INVESTIGATION OF LARGE IONIZATION BURSTS PRODUCED BY COSMIC RAY PARTICLES AT SEA LEVEL

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An array consisting of 128 ionization chambers with total area 10 m^2 was employed to study ionization bursts equivalent to the traversal of 1000 or more relativistic particles through the chambers. The exponent of the integral spectrum of bursts recorded by the large-area array $\gamma = 1.71 \pm 0.04$. For the individual particles the spectral exponent is $\gamma = 1.96 \pm 0.03$. The causes of this disparity and the nature of the large ionization bursts are discussed.

INTRODUCTION

INTERACTION processes in the $10^{12} - 10^{13}$ ev region have been studied during the last few years mainly by two methods, exposure of emulsion stacks to cosmic rays at great altitudes and by means of ionization chambers. A sharp disparity in the results of investigations by these methods has been observed. This disparity involves the following.

The emulsion method indicates that γ quanta (and consequently, π^0 mesons, too) are produced in air with a rapidly dropping spectrum [integral spectrum exponent ~ 3 (see reference 1) in the region of energy $\geq 10^{12}$ ev]. At the same time, it follows from the ionization method that the spectrum of ionization bursts, which should coincide with the spectrum of nuclear-active particles incident on the apparatus from the air, has an exponent of 1.5 — 1.6 (see references 2 and 8).

In our opinion, the experimental results presented below can explain the reason for this disparity.

The present work was performed on an array designed for the study of interaction processes involving particles of energy $10^{12} - 10^{13}$ ev with the aid of photographic emulsion.[3] A large number of ionization chambers in this array, along with a combination of lead-graphite filters, acted as an ionization calorimeter,[4] and at the same time was designed to determine the coordinates of the shower passing through the emulsion.

This array was recently assembled at an altitude of 3200 m above sea level on Mount Aragats. Before its installation on the mountain, a simplified version of this array was used in experiments in Moscow at a height of 50 m above sea level. In the experiments at sea level, data was obtained on the character of the ionization bursts produced by high-energy particles, on air showers associated with high-energy particles, and on the energy of the nuclear-active components in extensive air showers.

Comparison of the results of the measurements at sea level with the analogous results obtained at mountain altitudes with the same equipment is undoubtedly of interest, since later on in the analysis of the experimental data, it is possible to eliminate effects due to apparatus factors, which sometimes cannot be taken into account correctly when a comparison is to be made of data obtained at different altitudes on nonidentical arrays.

1. APPARATUS

The array used in Moscow is shown schematically in Fig. 1.

It consisted of four rows of ionization chambers I-IV (32 chambers in each row) between which were lead and graphite filters (the filter thicknesses are shown in Fig. 1). Each chamber consisted of a brass cylinder 330 cm long, 10 cm diam, and 2 mm wall thickness. The collecting electrode was made from a brass tube of 4 mm diam.[3] The chambers were filled with pure argon

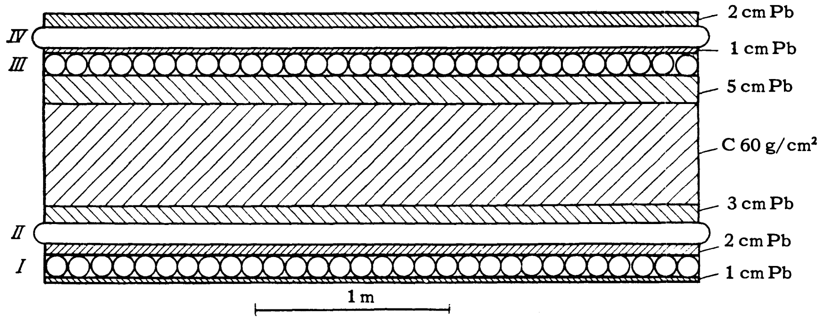

FIG. 1. Schematic diagrams of the arrangement employed. I–IV cylindrical ionization chambers.

to a pressure of 5 atm and operated with a potential difference of 1000 volts between electrodes. Special control measurements showed that saturation in the collection of electrons in the chamber occurred at a potential difference of 200 — 300 volts. During operation, the volt-ampere characteristics of all the chambers were taken periodically, and when contamination of the gas was detected (manifested by an increase in the potential at which the saturation of the ionization current occurs), the chambers were refilled with pure argon. Over the entire 7 months of operation, 26 of the 128 chambers in the apparatus were refilled.

The chambers of rows I and II, as well as the chambers of rows III and IV, were placed perpendicularly to one another. This arrangement of the chambers made it possible to determine the coordinate of the shower produced by the recorded bursts.

Each chamber was connected to an amplifier which permitted the measurement of the pulse amplitude for the individual chambers over a 300- to 400-fold range.

For rows I and II, the minimum registrable ionization pulse corresponded to the traversal of 200 relativistic particles. For the chambers of rows III and IV, the minimum pulse corresponded to 50 relativistic particles.* The pulse amplitudes were recorded on photographs of the screens of four single-sweep oscillographs to which each amplifier was connected, in turn, by means of mechanical commutators.[5]

The oscillograph was triggered by a special circuit which was actuated only if the total ionization exceeded a given threshold value simultaneously in each of any two rows.

These threshold values corresponded to a total ionization of 1200 relativistic particles for rows I and II and 2400 relativistic particles for rows III and IV.

To sum up the ionization pulses within each row, the pulses from each amplifier were fed to a summation unit and then to a summation amplifier. The pulses from the summation amplifer were fed to the control circuit of the apparatus and, at the same time, their amplitudes were recorded along with the pulses from the individual amplifiers.

The apparatus was installed in a special location with ~ 2 g/cm^2 of material of low atomic weight above it. A total of about 3 g/cm^2 of material, including counter units, was located above the apparatus.

During the operation of the apparatus, all amplifiers were calibrated electronically twice daily. Experience showed that the amplification of the great majority of amplifiers ($\geq 90\%$) changed by less than 2 — 3% during one day.

To check the stability of the apparatus, the operating frequency distribution for each chamber was plotted during the entire period of measurements. It turned out that, within the limits of statistical accuracy, all chambers of a given row operated the same number of times.

The operating rate of the apparatus during the entire period of the experiment also remained constant. During the first half of the entire period of measurement, the frequency of bursts of size $J_1 \geq 1200$ relativistic particles in row I was $(1.27 \pm 0.03) \times 10^{-1}$ hr^{-1} m^{-2} and during the second half of the period, the frequency of such bursts was $(1.25 \pm 0.03) \times 10^{-1}$ hr^{-1} m^{-2}.

2. RESULTS

a) Nature of ionization bursts in chambers under 60 g/cm² of graphite. Data on the ionization bursts in chambers under 60 g/cm^2 of graphite (chambers of rows I and II) were obtained during 2640 hours of operation of the apparatus.

The system of recording the ionization bursts (it was required that pulses from two rows of

*Here and in what follows the magnitude of the ionization pulse J is expressed in terms of the corresponding number of relativistic particles traversing simultaneously a path of length equal to the chamber diameter.

chambers be in coincidence and exceed 1200 relativistic particles in each row) practically excluded the recording of bursts from nuclear disintegrations in which the ionization in the chambers is produced by strongly ionizing particles of small range.

The recorded bursts could be produced only by cascade showers developing in the lead filters located over the chambers and between the chambers of rows I and II. One of the characteristic signs of electron-photon showers is the shift in the maximum of the showers to the region of larger thickness with an increase in the energy of the "primary" photons (electrons) producing these showers, i.e., with an increase in the size of the burst. Three centimeters of lead (~ 6 shower units) was above the second row of chambers and five centimeters of lead (~ 10 shower units) was above the first row; it should therefore be expected, firstly, that for the selected bursts with 1200 or more relativistic particles (which corresponds to an energy of $\geq 2 \times 10^{11}$ ev for the electron-photon component of the shower) the size of the burst in the first row will be bigger on the average than in the second row ($J_1 > J_2$), and, secondly, that the mean value of the ratio $(\overline{J_1/J_2})$ will increase with the size of the recorded bursts.

The experimental data obtained actually give $(\overline{J_1/J_2}) = 1.5 \pm 0.1$ for showers with 1200 to 2400 relativistic particles and $(\overline{J_1/J_2}) = 3.4 \pm 0.8$ for showers with more than 12 000 particles.

The same data indicate that the electron-photon component responsible for the bursts in the first and second rows of chambers is generated inside the apparatus and, in any case, does not come from the air. In the latter case, rows I and II would record showers far from the maximum of their development (a total thickness of ~ 22 shower units of lead was placed above the second row from the upper boundary of the apparatus) and the ratio $(\overline{J_1/J_2})$ would be ~ 0.5.

At sea level, the following two processes can lead to the production of an electron-photon component in the apparatus.

1. Interaction of high-energy nuclear-active particles in the graphite block (partially in the lead filters) of thickness $\sim 0.8 - 0.9$ of the interaction mean free path. Produced as a result of such an interaction are π^0 mesons whose decay gives γ quanta responsible for electron-photon showers in the lead.

2. Electromagnetic interactions of high-energy μ mesons in the filters of the apparatus (bremsstrahlung and high-energy δ electrons) can also lead to the production of showers containing a large number of particles.

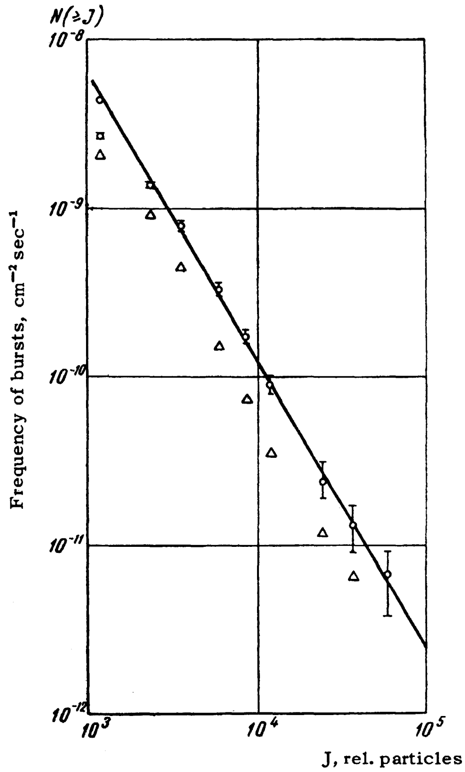

FIG. 2. Integral spectra of ionization bursts recorded in the lower rows of chambers: circles with errors – in row I with the control system operating at a threshold ≥ 1200 particles and o – at a threshold ≥ 600 particles; Δ – in row II with a threshold $\geq$ 1200 particles. The quantity J for the measured burst is laid off on the abscissa axis (without corrections); the number of bursts of size $\geq$ J is laid off on the ordinate axis.

Despite the small probability of the latter processes, a considerable excess of high-energy μ-meson flux over the flux of nuclear-active particles at sea level leads to a considerable contribution from μ mesons to the recorded bursts. However, some conclusions on the properties of the interaction of high-energy nuclear-active particles can also be drawn from an analysis of the experimental data obtained by us.

b) Spectrum of bursts recorded by arrays with large area and spectrum of individual particles. To construct the spectrum of ionization bursts, we took the total ionization recorded by all chambers in a given burst for the first and second rows, separately.

Figure 2 shows the integral spectra of the bursts recorded in the first and second rows of chambers.

If the obtained distribution is represented in the form of an exponential law of the type $N(\geq J) = AJ^{-\gamma}$, then we obtain for the exponent γ, by the method of least squares, the values: $\gamma_I = 1.71 \pm 0.04$ for the first row and $\gamma_{II} = 2.00 \pm 0.04$ for the second row. The steeper spectrum for the second row of chambers reflects the fact that with an increase in the size of the burst the electron-photon showers do not have time to attain their maximum development in the filter of 3 cm Pb above the second row of chambers.

A deviation of the spectrum of bursts from the exponential law in the region of $J \sim 10^3$ relativistic particles is an apparatus effect associated with the recording threshold of 1200 particles in both rows I and II. The apparatus operated with a recording threshold of 600 relativistic particles in rows I and II for 600 hours. The intensity of bursts with 1200 or more particles obtained during this period is denoted by the circles (without the errors) in Fig. 2.

Using the cascade curves for lead,[6] one can establish that, for a wide energy interval of electron-photon cascades, the showers recorded by the first row of chambers will be close to their maximum development. Therefore the further analysis of the bursts will refer to the first row of chambers.

The exponent of the spectrum obtained by us for the first row of chambers $\gamma_I = 1.71 \pm 0.04$ is in good agreement with the results of other authors,[2] despite an important difference in the areas of the apparatus employed. It should be noted that the data obtained by us do not confirm the change in the exponent in the region of large bursts which was observed by Murzina, Nikol'skii, and Yakovlev.[7]

Usually, the spectrum of ionization bursts is identified with the spectrum of nuclear-active particles at the level of observation (if the contribution from μ mesons in the recorded bursts is small). But the correctness of this identification essentially depends on the type of array employed. If the area of the array is so small that the nuclear-active particles recorded by it never arrive in groups, then in this case the spectrum of the bursts will correspond to the spectrum of the particles.

If the array has a large area, groups of nuclear-active particles will pass through it quite frequently and produce "bursts with a structure;"[8] in this case the spectrum of the bursts will no longer reflect the spectrum of the individual nuclear-active particles. Then, with an increase in the energy, the distance between particles in such a group diminishes,[8] and, consequently, the probability that the apparatus is recording several particles or an entire group of particles and not the individual particles of the group increases.

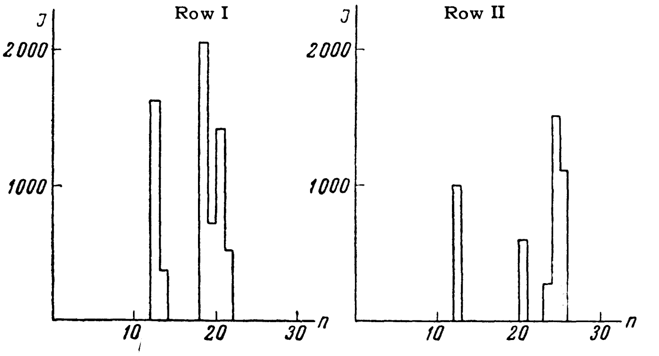

FIG. 3. Distribution of the ionization in chambers of rows I and II in one of the cases of a burst with "structure." The number of the chamber is laid off on the abscissa axis and the amount of ionization in the chambers, on the ordinate axis.

Owing to the large number of chambers in our array and independent recording of the ionization in each chamber, we were able to obtain experimental data on the influence of groups of nuclear-active particles on the shape of the spectrum of the bursts.

When ionization occurred in several chambers of row I or II, and was absent in chambers between them or was significantly less than in the neighboring chambers, we assumed that in these cases several nuclear-active particles were incident on the apparatus. Since these cases differed by a non-monotonic distribution of the amount of ionization in the chambers, we say that such bursts have a "structure." A typical example of one such burst is shown in Fig. 3.

The contribution of bursts with structure to the total number of bursts of different size is shown in Table I (the data refer to the first row of chambers).

A similar picture occurs for bursts recorded by the second row of chambers.

In order to see how the mean distance between particles of a group varies with their energy, we determined the mean distance $\bar{l}$ between chambers recording the maximum bursts due to the individual "structures" in the bursts with structure. Here

Table I

Burst size (in number of rel. particles)	Total number of bursts	Number of bursts with structure	Percentage of bursts with structure
$1.2\cdot10^3 \leqslant J < 2.4\cdot10^3$	1177	79	7
$2.4\cdot10^3 \leqslant J < 3.6\cdot10^3$	526	70	13
$3.6\cdot10^3 \leqslant J < 6.0\cdot10^3$	408	83	20
$6.0\cdot10^3 \leqslant J < 8.4\cdot10^3$	144	39	27
$8.4\cdot10^3 \leqslant J < 1.2\cdot10^4$	80	17	21
$1.2\cdot10^4 \leqslant J < 2.4\cdot10^4$	62	19	32
$2.4\cdot10^4 \leqslant J < 3.6\cdot10^4$	11	6	55
$3.6\cdot10^4 \leqslant J < 6.0\cdot10^4$	6	5	84
$J \geqslant 6.0\cdot10^4$	6	5	84

Table II

Burst size	$\bar{l}$, cm	Burst size	$\bar{l}$, cm
$1.2\cdot10^3 \leqslant J < 2.4\cdot10^3$	97	$1.2\cdot10^4 \leqslant J < 2.4\cdot10^4$	56
$2.4\cdot10^3 \leqslant J < 3.6\cdot10^3$	105	$2.4\cdot10^4 \leqslant J < 3.6\cdot10^4$	49
$3.6\cdot10^3 \leqslant J < 6.0\cdot10^3$	93	$3.6\cdot10^4 \leqslant J < 6.0\cdot10^4$	42
$6.0\cdot10^3 \leqslant J < 8.4\cdot10^3$	72	$J \geqslant 6.0\cdot10^4$	36
$8.4\cdot10^3 \leqslant J < 1.2\cdot10^4$	58		

we considered the two largest structures under the condition that the amount of ionization of one was less than twice the other.

The dependence of $\bar{l}$ on the size of the total burst with structure is shown in Table II (the data refer to the first row).

A similar dependence of the distance $\bar{l}$ on J also occurs for bursts recorded by the second row of chambers.

Since with an increase in the size of the burst, the transverse dimensions of a shower of nuclear-active particles decreases (see Table II), i.e., an increasing fraction of the energy of such a shower is incident on the apparatus, then the spectrum of the bursts is gradually transformed (with an increase in J) from the energy spectrum of particles into the energy spectrum of nuclear showers (showers of nuclear-active particles).

In order to obtain the spectrum of bursts produced by individual particles, we proceeded as follows. Each burst with structure was subdivided into the individual bursts of which it was composed ("structures"). These individual bursts were added to the single bursts (without structure) of corresponding size.

The spectrum of bursts from individual particles obtained in this way is shown in Fig. 4 (for the first row). As is seen, it also can be described by the law

$$N(\geqslant J) = BJ^{-\gamma}$$

with $\gamma = 1.96 \pm 0.03$ (the value of γ and its error were obtained by the method of least squares).

As is seen from the obtained data, the spectrum of the bursts ($\gamma = 1.71 \pm 0.04$) measured by an apparatus with a large area differs significantly from the spectrum of individual particles ($\gamma = 1.96 \pm 0.03$) observed at a given level in the atmosphere. The obtained exponent of the integral spectrum of bursts from individual particles may be somewhat lowered, since owing to the finite diameter of the ionization chambers (10 cm) it was possible to record a large burst as one without structure, although it was produced by a group of nuclear-active particles traveling at distances of $\lesssim 10$ cm from one another.

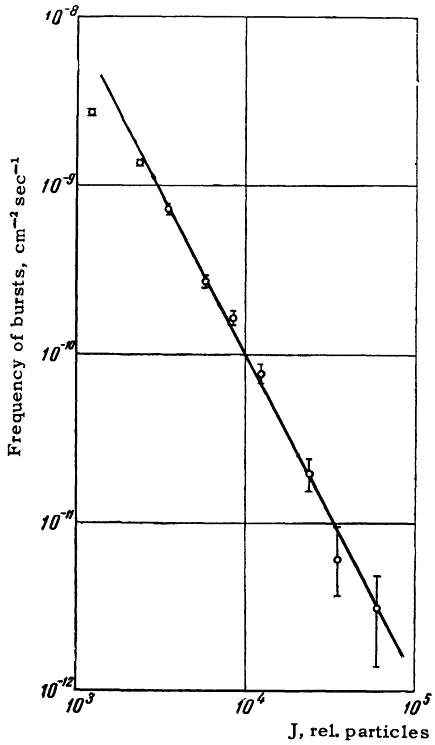

FIG. 4. Integral spectrum of bursts from individual particles. Axis of abscissas – size of burst J; ordinate axis – number of bursts of size $\geq$ J.

3. DISCUSSION OF RESULTS

As we have shown, the spectrum of the ionization bursts measured by an array with a large area does not reflect the true spectrum of the individual particles at a given level in the atmosphere. This is connected with the fact that if the ionization burst is of a sufficiently large size, the recorded burst is produced by a group of nuclear-active particles incident on the apparatus simultaneously. The size of the burst is then proportional to the total energy of the particles in the group.

The experimental data shown in Table I indicate that the large bursts (under conditions of an apparatus with an area of the order of several square meters) are produced by several nuclear-active particles, i.e, by a shower of nuclear-active particles. Of course, for a burst of sufficiently large size, practically the entire energy of such a shower will fall on the apparatus. Consequently, in this case, the size of the burst J will be proportional to the energy of the nuclear shower reaching the level of observation, i.e., the depth X g/cm^2 in the atmosphere. The altitude curve of such large bursts will now be determined by the altitude curve of the showers of nuclear-active particles with a given total energy and not at all by the altitude curve of the individual nuclear-active particles. What will be the altitude curve of the bursts in this case?

We assume that 1) the primary particles incident on the boundary of the atmosphere expend all their energy on the production of π mesons in a single interaction with the nuclei of the air atoms; 2) in each interaction, $\pi^{\pm}$ mesons give up an average of $1/3$ of their energy to π^0 mesons; 3) the interaction mean free paths of the primary particles and π mesons are the same and are equal to L; 4) the spectrum of the primary particles is exponential:

$$F(\geqslant E_0) = A/E_0^{\gamma}.$$

We denote the energy flux of all nuclear-active particles reaching the level X g/cm^2 by S(E;X). This energy flux will consist of the energy flux of the primary particles $S_n(E_0; X)$ not experiencing any interactions in a layer of X g/cm^2 of the atmosphere and of the π-meson energy flux $S_\pi(X)$.

Let N_0 particles of energy E_0 be incident on the boundary of the atmosphere. An average of N(X) particles reach the layer X, where $N(X) = N_0 e^{-X/L}$ (since their inelasticity coefficient can be taken equal to unity).

Since

$$S_n(E_0;\ X) = N(X)E_0 = N_0 E_0 e^{-X/L}, \tag{1}$$

then

$$S_n(E_0;\ X) = S_n(E_0;\ 0)\, e^{-X/L}. \tag{2}$$

The change in the π-meson energy flux in the layer dX will be (we neglect decays)

$$dS_\pi(X) = -\frac{1}{3} S_\pi(X) \frac{dX}{L} + \frac{2}{3} S_n(X) \frac{dX}{L}, \tag{3}$$

from which we have

$$S_\pi(X) = S_n(E_0;\ 0)\,(e^{-X/3L} - e^{-X/L}). \tag{4}$$

Hence the total energy flux of nuclear-active particles resulting from primary particles of energy E_0 will on the average vary with the depth X according to the law

$$S(X) = S_n(E_0;\ X) + S_\pi(X) = S_n(E_0;\ 0)\, e^{-X/3L}, \tag{5}$$

or

$$S(X) = N_0 E_0 e^{-X/L_E} = S_0 e^{-X/L_E}, \tag{6}$$

where L_E is the mean free path for the absorption of the energy flux in a nuclear shower and is equal to 3L.[9]

If it is assumed that, at a depth of X g/cm^2 in the atmosphere, the number of showers with a total nuclear-component energy $\geq$ E is equal to $N(\geq E; X)$, then, since these showers were produced by primary particles of energy $\geq Ee^{X/L_E}$, we have

$$N(\geqslant E;\ X) = F(\geqslant E e^{X/L_E}) = A/(E e^{X/L_E})^{\gamma} = (A/E^{\gamma})\, e^{-X\gamma/L}. \tag{7}$$

From this expression it follows, first, that the shape of the spectrum of larger bursts resulting from the recording of showers of nuclear-active particles coincides with the shape of the spectrum of primary particles incident on the boundary of the atmosphere. Second, the number of bursts with total energy $\geq$ E decreases with an increase in the depth of the atmosphere as e^{-X/L_a}, where the absorption mean free path $L_a = L_E/\gamma = 3L/\gamma$ does not depend on the energy of the burst if this energy is sufficiently large. Thirdly, we have the numerical value $L_a = 3L/\gamma \approx 200/1.7 \approx 120$ g/cm^2, i.e., the same as in the region of low-energy bursts when the bursts are produced by individual particles hitting the apparatus.

Hence, in the regions of small and sufficiently large ionization bursts, all the characteristics of these bursts are the same: the spectrum is exponential with the same exponent as for the primary particles and the variation of the number of bursts with altitude also does not depend on the size of the burst (at least, for the two extreme groups of bursts: very small and very large). This fact led some authors[10,11] to conclude that the elementary act of interaction of primary cosmic particles in the energy range from 10^{10} to 10^{13} ev is invariant.

However, as was shown above, the fact that the shape of the spectrum and the absorption mean free path L_a are independent of the size of the bursts can be explained even with the basic change in the character of the elementary act: a low inelasticity at energies of $\sim 10^{10}$ ev and complete inelasticity at energies of $\sim 10^{13}$ ev.

It thus follows that the conclusion[10,11] on the invariance of the elementary act over a wide range of energies based on an analysis of bursts without taking into account the above-mentioned properties of large bursts is, at least, ambiguous.

As is indicated by the data of Table II, the average distance between particles in a group decreases with an increase in the total energy of the particles of the group (size of the burst), and, consequently, the effect of recording groups of particles arriving from the air will be inherent in apparatus of any size. The difference between different arrays reduces only to the value of the "critical" energy of the group of particles E_c beginning with which a given energy release in π^0 mesons within the apparatus (for a burst of given size) involves, with a probability close to unity, a group of particles and not a single particle.

If bursts with structure are recorded and the nuclear-active particles are $\pi^{\pm}$ mesons, then the entire discussion above should also refer to π^0 mesons, i.e., to γ quanta reaching the apparatus from the air; hence both the spectrum of nuclear-active particles and the spectrum of γ quanta will reflect not only the spectrum of primary particles, but also the conditions of production of these particles in the shower.

Under certain assumptions, which seem to us to be natural ones, it is found that, only owing to the increase in the multiplicity of the secondary particles in the shower with the energy of the primary particles, the spectrum of individual particles will be softer than the primary particle spectrum for a constant inelasticity coefficient.

In fact, we assume that the mean number of particles $\bar{n}$ of energy ϵ in a shower whose total energy is E depends on E in the following way: $\bar{n} \sim E^m$, where $\epsilon = E/\bar{n}$.

The spectrum of showers at a given depth in the atmosphere has the form

$$F(E)\,dE = BE^{-(\gamma+1)}\,dE.$$

From this we readily find that the observed spectrum of individual nuclear-active particles has the form

$$N(\varepsilon)\,d\varepsilon \sim \varepsilon^{-\beta} d\varepsilon, \qquad \beta = (\gamma + 1 - 2m)/(1 - m). \tag{8}$$

The exponent of the integral spectrum of the particles is

$$\gamma^* = \beta - 1 = (\gamma - m)/(1 - m), \tag{9}$$

where γ is the exponent of the integral spectrum of the showers, or, what is the same thing, of the primary particles. Therefore

$$m = (\gamma^* - \gamma)/(\gamma^* - 1). \tag{10}$$

The data obtained by us indicates that the spectrum of individual nuclear-active particles is steeper than the shower spectrum. Unfortunately, we cannot make a quantitative estimate of the value of m from our measurements, since at sea level the main contribution to the number of recorded bursts comes from μ mesons. Owing to this, the exponent γ does not coincide with the spectrum of nuclear showers. But if we draw upon the mountain altitude data obtained by the Japanese group,[12] and assume that the integral spectrum of the showers at mountain altitudes has the exponent $\gamma \approx 1.7$ (in the energy region $\geq 10^{12}$ ev), then one would have to take $m = 0.5$ to explain the softness of the spectrum of individual nuclear-active particles.

It should be emphasized that m is not the mean multiplicity of particles produced in an elementary act, but associates the particle multiplicity in a shower with the shower energy at a given depth (the inappropriateness of the value $m = 0.5$ can be seen only after accurate calculation of the particle spectrum for a nuclear shower at various depths).

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