equal to 0.54 ± 0.07. As far as larger showers, with an effective number of particles 2.9×10^5, are concerned, the spectrum is considerably steeper at greater depths, and the spectrum exponent approaches unity (see Fig. 3).

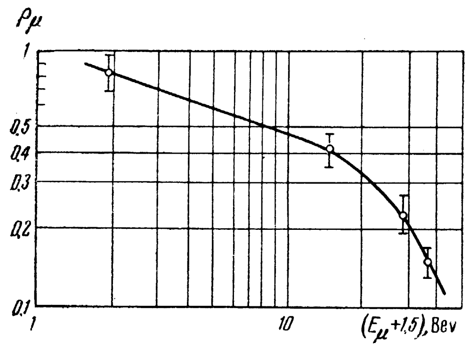

FIG. 3. Energy spectrum of the μ-meson component at an average distance of 28 m from the EAS axis for a shower with $\overline{N} = 2.9 \times 10^5$. The respective axes represent the same quantities as in Fig. 2.

Using the data on the lateral distribution of penetrating particles in EAS taken from references 3 and 5 for the depths of 61 and 127 m w.e., and also the measurements carried out in our laboratory at a depth of 160 m w.e., we have constructed the energy spectra of the showers as a whole. These spectra are shown in Fig. 4. It can be seen that each spectrum can be represented by a straight line with a slope close to unity. The maximum value of the exponent of the energy spectrum was obtained for showers with a mean number of particles equal to 2.9×10^5. This exponent is equal to 1.25 ± 0.20.

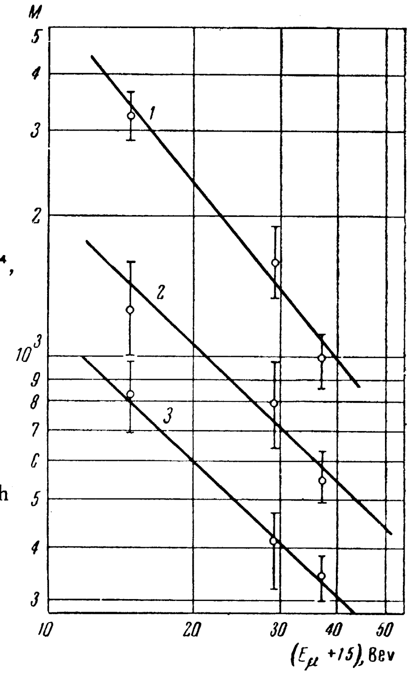

FIG. 4. Energy spectrum of the μ-meson component of EAS: 1 – for $\overline{N} = 2.9 \times 10^5$, 2 – for $\overline{N} = 7 \times 10^4$, 3 – for $\overline{N} = 1.4 \times 10^4$. The y axis represents the total number of μ mesons in EAS and the x axis the energy of μ mesons, taking into account the losses in their passage through the atmosphere.

According to the spectrum obtained, the mean energy of μ mesons of the penetrating component of EAS with $\bar{N} = 2.9 \times 10^5$ is, even at sea level, greater than 7 Bev, which fully confirms the results obtained by our group in previous years.

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