INVESTIGATION OF NUCLEAR-ACTIVE PARTICLES AND ELECTRON-PHOTON SHOWERS WITH ENERGIES > 10^{12} ev *AT* 3860 m *ALTITUDE*

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An experimental arrangement for studying the interaction between nuclear-active particles with energies > 10^{12} ev and air and carbon nuclei is described. Preliminary results on the energy spectrum of nuclear-active particles with energies > 10^{12} ev are discussed.

THE present experiment was intended to study the nuclear-active and electron-photon components of high-energy cosmic radiation, in order to obtain additional data on the character of nuclear interactions at energies $\geq 10^{13}$ ev.

The measurements were carried out in the autumn of 1959 on the Pamirs, at 3860 m altitude.

The main part of the experimental array consisted of a detector of nuclear-active particles and high-energy electron-photon showers. The detector comprised four rows of ionization chambers, separated by lead and carbon (Fig. 1a). The first row contained 12, and the remaining rows 20 ionization chambers each. The chambers were 25 cm in diameter and 5 m long. The axes of the chambers of the rows 1 and 2 and also of the rows 3 and 4 were mutually perpendicular. Ten 12-counter hodoscope trays were placed above the detector. The area of each counter was 330 cm^2. The hodoscope served to determine the number of particles in the showers (Fig. 1b). To prevent the particles scattered in lead from reaching the hodoscope counters, the detector was covered by a layer of lead 3 g/cm^2 thick.

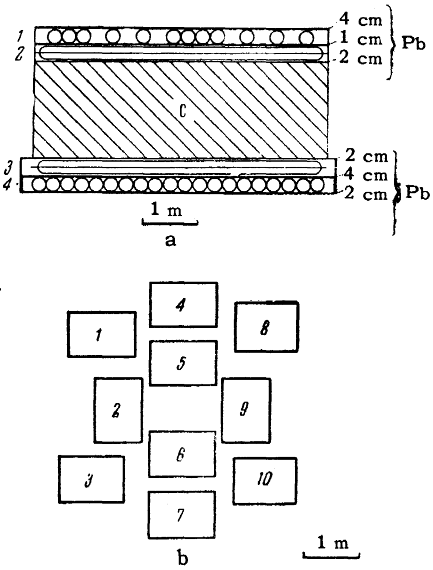

FIG. 1. a – vertical cross section through the detector of nuclear-active particles and high-energy electron-photon showers; b – position of the hodoscope points above the detector.

In addition to the elements of the array shown in Fig. 1b, two cylindrical chambers were placed 7 m from the center of the array, which made it possible to increase the range of detectable shower sizes. An additional hodoscope point, and a detector of the electron-photon energy density consisting of three ionization chambers covered by 2 cm of lead, were placed 28 m from the center of the array for the study of the fluctuations in the particle flux and in the energy density flux of extensive air showers (EAS).

The electronic block diagram of the array is shown in Fig. 2. The pulses from each ionization chamber were fed to a separate amplifier. Independently, the pulses from the chambers in each row which were fed to the trigger circuit [i.e., chambers 3 — 7 of the first row, 6 —15 of the second row, and 2 — 19 of the third and fourth rows (the chambers are counted from left to right in each row)], were added together. Whenever a coincidence of pulses from the triggering chamber groups in rows 1 and 2 or 3 and 4, greater than a certain threshold value, occured, the trigger and control circuit produced the master pulse that gated the circuits recording the pulses from the ionization chambers and initiated a scanning of the memory cells by means of a mechanical commutator. Pulses from the mechanical commutator were fed to an oscillograph with triggered sweep (one oscillograph was used for each chamber row) and were photographed. Simultaneously, the readings of the total-ionization analyzer and of the

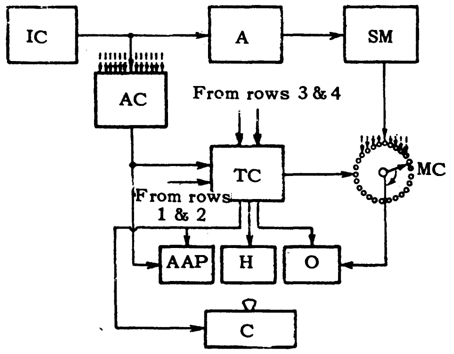

FIG. 2. Block diagram of the electronic circuitry: IC – ionization chamber, A – amplifier, SM – switch and memory cell, AC – addition circuit, TC – trigger and control circuit, AAP – analyzer of added pulses, H – hodoscope, O – oscillograph, C – camera, MC – mechanical commutator.

hodoscope, both triggered by the master pulse, were photographed. The array was tested automatically several times a day.

As can be seen from the above description, the hodoscope made it possible to determine the number of particles in the shower accompanying nuclear-active particles or in high-energy electron-photon showers. If the axis of an EAS fell upon the detector (regardless of the actual location in it), the number of particles in the shower was determined from the formula $N = 1000\rho$, (where ρ is the effective particle-flux density per m^2, determined assuming statistical independence of the shower particles.

The energy carried by electron-photon and nuclear-active components was determined from the ionization produced in the ionization chambers. The ionization chambers used in the detector were made of polyethylene 0.02 g/cm^2 thick, which practically excluded the transition effect in the chamber walls. The internal surfaces of the chambers were coated with a colloidal solution of graphite, forming a conducting layer. The chambers were filled with argon to a pressure equal to the atmospheric pressure at 3860 m altitude. Because of insufficient purity and poor seals, the argon in the chambers became gradually contaminated, which caused the electron current of the ionization pulses to change with time. The absolute calibration of the chamber sensitivity was made by comparing the spectrum of pulses obtained during short periods of time, separately for each chamber, with the spectrum obtained immediately after filling the same chamber. The sensitivity of the ionization chambers immediately after filling was assumed to equal the calculated sensitivity.

The energy carried by the electron-photon component was calculated from the number of particles measured in the two top-layers of the chambers, using cascade curves for lead and assuming that the cascade develops from a single photon.

In passing through a layer of lead equal to 14 radiation lengths, the energy of electrons and photons decreased to the order of the critical energy for lead. They were then rapidly absorbed in the carbon layer, since the critical energy for lead is much less than that for carbon.[1]

The thickness of the carbon (210 g/cm^2) was chosen so that, as a result of consecutive interactions of nuclear-active particles in the carbon, all the particle energy was transferred to the electron-photon component originating in the decay of the π^0 mesons. One can assume that the cascade multiplication and the absorption occur in lead only, if we take into account the relatively small number of radiation units in carbon and the great difference between the critical energies of electrons for carbon and lead, and if we assume that nuclear-active particles transfer their energy to a small number of π mesons.

The energy of nuclear-active particles was estimated under the assumption that nucleons and π mesons transfer one third of their energy to newly-produced π mesons in each act of interaction. The nuclear-interaction mean free path in carbon was taken as 70 g/cm^2.

The estimate results in the following relation between the number N of particles observed in one of the chambers of the lower row and the energy E of the nuclear-active particle which had interacted in the detector:

$$E = 2.3 \cdot 10^8 N^{1.04} \text{ ev}.$$

The relation is correct for 10^{11} ev $\le E \le 5 \times 10^{14}$ ev. This relation was used in finding the energy spectra of the electron-photon showers in the atmosphere and of the nuclear-active particles which interacted in the array, as shown in Figs. 3 and 4.

A large fraction of bursts, produced both by electron-photon showers from the atmosphere and by nuclear-active particles which interacted in the matter of the detector, is accompanied by showers of charged particles in the atmosphere. The number of particles in the showers accompanying the ionization bursts was found from the readings of the hodoscope counters, assuming that the lateral distribution function in air is independent of the shower size. The number of ionization bursts unaccompanied by showers, or, more exactly, accompanied by showers with a total number of particles at the observation level $< 6 \times 10^3$,

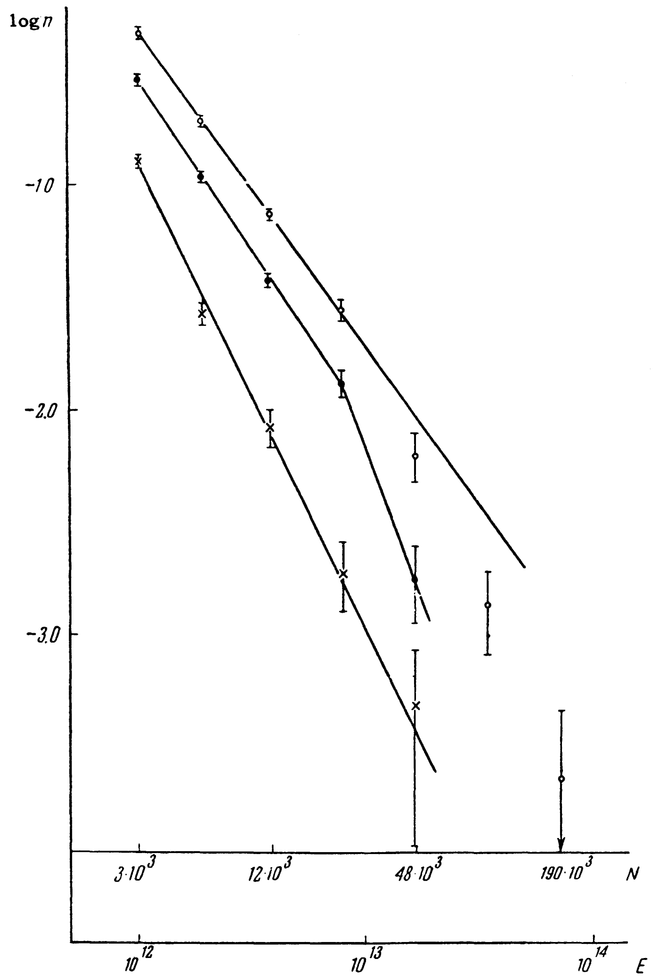

FIG. 3. Integral size distribution of ionization bursts produced by nuclear-active particles (lower scale shows the particle energy): o – all cases; • – bursts unaccompanied by showers with a number of particles $\geqslant 10^5$; x – ionization bursts unaccompanied by showers with a number of particles $\geqslant 6\times 10^3$. The y axis represents the flux of nuclear-active particles per m^2 per hour (logarithmic scale).

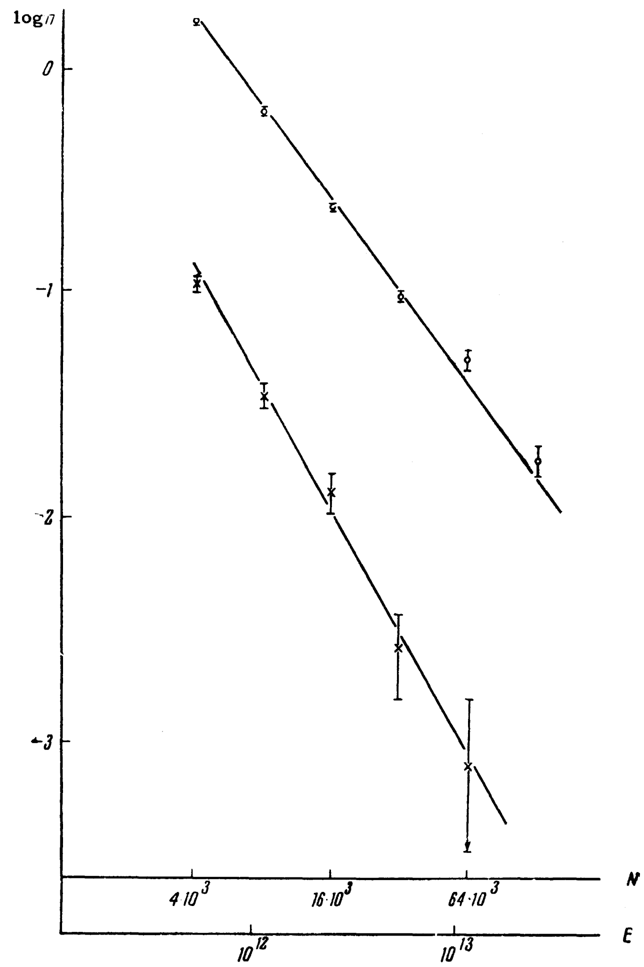

FIG. 4. Integral size distribution of ionization bursts produced by high-energy electron-photon showers: o – all events, x – bursts unaccompanied by showers with a number of particles $\leqslant 6\times 10^3$.

is shown in Figs. 3 and 4 by crosses. An approximately similar value of the absolute number of ionization bursts with a small density of the accompanying shower among nuclear-active particles and among electron-photon showers from the air, and also the relatively "soft" spectrum of the bursts, indicate that high-energy μ mesons may be one of the possible causes of these events. However, the comparison of our results with available data on the number of high-energy μ mesons[2] shows that not more than 15% of the events with a small accompanying density of charged particles in air can be attributed to μ mesons and, consequently, these cases should be associated with primary nucleons traversing the atmosphere with a small energy loss, or without any interaction whatsoever. The soft spectrum of the ionization bursts with a small accompanying density, as compared with the spectrum of all nuclear-active particles in the same energy range, indicates that the cross section for nuclear interactions does not decrease with increasing energy of interacting nucleons.

The high-energy electron-photon showers accompanied in air by a shower with a number of particles $< 6\times 10^3$ may represent EAS produced in the depth of the atmosphere above the experimental array. We can calculate the contribution of such young showers to the flux of EAS observed at sea level if we compare the number of such events with the total number of electron-photon showers of the same energy. As can be seen from Fig. 4, for electron-photon showers of $\sim 10^{12}$ ev, this contribution amounts to less than 10%, which is in agreement with calculations.[3]

In measurements reported earlier,[4] a change in the energy spectrum of nuclear-active particles at mountain altitudes in the energy range $10^{13}-3$

$\times 10^{13}$ ev was observed. According to the experimental data of other investigators, the integral energy spectrum in the $10^{12} - 10^{13}$ ev energy range can be expressed in the form $f(E) \sim E^{-n}$, where $n = 1.57 \pm 0.1$. For higher energies, the exponent n is greater than 2.5. As has been mentioned earlier,[4] these variations in the energy spectrum at mountain altitudes may be explained naturally by assuming that a change in the character of the elementary act of nuclear interaction occurs at $10^{14} - 3 \times 10^{14}$ ev.

However, such an explanation is not the only possible one. In particular, the experimental results given in reference 4 can also be explained by assuming a decrease in the energy fraction transferred to π mesons at $> 10^{12}$ ev nucleon energy.[5] Such an interpretation of the results of reference 4 is possible only because the total thickness of matter in which the nuclear-active particles interacted was about one mean free path. Because of this, a major fraction of the energy of the interacting particle might be missed during the measurement. The fact that in the present experiment we have used a large layer of matter in the nuclear-active particle detector, has improved the measurement accuracy of the energy of nuclear-active particles incident upon the detector. The estimate of the energy of nuclear-active particles in our measurements does not depend greatly on the model of the elementary act, provided we assume that no nuclear-passive particles are produced.

The energy spectrum of nuclear-active particles observed in the experiment is shown in Fig. 3. The integral energy distribution of nuclear-active particles in the energy range $10^{12} - 10^{13}$ ev can be expressed as $f(>E) \sim E^{-n}$, where $n = 1.5 \pm 0.1$. In the energy range $10^{13} - 10^{14}$ ev, the exponent n becomes equal to 2.1 ± 0.4. This confirms the previous experimental data[4] and their interpretation. It does not seem reasonable to explain the observed kink in the energy spectrum of nuclear-active particles at mountain altitudes by a possible change in the energy spectrum of primary cosmic radiation, since the size spectrum of EAS in the corresponding interval does not show any peculiarities.

In the present experiment, the spectrum of ionization bursts corresponding to nuclear-active particles of $10^{13} - 10^{14}$ ev was found to be harder than that obtained in reference 4. Although large statistical errors do not permit us to consider this difference (3.5 ± 1 and 2.1 ± 0.4) as being serious, it is nevertheless necessary to point out a possible instrumental reason for the difference in the spectra of ionization bursts in the present experiment and in the earlier one.[4] The ionization chambers used in our experiments had effective dimensions of $0.25\,\text{m} \times 5\,\text{m}$ each. For the resulting area, it is very probable that several nuclear-active particles fall upon one chamber, which is certainly true for the passage of the EAS cores through the chamber. The events accompanied by a shower are easily detected by the hodoscope counters. The results of selecting those cases that are not accompanied in air by a shower with a number of particles $\geq 10^5$ are shown in Fig. 3. As can be seen, such a selection did not change the form of the energy spectrum in the energy range $10^{12} - 10^{13}$ ev. For ionization bursts corresponding to nuclear-active particles with energies $> 10^{13}$ ev, the spectrum exponent becomes equal to 3 ± 0.8.

It should be noted that, if the interpretation of the peculiarity in the energy spectrum observed at mountain altitudes at energies $> 10^{13}$ ev is correct, then the form of the energy spectrum at mountain altitudes in the energy range $10^{13} - 3 \times 10^4$ ev does not have a clear physical meaning. For an energy of nuclear-active particles $< 10^{13}$ ev at mountain altitudes, the energy spectrum is determined by the energy spectrum of primary particles, by the mean free path for the interaction of nucleons, and by the inelasticity factor. If it is meaningful to introduce the inelasticity factor for nucleon energies $> 3 \times 10^{14}$ ev, then the same physical factors also determine the shape of the energy spectrum at energies $> 3 \times 10^{14}$ ev. For an inelasticity factor equal to one, the spectrum of nuclear-active particles at mountain altitudes represents the spectrum of primary cosmic-ray particles which reach the observation level without interaction.

In the intermediate range, the energy spectrum is not given by a power law and, in addition to the above factors, is determined by the fluctuations in the number of collisions and in the magnitude of the inelasticity factor, and also by the energy-measurement accuracy for each separate case of detection of a nuclear-active particle. If we attempt to estimate the value of the exponent n averaged over the whole range $10^{13} - 3 \times 10^{14}$ ev, and if we base ourselves on the interval width and assume that, for energies $> 3 \times 10^{14}$ ev, only those primary particles which passed the atmosphere without collisions are detected at the observation level, then $n \approx 2.5 - 3$. This value is in good agreement with the experiment.

Thus, the data on the energy spectrum of nuclear-active particles at mountain altitudes is yet another indication of the change in the character of the elementary interaction act of nucleons with energy $> 10^{14}$ ev.[6] Unfortunately, all experimental data indicating the peculiarity of the elementary act of interaction of nucleons with energy $> 10^{14}$ ev are indirect. This makes it difficult to find details of the collisions at energies $> 10^{14}$ ev. One of the simplest assumptions which makes it possible to explain the results of the experiments on EAS was discussed by Nikol'skii and Pomanskii.[6] According to this assumption, a large fraction of the energy of the primary nucleon is transferred to the electron-photon component in collisions of nucleons with energies $> 10^{14}$ ev.

The existence of such a process should lead to a relative increase of the number of electron-photon showers with a total energy $\gtrsim 10^{14}$ ev in the upper layers of the atmosphere, which is apparently observed experimentally.[7] However, in the lower part of the atmosphere, this effect should disappear because of the faster absorption of electron-photon showers in the atmosphere as compared with the absorption of electron-photon showers which are in equilibrium with nuclear cascade showers produced by primary nucleons with energies $\lesssim 10^{14}$ ev. Nevertheless, as can be seen from the comparison of the upper curves in Figs. 3 and 4, the spectrum of electron-photon showers with energy $\geq 10^{13}$ ev tends to become steeper, and this is exactly the opposite of the change in the spectrum of nuclear-active particles.

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