THE INTERACTION BETWEEN LIGHT ATOMIC NUCLEI AND PARTICLES WITH ENERGIES OF 10^{12} TO 10^{13} EV

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Submitted to JETP editor April 29, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 1099-1109 (1957)

At an altitude of 3200 meters above sea level, a study has been made of the spectrum of large pulses of ionization from 44 ionization chambers shielded by 10 and 12 cm of lead. The probability of an ionization event coinciding with an air shower affords some indication as to the range in air of particles with an energy of the order of 10^{12} ev. Some cases have been observed in which two or three pulses of commensurate magnitude have occurred simultaneously in ionization chambers at some distance from each other (ionization events with spatial structure).

1. APPARATUS

A study of the interaction between high-energy nuclear-active particles and the nuclei of air atoms has been carried out with the aid of an assembly (Fig. 1) consisting of two layers of ionization chambers, I and II. The chambers were cylindrical with a length of 90 cm, a diameter of 40 mm, and walls 1 mm thick, made of brass and filled with pure argon at a pressure of 5 atm. The collector electrodes were 0.4 mm in diameter. A potential of 800 volts was applied to the chambers. According to published data[1] this should be sufficient to reduce the electron collection time below 10 microseconds.

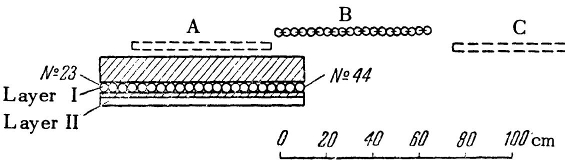

FIG. 1. Diagram of the assembly. I — upper layer of ionization chambers, numbers 23 to 44. II — lower layer of ionization chambers, numbers 1 to 22. The letters A, B, and C show the location of the counter tray in the different series of measurements.

There were 22 chambers in each layer, giving an overall active area of some 0.6 square meters. The chambers in each layer were oriented at right angles to those in the other layer. A 2 cm lead filter was placed between the two layers, and a 10 cm lead shield covered the upper layer.

Each ionization chamber was connected to its own individual amplifier, capable of recording the size of an ionization pulse in the range 100 to 500 relativistic particles. (In this paper the ionization pulse sizes will be expressed in terms of the number of relativistic particles which would give the same ionization if they passed through the chamber along a diameter perpendicular to its axis.) The pulses from each chamber were amplified and greatly prolonged by a special circuit, and applied to a segment of a mechanical commutator, whose wiper connected them in sequence to an oscilloscope with a long-persistence screen. In addition, the pulses from all amplifiers (before being stretched) were added together in a mixer. If the total pulse was equivalent to the ionization from 600 relativistic particles (this value, corresponding to 5 — 6 Po α-particles, was taken as the 100% probability level on the oscilloscope scale) it triggered the recording mechanism and photographed the amplitudes of all ionization chamber pulses.

Figure 2 shows the appearance of the photographs taken during the ionization events. With the system described above, the dead time for recording an event was about 0.25 seconds. Since the events were recorded at a rate of about two per hour, we can reasonably neglect the possibility of finding two separate events recorded on the same photograph. At periodic intervals, several times a day, calibrating signals were applied to the amplifiers to provide a continual check on the amplification factor of each amplifier.

In addition to the ionization chambers, there was a tray of ten Geiger counters, each connected to a hodoscope. A gating pulse to operate the hodoscope was generated every time the control system was triggered, i.e., whenever the total signal exceeded 600 particles. The resolving time of each hodoscope cell was about 15 microseconds. The area of each counter was 420 cm^2 (when used in positions A and B in Fig. 1) and 330 cm^2 in the third series of experiments (with the counters located at C). The number of chance coincidences was determined experimentally for each group of counters, and amounted to 0.9 ± 0.3% of the number of triggering pulses. During each event, the discharge of any counter was indicated on the same photograph which recorded the amplitudes of the ionization chamber pulses (cf. Fig. 2).

The measurements were carried out on Mount Aragats at a height of 3200 meters above sea level. The basic measurements were made with the center of the counter tray 70 cm away from the center of the ionization chamber assembly (position B). Some of the measurements were made with the counters lying on top of the chambers (position A); in this case the counters covered about 70% of the total area of the assembly. A third series of measurements was made with the counters separated by a distance of 2 meters from the center of the chamber assembly (position C).

2. RESULTS OF THE MEASUREMENTS

1. Spectrum and Nature of the Events

We have analyzed separately the events registered in a single layer of chambers (either top or bottom), and the events registered simultaneously in both layers. In the latter case we could consider the pulse amplitude distribution in either layer to be independent of the pulse amplitudes in the other layer only if a pulse of at least 100 particles was recorded in the other layer.

There is some physical significance in treating the two cases separately. If we had selected only those events which produced pulses in both layers, we would have had a greater probability of selecting showers with larger numbers of relativistic particles. On the other hand, a significant fraction of the pulses in a single layer could be the result of strongly ionizing particles coming from radioactive nuclear disintegrations in the lead, brass, or argon of the chambers.

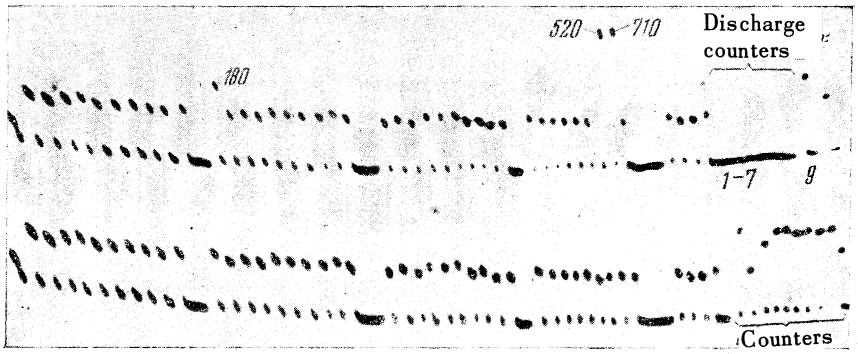

FIG. 2. Typical record of pulses from the chambers, and the hodoscopic chart of the discharged counters, from one of the recorded events. The figures beside the individual pulses denote the amount of ionization (as a number of relativistic particles) produced in each chamber. On the right-hand side of the figure, the numbers indicate which of the counters were operated by the event.

The results of these separate analyses are shown in Figs. 3 and 4. In both figures, the sizes of the recorded events are plotted along the X axis in terms of the equivalent number of relativistic particles N. The number of events per second per cm^2, which are greater than or equal to N, is plotted along the ordinate axis. Figure 3 shows the events which were recorded in a single layer only, and Figure 4 shows the events which were registered in both layers simultaneously. It is evident from Figs. 3 and 4 that the spectrum of events registered in a single layer has the same form as the spectrum of events involving both layers. They can be approximated by a power-law function of the type $AN^{-\gamma}$ with the exponent γ equal to 1.6 ± 0.2.

We shall now consider in more detail the recordings of both types of event where the magnitude of N is 1000 or more. As already mentioned, the two-layer events appear to be due to showers of relativistic particles. A large number of the particles in the shower (1000 or more) might arise merely from electron-photon showers developed in the lead. In principle, there are two possible reasons for the appearance of such showers under 10 — 12 cm of lead. In the first place, electrons (or photons) of high energy may strike the lead from the air above it. In this case, however, the maximum intensity of the shower would lie at a depth of about 5 cm, and all the pulses in the upper layer would be, on the average, twice as large as the pulses in the lower layer.

Before continuing the discussion of the experimental data, we must mention that the two layers of chambers in our assembly were not in identical surroundings. Located underneath the upper layer was a layer of lead, which would scatter the slow electrons that occur in large numbers in the showers. There was no lead underneath the lower layer of chambers, which was supported on a wooden platform. Thus, a "reverse current" of particles was practically non-existent in the lower layer. From the literature[2] we may estimate that, in the events observed in our apparatus, the reverse current of particles amounted to about 30% of the forward current. Hence, if the event in the upper layer of chambers is equivalent to N particles, then the same shower in the lower layer of chambers would give a pulse equivalent to 0.7 N particles.

In Figure 4, curve 1 is the distribution of pulses in the upper layer, and curve 2 is the distribution of the lower-layer pulses, for events recorded simultaneously in both layers. Had the recorded events been due to high-energy electrons (or photons) knocking the assembly out of the air, then the number of events exceeding N in the upper layer should have been $(2 \times 1.4)^{1.6} = 5$ times larger than the number of events of the same size in the lower layer. This is three times as large as the observed ratio of 1.7 (cf. Fig. 4). Furthermore, there should be no events in which the lower layer gives a larger pulse than the upper one.

A second possibility is that the events are a result of nuclear interactions between high-energy particles and lead nuclei. The π^0 mesons generated by this interaction could cause the electron-photon showers. This mechanism would allow cases in which the pulse from the lower layer of chambers is greater than the pulse from the upper layer. The experimental results show that, out of a total of 142 events with $N \geq 1000$, the upper layer gave a bigger pulse than the lower layer in 85 cases, while in 57 cases the reverse was true. Thus, the upper-layer pulse was the larger of the two 1.49 ± 0.25 more times than the lower-layer pulse. Theoretical calculation (cf. Sec. 3) gives a value of 1.56 for this ratio.

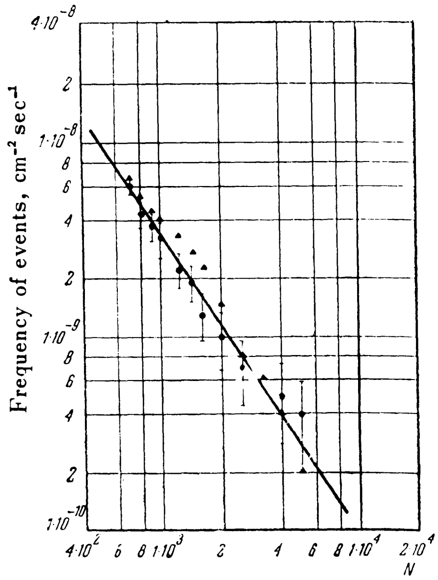

FIG. 3

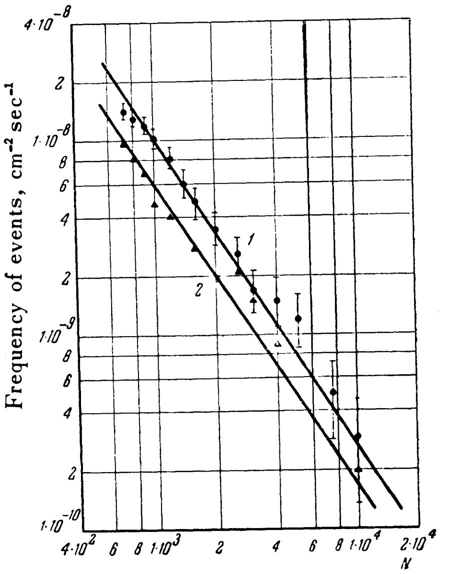

FIG. 4

FIG. 3. Integral distribution of events recorded in one layer of chambers only. Circles — events in the upper layer. Triangles — events in the lower layer (the statistical error is the same as in the case of events in the upper layer of chambers).

FIG. 4. Integral distribution of events recorded simultaneously in both layers of chambers. Curve 1 — distribution of events in the upper layer of chambers. Curve 2 — distribution of events in the lower layer of chambers (the statistical errors are the same as for the points of Curve 1).

These experimental results make it possible to conclude that events recorded in both layers simultaneously are fundamentally caused by the interaction of high-energy nuclear-active particles with lead nuclei.

2. Atmospheric Effects Accompanying the Events

An analysis of the Geiger counter operation can give some information about the atmospheric phenomena accompanying events of different types and sizes. The experimental results show that events which are recorded in only a single layer of chambers (the upper one only) are practically never accompanied by the discharge of a counter. The average probability that a counter will fire (in positions A and B) when only the upper layer of chambers is activated, amounts to $10 \pm 7\%$. The small probability that an atmospheric event accompanies such an ionization event is apparently due to the fact that a pulse from a single layer is generally caused by a nuclear disintegration.

The situation is quite different for events which are recorded in both layers. Such events are accompanied as a rule by atmospheric events; there is a high probability that a large number of the counters will be discharged.

Table I shows the number of cases in which n of the counters ($0 \leq n \leq 10$) are discharged during the recording of an event of size N from one of the layers, while the other layer registers a pulse equal to or less than N. From Table I it can be seen that the probability of an atmospheric event increases with the number of particles in the ionization event (i.e., with increased energy of the nuclear-active particles which trigger the recording). The closer the counter tray is to the chamber assembly, the greater is the observed frequency of the accompanying atmospheric events, and the greater their density. When the counters are lying on top of the chamber assembly (position A), it is only once in 11 times that a single counter is discharged; the rest of the time two or more counters fire. Hence the discharging of the counters in this case cannot be due entirely to the passage of the primary nuclear-active particle, which causes the event, through the counter tray.

TABLE I

Number of counters discharged	Counters in position A			Counters in position B			Counters in position C	
	$1000>N$	$1000\leqslant N\leqslant 5000$	$N>5000$	$1000>N$	$1000\leqslant N\leqslant 5000$	$N>5000$	$1000\leqslant N\leqslant 5000$	$N>5000$
10	0	3	2	6	9	4	2	0
9	0	1	0	5	2	2	0	0
8	1	1	0	2	0	1	1	0
7	1	2	0	6	2	0	0	0
6	3	0	0	1	5	2	1	0
5	2	0	0	6	2	0	0	0
4	5	0	0	10	1	0	2	0
3	2	2	0	6	1	0	1	1
2	2	1	0	8	4	0	2	0
1	8	1*	0	13	2	0	1	0
0	12	0	0	83	12	0	11	0
Total	36	11	2	146	40	9	21	1
Percentage of cases in which any counters operated	66 ± 10	90 ± 10	100	43 ± 7	70 ± 9	100	48 ± 19	
Average number of counters discharged in one event	2.2 ± 0.5	6.3 ± 2.0	10	2.0 ± 0.2	4.5 ± 0.8	8.7 ± 1.0	2.4 ± 0.6	

* This case does not contradict the assumption that the counter was operated by the passage of the nuclear-active particle which produced the event. We therefore consider that in this case there were no atmospheric effects.

Another reason for the high probability of discharging a counter might be the reverse current of particles coming up out of the lead. However, the following considerations contradict this assumption. When the counters are located off to one side of the assembly (position B), 30% of the recorded events (for N between 1000 and 5000) were not accompanied by any discharge of the counters. There could be two reasons for this. Either 30% of the events were actually not accompanied by atmospheric showers, or else the showers exist but are of such small area that they are not recorded by the counter tray located 70 cm away from the center of the assembly. In order to decide which of these two hypotheses was correct, we carried out the following test.

Chambers 23 to 44 of the upper layer were arranged parallel to the counters (the counter tray being in position B). From a total of 40 events we selected those in which there was no accompanying discharge of a counter (12 events) and those in which only a small number (four or less) of the counters fired. But if the particle producing the ionization pulses produces no accompanying atmospheric shower, then the selection of events with $n = 0$ does not imply any discrimination on the part of the different ionization chambers, i.e., it would be expected that the pulses would occur with equal frequency in the left-hand chambers (Nos. 23 to 33) and in the right-hand chambers (Nos. 34 to 44), see Fig. 1. However, if the particles which caused the ionization also produced narrow atmospheric showers, then to select the cases where $n = 0$ would effectively mean to "repel" the generating particle and its accompanying shower to the side away from the counter tray. In this case ionization chambers 23 to 33 should operate more often than chambers 34 to 44.

Table II shows the experimental frequency distribution of the two halves of the chamber assembly (chambers 23 to 33, and chambers 34 to 44) for the cases $n = 0$; $1 \leq n \leq 4$; and $n > 4$, for events with $1000 \leq N \leq 5000$ and $N < 1000$.

The large difference in the frequency with which events were recorded in the two halves of the assembly indicates that, even when $n = 0$, the events are in fact accompanied by atmospheric showers, albeit of small area. The last line in Table II shows that the observed dependence of the different chambers' operating frequencies upon the number of counters discharged, for events with $1000 \leq N \leq 5000$ particles, is not due to a difference in the sensitivities of the individual chambers or amplifier channels. If we assume that for $n = 0$, the two cases of events in chambers 34 to 44 correspond to the absence of atmospheric effects, then we must expect the same number of analogous cases to occur when the event takes place in chambers 23 to 33. Then the remaining $10 - 2 = 8$ events were accompanied by narrow showers. That is, out of 40 events, only 4 ± 2 were unaccompanied by atmospheric effects. Consequently, the probability of atmospheric effects is equal to $90 \pm 5\%$, which is the same figure resulting from direct measurement, with the counter tray lying on top of the chambers (position A).

TABLE II

Number of counters discharged	Number of cases where chambers operated: No. 23 to 33	No. 34 to 44	Remarks
$n=0$	10	2	Events with $1000 \leqslant N \leqslant 5000$ particles
$1 \leqslant n \leqslant 4$	6	2	
$n > 4$	6	9	
$n=0$	42	41	Events with $N < 1000$ particles

3. Ionization Events with Spatial Structure

The use of ionization chambers 4 cm in diameter, covering a relatively large area, made it possible to observe cases in which two or more widely separated chambers gave ionization pulses, although there was no ionization in the intermediate chambers. Events with this type of spatial structure will hereafter be referred to as "structured" events. An example of one such event is shown in Fig. 5. If we consider only the pulses with $N \geq 300$ relativistic particles to be contributing to the structure of an event, then the frequency of structured events is given in Table III as a function of the type and size of the recorded event.

TABLE III

	Events in one layer only		Events in both layers of chambers		
	$500 \leqslant N \leqslant 1000$	$1000 \leqslant N \leqslant 5000$	$500 \leqslant N \leqslant 1000$	$1000 < N \leqslant 5000$	$N > 5000$
Total number of events	163	69	129	102	14
Number of events with structure	1	2	1	17	5
Average distance between chambers giving structured pulses	—	—	—	35 cm	15 cm

Events which occur in only one layer of chambers are, in general, caused by nuclear disintegrations. Hence the small percentage of structured events occurring in a single layer shows that the structure cannot be attributed to nuclear disintegrations (if we limit ourselves to amplitudes ≥ 300 particles). It can be seen from Table III that structure appears in a considerable fraction of the events involving both layers of chambers. The proportion of structured events increases with increasing total amplitude of the event. It is particularly noteworthy that the larger the event, the smaller is the average distance between ionized chambers when structure is present.

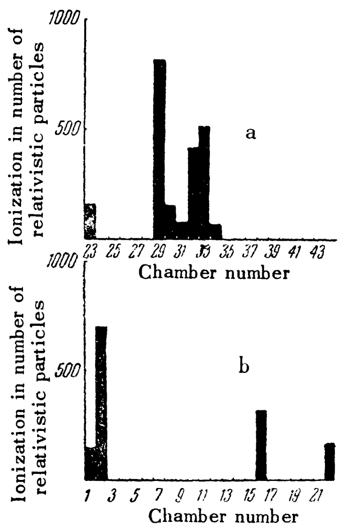

FIG. 5. Example of an event with spatial structure. In the upper layer (a) chambers 23, 29, 30, 31, 32, 33, and 34 operated, with pulses of 160, 810, 160, 80, 420, 510, and 80 relativistic particles respectively. In the lower layer (b) chambers 1, 2, 16, and 22 operated, with pulses of 150, 700, 320 and 160 particles, respectively.

As a measure of the amplitude differences in the ionization pulses making up the structure of an event, we used the mean ratio between the amplitudes of the smallest and largest pulses, $\overline{V_{min}/V_{max}}$. For 17 structureed events with $1000 \leq N \leq 5000$ particles, $\overline{V_{min}/V_{max}}$ was 0.55 ± 0.23. For the five structured events with $N > 5000$ particles, $\overline{V_{min}/V_{max}}$ was 0.5. From these mean values of V_{min}/V_{max} it follows that the ionization pulses produced during structured events are all of the same order of magnitude, and that in a large majority of cases they differ by less than a factor of 2.

In six of the 22 cases of structured events with $N \geq 1000$ particles, the structure appeared only in the lower layer of chambers, while the total ionization in the upper layer was considerably less than the total ionization in the lower layer of chambers. This circumstance rules out the formation of structured events by electrons (or photons) of high energy striking the assempty from the atmosphere.

From a study of the experimental data it can be concluded that the structured events are due to several nuclear-active particles of high energy, striking the assembly simultaneously. Events which have spatial structure are accompanied by more extensive atmospheric showers. Thus, the average number of discharged counters (when the tray is in position B) amounts to 3.9 ± 0.7 for events without structure, and 6.5 ± 0.7 for structured events with $1000 \leq N \leq 5000$ particles.

3. DISCUSSION OF RESULTS

1. Estimates of the Recording Efficiency and of the Energy of the Particles Causing the Events

Events of a given size (N particles) could be caused by particles of various energies, depending on the distance between the nuclear interaction and the ionization chamber. In order to estimate the efficiency of recording the particles which cause an event of a given size, we have made the following assumptions:

(1) Particles with energy E lose 50% of their energy during interaction with a lead nucleus; the π^0 mesons carry away one third of the energy lost.

(2) The π^0 mesons produce an electron-photon cascade in the shield, described by a cascade curve for a photon with half the total energy acquired by the π^0 mesons during the nuclear interaction.

(3) We have taken the range of the particles for interaction with lead to be 160 g/cm^2.

The calculated recording efficiency for particles which cause events from 1000 to 5000 particles in size, and which are registered in both layers of chambers, is equal to 24%. In this case E_{min}, the smallest energy which will enable a particle to cause such an event, is 6×10^{11} ev, and the average energy (taking into account the variation in recording efficiency with particle energy, and the upper limit of 5000 particles for the recorded events) is $2.6\ E_{min}$, namely 1.6×10^{12} ev. The recording efficiency for particles which cause events with $N \geq 5000$ particles is 30%.

Using the same cascade curve which we used in estimating the recording efficiency, we calculated the ratio of the number of events with $1000 \leq N \leq 5000$ in which the pulse from the upper layer of chambers was greater than the pulse from the lower layer, to the number of events in which the lower layer gave the larger pulse. The calculated ratio was equal to 1.56. The experimental value of this same quantity, derived above, was 1.49 ± 0.25. Hence the agreement between calculation and experiment is still another argument in favor of the view that the events which involve both layers are caused, in the overwhelming majority of cases, by nuclear-active particles interacting with the lead in the shield.

2. Interaction Range of Particles with $E \sim 10^{12}$ ev

We denote by $n(x; \geq E)$ the number of all particles with energy E at a depth of x g/cm^2 in the atmosphere; and by $n_1(x; \geq E)$ the number of particles with the same energy, at the same depth, which are unaccompanied by any atmospheric events. If L_a is the range of particles with energy E for absorption, and L_i is their range for interaction in the atmosphere, then

$$n(x; \geqslant E) = n(0; \geqslant E) \exp\{-x/L_a\}. \quad (1)$$

The number of particles which arrive from the top of the atmosphere without any interaction is denoted by $n_0(x; \geq E)$, and is equal to

$$n_0(x; \geqslant E) = n(0; \geqslant E) \exp\{-x/L_i\}. \quad (2)$$

It is obvious that $n_1(x; \geq E) > n_0(x; \geq E)$ if $x \sim 700$ g/cm^2. Therefore

$$n_1(x; \geqslant E) > n(0; \geqslant E) \exp\{-x/L_i\}. \quad (3)$$

Dividing (3) by (1), we obtain

$$\frac{n_1(x; \geqslant E)}{n(x; \geqslant E)} > \exp\left\{-x\left(\frac{1}{L_i} - \frac{1}{L_a}\right)\right\}$$

and hence

$$\frac{L_a}{L_i} > 1 + \frac{L_a}{x} \ln \frac{n(x; \geqslant E)}{n_1(x; \geqslant E)}. \tag{4}$$

From our experimental results (section II), $n_1/n = 0.1 \pm 0.05$. From the literature[3] $L_a = 112 \pm 11$ g/cm^2 for particles with energy $E \sim 10^{12}$ ev. Hence, according to the inequality (4),

$$L_a / L_i > 1.36^{+0.11}_{-0.04}$$

and, taking $L_a = 112$ g/cm^2, we obtain

$$L_i < 84^{+4}_{-6} \text{ g/cm}^2.$$

Our results show that as the size of the recorded event increases, the probability of atmospheric side-effects does not decrease. Thus, for events with $N > 5000$ particles, corresponding to a mean energy of the order of 10^{13} ev for the original particle, the probability of an accompanying air shower is almost 100%. This means that for particles with $E \sim 10^{13}$ ev, the range for interaction in air is no greater than 80 g/cm^2.

3. The Relation of High Energy Particles to Extensive Atmospheric Showers

The tray of counters connected to the hodoscope enable us to estimate the number of particles in the air showers accompanying the ionization events. To estimate the number of particles, we started from two assumptions:

(1) The current density of the counted particles $\rho(r)$ is a single-valued function of r, the distance of the counter from the shower axis. For small r, the function is of the form $\rho(r) = AN_s/r$, where N_s is the total number of particles in a shower.

(2) The axis of the shower coincides approximately with the trajectory of the nuclear-active particle causing the ionization event (within 30 — 50 cm).

The results we obtained for the density of atmospheric showers accompanying ionization events are shown in Figure 6. N_s, the number of particles in the atmospheric showers accompanying ionization events of 1000 to 5000 particles, is plotted along the abscissa. The ordinate axis represents the number of ionizing particles which are accompanied by showers of N_s or more particles. (The right-hand scale shows the relative fraction of such particles, taking as 100% the nuclear-active particle flux equivalent to the total of all the observed events, regardless of whether or not they were accompanied by showers.) The solid line in the figure gives the absolute number of large atmospheric showers with N_s or more particles which fall on 1 cm^2 every second at an altitude of 3200 meters above sea level.* Comparing this curve with our experimental data shown in Fig. 6, we may conclude that in showers of more than 10^5 particles there are on the average one or two particles with energies $\bar{E}$ of the order of 10^{12} ev. In showers where $N_s \geq 10^4$ there is on the average only one particle with $\bar{E} \sim 10^{12}$ ev in every three showers, i.e., not every shower contains even one particle lying in the energy range from 6×10^{11} to 3×10^{12} ev.

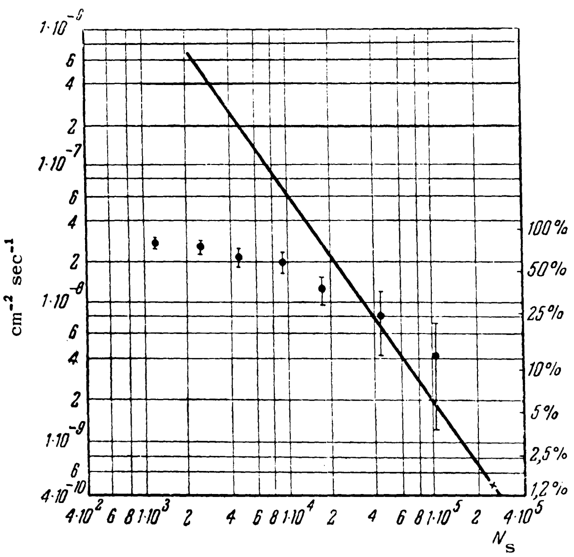

FIG. 6. Atmospheric effects of particles with energy 6×10^{11} to 3×10^{12} ev.

If we assume, as several authors have done,[4] that the formation of large atmospheric showers is due to individual high-energy particles, then in order that each shower with 10^4 or more particles at mountain-

*The curve was constructed by using the size distribution of showers taken from the data placed at our disposal by A. P. Abrosimov, N. N. Goriuniv, A. V. Dmitriev, V. I. Solov'ev, B. A. Krenov, and G. B. Christiansen from their paper which is being prepared for publication.

top altitudes can be ascribed to a single energetic particle with energy E_1, it follows that this energy must be about $3^{1/\kappa}$ times smaller than 6×10^{11} ev. For large atmospheric showers, $\kappa \simeq 1.5$. Hence $E_1 = 3 \times 10^{11}$ ev. But if the shower contains N_s particles, then in order to avoid contradicting our data we must assign to the primary high-energy particle an energy of

$$E_{\text{primary}} = 3 \times 10^{11} N_s \times 10^{-4} \text{ ev} = 3 \times 10^7 N_s \text{ ev}.$$

It is easy to show that such a particle could only lengthen the mean range of showers between the mountain tops and sea level by about 15 g/cm^2 in all, i.e., if each large shower at mountain-top level also has its energetic primary particle, then on the average its energy is not sufficient to account for the subsequent absorption of showers in the lower atmosphere.

We come to exactly the same conclusion by comparing the absolute flux of nuclear-active particles in the atmosphere at a depth of $x = 700$ g/cm^2, which can be obtained from the literature[5] by extrapolation into the high-energy region, to the number of showers with the given number of particles.

4. Events with Spatial Structure, and the Nature of the Interaction Between Light Nuclei and Particles with Energies of 10^{12} to 10^{13} ev

About 20% of the events possessed structure. If we take into account the recording efficiency for the events and the fact that in the majority of cases the structured events are characterized by pulses in both groups of chambers, we may estimate the relative number of cases in which the showers falling on our assembly contained particles with an energy $\sim 10^{12}$ ev. It is estimated that, in about 40 — 50% of the cases where events with more than 1000 particles were registered, groups of 2 or 3 nuclear-active particles with energies of about 10^{12} ev fell on the 0.6 square meter area of the assembly.

The relatively frequent occurrence of showers composed of several nuclear-active particles with energies of 10^{12} ev or more in the atmosphere, accompanied as a rule by a greater density of air showers than in the case of individual nuclear-active particles of the same energy, suggests that the interactions of particles with energies of $10^{12} - 10^{13}$ ev with light nuclei can be divided schematically into two classes of interaction. One class is a relatively weak interaction, as a result of which the nuclear-active particle loses a small part of its energy, and the remainder is carried away by a single particle, possibly of the same type as the "primary" particle. The second class is a strong interaction, in which the "primary" particle loses all its energy. As a result of the second type of interaction, there is formed a shower of a few high-energy nuclear-active particles, which give ionization events with spatial structure, accompanied by wider atmospheric showers.

The assumption that there are two classes of interaction may be reconciled with the observed height dependence of the number of 10^{12} ev particles, if we assume that in the "weak" interactions the average energy loss amounts to 20 — 30%, and in the "strong" interactions the energy loss is practically 100%. It is curious to note that if such a mechanism of interaction is extrapolated to the region of super-high nucleon energies, corresponding to the formation of extensive atmospheric showers, then it is possible to explain almost quantitatively such shower characteristics as (1) the variation of showers with height, (2) the spectrum of showers with a given number of particles, and (3) the small variation in shower diameter S as the altitude varies from 0 to 4000 meters above sea level.

In conclusion, the authors express their thanks to A. I. Alikhanian, who made it possible for us to carry out the experiments on Mount Aragats; to N. M. Kocharian and his co-workers for the substantial kindness they showed us during the course of the experiments on Mount Aragats; to A. A. Sanin for his assistance in developing the electronic apparatus, and to A. E. Chudakov for valuable comments during the discussion of the results.

[1] B. Rossi and G. Staub, "Ionization Chambers and Counters" New York, 1949.

[2] O. N. Vavilov, Dissertation. Trudy, Phys. Inst. Acad. Sci., (U.S.S.R.) 4, Acad. of Sci. Press, Moscow 1949.

[3] K. P. Ryzhkova and L. I. Sarycheva, J. Exptl. Theoret. Phys. (U.S.S.R.) 28, 618 (1955), Soviet Phys. JETP 1, 572 (1955).

[4] Nikol'skii, Vavilov, and Batov, Dokl. Akad. Nauk SSSR 111, 71 (1956), Soviet Phys. "Dokalady" 1, 625 (1956).

[5] Kocharian, Saakian, Aivazian, Kirakosian, and Aleksanian, Izv. Akad. Nauk SSSR, Ser. fiz. 19, 515 (1955).

Translated by D. C. West
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