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III-2-13. Primary Cosmic-Ray Component in Superhigh-Energy Region

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Data on the energy-spectrum and composition of the primary cosmic-ray component in the superhigh-energy region have been obtained with the help of the Moscow State University's device intended for the complex study of extensive air showers. Let us first of all consider the data on the extensive air-shower size (N) spectrum at sea-level. The device has provided data on this spectrum in the interval of change N from 10^5 to 10^7, with good statistical accuracy (see Fig. 1). As is seen in the figure, a notable irregularity is observed in the region of $N \sim 5 \cdot 10^5$, in the integral spectrum. If the shower size spectrum is approximated size spectrum by the power law of the $N^{-\kappa}$ type, then in the interval of $10^5 < N < 3 \cdot 10^5$, $\kappa = 1.45 \pm 0.1$, with $5 \cdot 10^5 < N < 2 \cdot 10^6$, $\kappa = 2.0 \pm 0.1$ and if $2 \cdot 10^6 < N < 10^7$, $\kappa = 2.0 \pm 0.1$. This irregularity may, perhaps, be explained, if we suppose that the primary energy-spectrum is described by a smooth function, but with a sharp change in the form of the cascade curve for showers of sufficiently big size. In this case the shower of great size must reach maximum of its development in the higher layers of the atmosphere than a low energy shower. The latest experiments[1] show that in the region of values of N which is interesting to us, *i.e.*, $N \sim 10^6$, the reverse situation rather takes place.

Thus the cause of shower size spectrum irregularity is to be sought for in the presence of certain changes in the energy-spectrum and the composition of primary cosmic rays in the region of energies of interest. From the view point of the present-day conception of cosmic-ray production and diffusion in the Galaxy these changes may appear as a result of a diffusion-coefficient increase in the interplanetary fields, if the particle-energy E begins to exceed a certain critical value E_{cr} (where E_{cr} is the energy of the particle, whose radius of curvature in the magnetic field is of order of size of the field-homogeneity region).

Indeed, if $E \ll E_{cr}$, then the diffusion-coefficient is constant and does not depend on

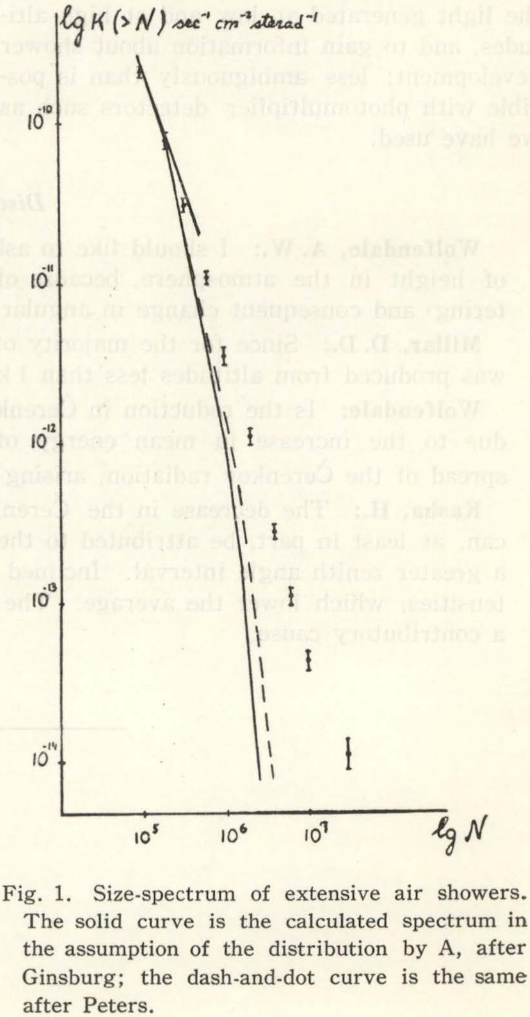

Fig. 1. Size-spectrum of extensive air showers. The solid curve is the calculated spectrum in the assumption of the distribution by A, after Ginsburg; the dash-and-dot curve is the same after Peters.

energy; but if $E \gg E_{cr}$, it increases as E^2 [2]. As it is generally known, the particles-build-up factor in the Galaxy in the order of magnitude is equal to H/l, where H is the linear dimensions of the Galaxy, and l is a mean free-path length proportional to the diffusion-coefficient. Thus, if the given-type-particle spectrum produced by the sources has the appearance of $E^{-\gamma}$ and is characterized by a constant exponent then, as a result of the particle-diffusion with $E \ll E_{cr}$ the appearence of the exponent is preserved, but with $E \gg E_{cr}$ it falls more abruptly to $E^{-(\gamma+2)}$. It is obvious that E_{cr} for nuclei with the charge Z and the mass number A is $Z \simeq A/2$ times as much as for protons. Thus, the character of changes of the energy-spectrum and the composition of primary cosmic rays in the energy range greater than E_{cr} for protons will substantially depend on the relative presentation of nuclei with various Z (or A).

It is evident that the appearance of the shower-size spectrum concerned will be influenced not only by changes of the primary cosmic-ray energy-spectrum, but also by changes in its composition. For example, for nuclei with greater A one may expect a considerable weakening of the fluctuation in the cascade development (particularly weakening of the fluctuation of the altitude of shower origin). Furthermore, if the cascade maximum position from the proton with the energy E_0 is determined as $X_m = b \ln E_0$, then, evidently, for a primary nucleus with the same energy E_0, $X_m = b \ln E_0/A$.

Taking into account all above considerations, we have calculated shower-size spectrum at sea-level. The following assumptions have been drawn.

The energy-spectrum of primary particles with the mass-number A has the appearance of $E_0^{-(\gamma+1)} dE$ (with $\gamma = 1.5$) up to the energy of $E_0 \ll 1/3 E_{0cr} \cdot A$ and after that it passes smoothly into the spectrum $E_0^{-(\gamma+3)}\, dE_0$, with $E_0 \geq 3E_{0cr} \cdot A$. Mass number A spectrum was taken from the paper 3) by B. Peters, and also, in the second variant, from the papers by Ginzburg and Sirovatsky[4]. Fluctuations in the development of a primary particle of the energy E_0 were considered in the simplest variant, which assumes regard being given to fluctuations in the depth of the shower origin X_0 (details of the model are given below). The number of particles in the shower N was determined as

$$N(E_0, X_0) = kE_0 \exp\left(-\frac{X-(X_m+X_0)}{\Lambda}\right),$$

$$k = 5 \cdot 10^{-10}, \quad (E_0 \text{ in ev.}), \quad X = 1030\, g/\text{cm}^2.$$

$$X_m = b \ln E_0/A, \quad b = 13\, g/\text{cm}^2.$$

Λ is the absrorption path of shower-particles $= 200\ \text{g/cm}^2$, X_0 is the depth of shower origin. The distribution of X_0 may apparently be expressed as $\exp(-X_0/l) dX_0/l$

l was defined from the formula

$$l = A_{air}/N\pi[1.45 \cdot 10^{-13}(A^{1/3} + A_{air}{}^{1/3} - 1.17)]^2,$$

where N is Avogadro's number (see "Proceedings of the International Conference on Cosmic Rays, 1959, Vol. III). The critical energy E_{cr} for a proton was assumed to be equal to $5 \cdot 10^{15}$ ev. The results of calculations have been cited in Fig. 1. It is seen in the figure, the spectrum calculated by us, reveals a notable irregularity (like the experimental one). However, in the region of $N > 10^6$, the spectrum calculated falls more abruptly than the experimental, so that with $N \sim 10^7$ it differs dozens of times from the latter*. It should be noted that the change of the A spectrum hardly changes the situation during the transition from the spectrum according to Ginsburg to the spectrum according to Peters. Certainly, one may modify the assumption regarding the character of fluctuations in shower development. However, in the case of shower development from nuclei, the fluctuations are hardly much greater than those we have assumed.

Thus, we have succeeded in explaining the irregularity observed in the shower-size spectrum: the natural assumption about the variation in the energy-spectrum and the composition of the primary cosmic rays in the superhigh energy region. At the same time, the calculation shows that the constancy of the size-spectrum exponent experimentally observed, κ, in the region of $N \sim 10^6 \sim 10^7$ cannot apparently be understood, if one does not assume 1) either the A number

* It should be noted that accordingly to this, for $N < 10^6$, the integral spectrum calculated by us is characterized by a greater value of the exponent than the experimental, and the primary cosmic-ray spectrum assumed by us. However, for the differential spectrum we obtain rather reasonable values of the exponent.

spectrum is sufficiently different from that one in the region of smaller energies 2) or there are additional extra-Galaxy sources of cosmic rays in the region of superhigh-energy, $>10^{16}\sim10^{17}$ ev.

The use of the detector of μ-mesons with a great area made it possible to consider the question of the presence of super-high-energy electromagnetic radiation (γ-quanta) in the composition of the primary cosmic rays.

While considering the question we made use of the fact that in showers appearing in the atmosphere from a nuclear cascade there must be many μ-mesons, whereas in showers from γ-quanta their number is comparatively small. Indeed, in an electron-photon cascade μ-mesons may appear owing mainly to decay of $\pi^{\pm}$ mesons, appearing as a result of the photoeffect of γ-quanta upon air atomic nuclei. Let us now compute an expected μ-meson number with the energy of E_0 in the shower produced by γ-quantum with the energy of E_0. This number is

$$N_\mu{}^\gamma(E) \leq \int_E^{E_0}\int_0^{t_0} I_0 \Gamma(E_0, E', t) n_\pi(E', E) dE' dt$$

where $\Gamma\,(E_0, E', t)$ is the differential spectrum of γ-quanta at the depth of t in the shower from the primary γ-quantum with the energy of E_0; I_0 is the probability of nucleus photo-effect section for a single radiation t-unit; t_0 is the observation level. The sign $<$ is used, for it is supposed that the probability of π-meson decay is equal to 1; $n_\pi(E', E)$ is the number of $\pi^{\pm}$-mesons with the energy of $> E$, produced by the γ-quantum with the energy of E'.

Suppose that

$$N_\pi(E', E) = (E'/E)^\alpha, \quad \alpha \leq 0.5 \,.$$

Then, since t_0 for sea-level is great enough, we find

$$N_\mu{}^\gamma(E) \leq I_0 \int_E^{E_0} \frac{dE'}{E'^2 1.8}\left(\frac{E'}{E}\right)^\alpha = \frac{I_0 E_0}{1.8(1-\alpha)E} .$$

(the expression for an equilibrium spectrum has been taken according to 5).)

Supposing

$$I_0 = 10^{-28}\ \mathrm{cm}^2 \cdot 6 \cdot 10^{23}/A^{1/3} \cdot 34\, g/\mathrm{cm}^2 < 10^3$$
(for all A concerned),

$E_0 \simeq 10^{16}$ ev (the number of electrons corresponds to such primary energy at sea-level $N=7\cdot10^6$); $E_\mu = 10^{10}$ ev, (which corresponds to the energy of μ-mesons recorded in underground premises) $\alpha = 0.5$, we obtain the following:

$$N_\mu{}^\gamma(10^{10}) \leq 10^3 .$$

On the other hand, the number of μ-mesons $N_\mu{}^n$ in the showers produced from the nuclear cascade has been measured at our device. According to these data we should expect $8\cdot10^4$ μ-mesons, in average, with the energy $E \geqq 10^{10}$ ev, in the showers with the total number of particles $N=7\cdot10^6$.

Consider now the lateral distribution of μ-meson flux for these two types of showers.

The lateral distribution of μ-meson fluxes $\rho_\mu{}^n(r)$ and $\rho_\mu{}^\gamma(r)$ in the showers $N=7\cdot10^6$. $\rho_\mu{}^n(r)$ is the experimental data obtained by our device, $\rho_\mu{}^\gamma(r)$ is the results of theoretical calculations. In calculating $\rho_\mu{}^\gamma(r)$ it was assumed that the lateral divergence of μ-mesons is determined by the angular deflection of $\pi^{\pm}$-mesons appearing in the nuclear photo-effect. The distribution of $\pi^{\pm}$-meson transverse momenta was supposed to be identical to the transverse momenta of $\pi^{\pm}$-measons in the nuclear collision and was taken as $P_\perp{}^2 \cdot \exp\{-(P_\perp{}^2/P_0{}^2)\}$ ($P_0 = 10^8$ ev/c).

It is easy to show that the lateral and angular distribution of γ-quanta producing the photo-effect and also the Coulomb scattering of μ-mesons themselves are not of considerable importance.

Due to the small difference in the lateral distribution $\rho_\mu{}^n(r)$ and $\rho_\mu{}^\gamma(r)$ the corresponding densities differ, in the distance range,

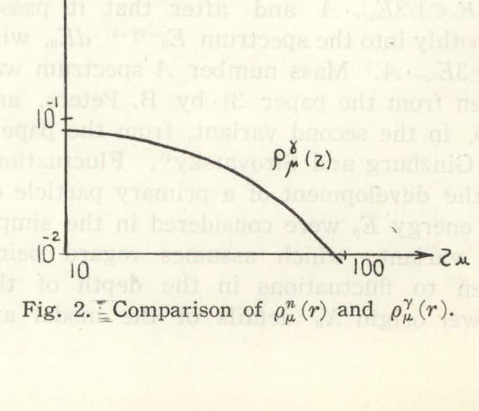

Fig. 2. Comparison of $\rho_\mu^n(r)$ and $\rho_\mu^\gamma(r)$.

from the shower axis, from tens of metres to 100 metres (these distances are characteristic for our device, also about 100 times). Since the number N_μ^n, as is shown in our papers, fluctuate, this difference may be even smaller in some showers.

Thus, with small but final probability the shower from n particles may give no single μ-meson on the detector's area; and at the same time the shower from γ may give one or more μ-mesons in this area.

Suppose, that in the total number n of the showers recorded, we did not observe showers unaccompanied by μ-mesons which pass through the detector. Then the probability that the average number of γ-showers during the observation period must be $\alpha \cdot n$ is expressed as follows:

$$P(\alpha n) \sim \sum_{m=0} \frac{e^{-\alpha n}(\alpha n)^m}{m!} \{1-\exp(-\rho_\mu{}^\gamma S)\}^m ,$$

$$S = 6.3\,\mathrm{m}^2 .$$

In our experiment 140 showers were observed all of them accompanied by μ-mesons.

Hence, we have $\alpha < 10^{-2}$ with 80% of probability. Analyzing our data concerning the fluctuations of the μ-meson, we can determine the upper limit for the mean free path relatively to the interaction of the primary superhigh-energy cosmic rays with atomic nuclei of the air.

Several models of extensive air shower development are known in literature, predicting the important role of fluctuations in the development of a cascade from the primary nuclear-active particle of superhigh energy. The simplest of them (considered in papers by Zatsepin and Saricheva, Kraushaar, and, recently by Miyake and Oda) assumes that fluctuations are reduced only to those of the origin-point altitude of an extensive air shower. This is naturally connected with the final value of the free-path length of the primary particle. In this model there exists singlevalue correspondence between the primary particle energy E_0 and the depth of its interaction point X_0 on one hand, and between the total number of shower-particles N and μ-meson number N_μ, on the other hand. This correspondence within the framework of the given model must be determined by an analysis of the whole complex of experimental data on extensive air showers. The analysis has resulted in the following relations:

$$N = k_e E_0 \exp\{-[X-(X_m+X_0)]/\Lambda\} ,$$
$$N_\mu = k_\mu E_0{}^\alpha .$$
$$\Lambda = 200 \pm 20\ \mathrm{g/cm^2} , \quad \alpha = 0.8 \pm 0.1 ,$$
$$X_m = b \ln E_0 , \quad b = 13\ \mathrm{g/cm^2} , \quad E_0 \text{ in ev.}$$

If, further, one sets the value of the mean free path of the primary particle λ, and the primary energy-spectrum as $A \cdot E_0^{-(\gamma+1)} dE_0$, it will be possible to show that with a fixed N the distribution by N_μ may be expressed as $W(N_\mu)dN_\mu = N_\mu{}^{\varepsilon/\alpha} dN_\mu$, $\varepsilon = (\Lambda+b)/\lambda - \gamma - 1$, where N_μ varies in the range from $N_{\mu\min} = k_\mu (N/k_0)^\alpha$ to $N_{\mu\max} = k_\mu \{N/k_e \cdot \exp([X-X_m]/\Lambda)\}$. It is characteristic that the distributions of $W(N_\mu)$ for various λ differ rather substantially. This is shown in Fig. 3, which presents the curves $W(N_\mu)$ for various values of λ:

$$\begin{cases} \lambda = 92\ \mathrm{g/cm^2}, & \varepsilon = -0.5, \\ \lambda = 75\ \mathrm{g/cm^2}, & \varepsilon = 0 \\ \lambda = 68\ \mathrm{g/cm^2}, & \varepsilon = 1 \\ \lambda = 50\ \mathrm{g/cm^2}, & \varepsilon = 2 \end{cases}$$

Comparison of the experimental and theoretical distribution gives the value of $\lambda = (75 \pm 7)\ \mathrm{g/cm^2}$ with a trustworthy limit of 10%. This value should be considered as the upper limit λ because of number of methodical factors, deforming the distribution of $W(N_\mu)$. On the other hand, a comparison of the experimental distribution of $W(N_\mu)$ with the simplest model calculating fluctuations of the shower-origin altitude without consideration of the further fluctuations in a cascade de-

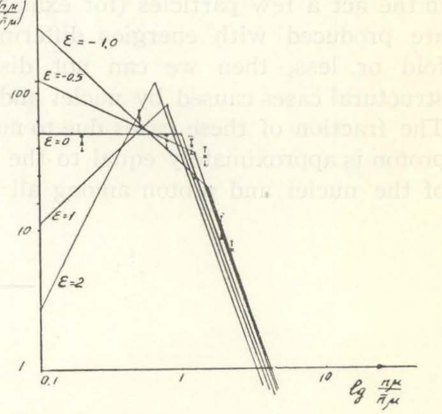

Fig. 3. Distribution of $W(N_\mu)$ by the number of μ-mesons falling on the device $S = 6.3\,\mathrm{m}^2$.

velopment, would naturally produce an excessive values of λ. Thus, the method described makes it possible to determine only the upper limit of λ. Therefore, $\lambda \leqq 70$ g/cm^2. However the value proved considerably lower than that upper limit for the λ which had been long ago determined as a result of numerous experiments on an altitude curve of extensive air shower, and is equal to (110–130) g/cm^2 in the region of the observed energies $\geq 4.10^{16}$ ev.

In conclusion, a few remarks should be made on the question of possibility of determining the fraction of nuclei in the primary cosmic rays of superhigh energy.

During registration of the nuclear-active component of extensive air showers two or more high-energy particles in a number of cases fall simultaneously upon the detector (so-called structural bursts). In some papers[3] such cases are explained by the origin of these showers from the primary cosmic-ray nuclei, and attempts are being made to compare the number of burst with the nucleon number A of a nucleus. Such comparison of structural bursts and showers from primary nuclei is not unquestionable. We have calculated the probabilities of observing two particles of high energy at sea-level for cases of production of cascade nuclear-active particles from a proton and nucleus with $A=8$, with the same initial energy. For the calculations we used various simplest models of an elementary act, similar to those used in paper 6). It was found that the relation of the probabilities mentioned above depends substantially on the type of act. Thus, if in the act a few particles (for example, two) are produced with energies differing threefold or less, then we can not distinguish structural cases caused by nuclei and proton. The fraction of these cases due to nuclei and proton is approximately equal to the fraction of the nuclei and proton among all primary particles with the given total energy (a few high-energy particles observed originate from one nucleon of a nucleus and provide no information of nucleus composition). In the case of production, in the act, of only one particle strongly distinguished by energy, the high-energy particles observed originate from various nucleons of the nucleus, and among all structural cases of shower production from nuclei predominate.

Since our knowledge of the elementary act is insufficient, we can not discriminate these cases. However, the connection between the structural cases and the primary cosmic-ray nuclei may be tested in another way: by the experimental study of various characteristics of such showers. Since such showers must have a different character of development (actually they consist of several showers with lower energy), there is a reason to suppose that their characteristics must differ from those of the other showers. At present, at the device of Moscow State University, systematic study is being carried out of the following characteristics of structural showers: the energy flux of electron-photon and nuclear-active components, the function of lateral distribution of particles, and μ-meson flux.

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