NUCLEAR-ACTIVE PARTICLE SPECTRUM AT 3260 m ABOVE SEA LEVEL

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The energy spectrum of nuclear-active particles at 3260 m above sea level was studied with an ionization calorimeter. In the energy range 2×10^{11}—2×10^{12} eV the integral energy spectrum can be represented by a power law with an exponent $\gamma = 1.92$, with a statistical error of 5—7%, and methodological uncertainty of 0.05.

INTRODUCTION

THE knowledge of the form of the energy spectrum of nuclear-active particles permits us to draw a number of important conclusions concerning the interaction of particles with atomic nuclei at various energies. Many experiments have therefore been devoted to the study of the form of the energy spectrum. A widely used method of determination of the energy spectrum of nuclear-active particles is to study the burst spectrum in ionization chambers. It is then necessary to assume that a constant fraction of energy is transferred to the soft component at different energies of the nuclear-active particles. As has been shown earlier,[1] if the size of the array is large, the form of the burst spectrum may not coincide with that of the nuclear-active particles, even if the above condition is satisfied. The difference between the spectra is then due to the large number of events in which several nuclear-active particles reach the detector simultaneously. In principle, this effect plays no role only in emulsion measurements, where the spectrum of separate particles can be studied. In practice it is found, however, that even for a detector size of the order of 10 cm the spectra measured by the burst method and according to the electron-photon component in the emulsion coincide.[1,2] Consequently, the difference between the burst spectrum and the spectrum of nuclear-active particles is then only due to the difference in the energy fraction transferred to the electron-photon component at different energies of the nuclear-active particle.

The spectrum of nuclear-active particles can be found by measuring the energy of these particles with an ionization calorimeter. This has been the subject of the present experiment.

METHOD

We have measured the energy spectrum of nuclear-active particles in the atmosphere using an ionization calorimeter (see Fig. 1).[3]

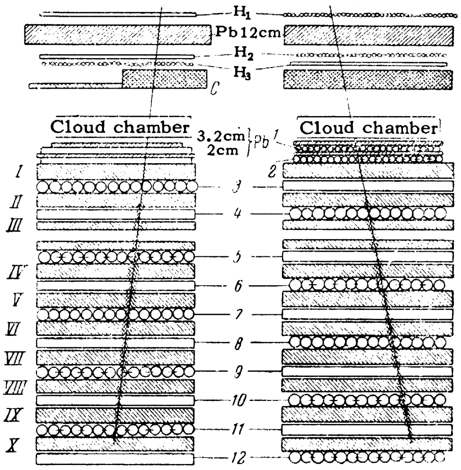

FIG. 1. Diagram of the ionization calorimeter (in two projections): H_1–H_3 – hodoscope counters, I–X – layers of steel, 1–12 – rows of ionization chambers.

The energy of a nuclear-active particle[1)] incident upon the instrument was determined by 12 rows of ionization chambers separated by layers of steel (lead for the two top layers of the chambers). As is well known, this energy E_0 is given by the equation

$$E_0 = \varepsilon \int_0^\infty n_e(x)\,dx,$$

[1)]Electrons and photons from air were filtered out by a lead absorber, 25 radiation units thick, placed above the array. The expected number of bremsstrahlung cascades from muons is less than 1%.

where $n_e(x)$ is the number of relativistic particles at the depth x (measured in g/cm^2) and ϵ is the ionization energy loss of a relativistic particle per g/cm^2 of matter. For iron ϵ was assumed to be equal to 1.5×10^6 eV and for lead to 1.2×10^6 eV.

In practice, the integration is carried out to a certain finite thickness. In our experiment the total absorber thickness was equal to 730 g/cm^2. This assured the detection of more than 80—85% of all the energy of a particle[2)] and enabled us to indicate the energy range for which we have determined the form of the energy spectrum.

A number of difficulties arises in the determination of the form of the energy spectrum. The first one is due to a possible distortion of the spectrum by instrumental effects. When using an instrument with a given threshold of detection, distortions of the spectrum may arise if not all the rows of ionization chambers participate equally in the production of the master signal. The spectrum is especially strongly distorted if the upper rows of chambers are excluded from the master system. These rows give, on the average, the maximum contribution to ionization. The events in which the ionization does not attain the threshold value in the master rows will be missing in the spectrum if the total energy belongs to the range studied. Evidently, this effect is predominant at small energies and practically vanishes for sufficiently large energies of the nuclear-active particles. It will tend to make the energy spectrum less steep. In order to avoid this, we have selected events according to the total energy release in the ten upper layers of the absorbers. This was done by adding the ionization in the ten upper rows of the chambers. The energy detection threshold was equal to 2×10^{11} eV.

An equally important influence on the form of the energy spectrum is due to the incidence on the array of groups of nuclear-active particles. The simultaneous incidence on the detector of two particles of comparable energy can occur in approximately 10% of cases (for an array with linear dimensions of the order of 70 cm). One can separate the events if one shower is present in the calorimeter. In a number of cases the particles can be so close that their nuclear cascades cannot be separated. The exponent of the energy spectrum γ determined by such a method will be somewhat underestimated.

This can be avoided if we select only those events in which one particle falls on the array. Using two rows (2 and 3) of hodoscope counters,[3)] it is possible, in most cases, to establish that only one nuclear-active particle has penetrated into the calorimeter. For this purpose we selected events in which no counters (or at most one counter) were discharged along the direction of the core of the electron-nuclear shower. The discharge of one to three counters on the sides was accepted, since the expected number of chance coincidences in the hodoscope due to muons could amount to 25%.

To exclude completely the cases of a simultaneous passage of several particles through the apparatus, we considered only the events due to nuclear particles without accompaniment in air.[4)] Such a method of selection could make the spectrum more steep, since the probability of an accompaniment in air increases with increasing energy of the nuclear-active particle. The exponent of the energy spectrum γ thus obtained may prove to be overestimated.

We determined the exponent of the energy of nuclear-active particles for both cases described above. It was found that both methods give very close results and, therefore, we can find the real value of the spectrum exponent.

RESULTS

We found a total of 351 events in which a sharply delimited core of an electron-nuclear shower was visible in the calorimeter, originating in an interaction of a nuclear-active particle in the lead absorber under the cloud chamber or in the calorimeter itself. Events in which the nuclear-active particle interacted in the lead absorber above the array were not considered, since the energy would then be underestimated. The selection was done independently of the indication of the hodoscope counters.

The integral energy spectrum of nuclear-active particles is given in Fig. 2. In the energy range 2×10^{11}—2×10^{12} eV the spectrum can be represented by a power law $N(>E) = AE^{-\gamma}$, with $\gamma = 1.87 \pm 0.11$. The value of γ was obtained from the distribution shown in Fig. 2 by the least-squares method.

The integral energy spectrum of single nuclear-active particles without accompaniment in air is also shown in the figure. We selected 209 events produced by particles with energy $\geq 2 \times 10^{11}$ eV,

[2)]For interactions which occurred in the upper row of the calorimeter.

[3)]The hodoscope counters were 2 cm in diameter and covered, in two projections, the whole area of the array.

[4)]Groups of nuclear-active particles in the air propagate usually accompanied by other particles.[4]

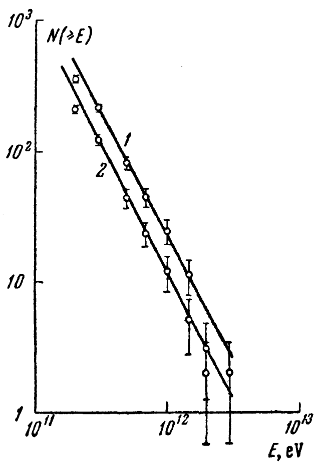

FIG. 2. Integral energy spectrum of nuclear-active particles at the altitude of 3260 m above sea level: 1 – spectrum of all particles, 2 – spectrum of single nuclear-active particles (without accompaniment in air).

excluding from among them the events which could be due to a simultaneous incidence on the array of two or more nuclear-active particles. The energy spectrum of single nuclear-active particles can be described by a power law with an exponent $\gamma = 1.97 \pm 0.17$. The real value of the exponent of the integral energy spectrum of nuclear-active particles lies within the found limits, $1.87 \leq \gamma \leq 1.97$, i.e., $\gamma = 1.92$ with a methodological indeterminacy of 0.05, and statistical error of the order of 5–7%.

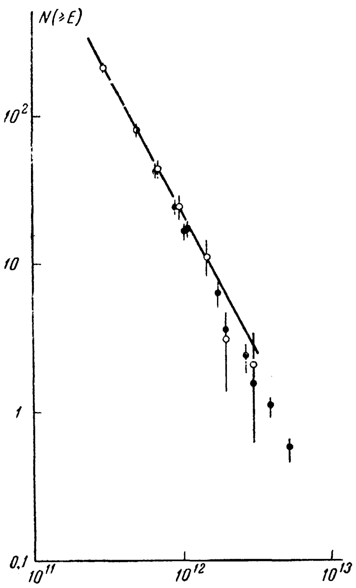

FIG. 3. Comparison of the integral energy spectrum of nuclear-active particles and of the energy spectrum of electron-photon cascades from data in the emulsion: ○ – integral energy spectrum of nuclear-active particles measured in the present experiment (the energy scale on the x axis refers to this curve), ● – integral spectrum of energy released as soft component according to Perkins et al.[2] (for this curve the x axis represents the energy of the electron-photon component and the y axis the intensity in arbitrary units), ◑ – normalization point.

DISCUSSION OF RESULTS

The results of the measurements of the spectra of nuclear-active particles, bursts, and of the energy spectrum of electron-photon cascades in the emulsion are shown for comparison in Figs. 3 and 4. The results of Perkins et al.[2] shown in Fig. 3 have been obtained by the emulsion method. In that experiment the energy of electro-magnetic cascades produced by photons originating in nuclear interactions in the emulsion were measured directly. Since the transition from the photon energy of the nuclear-active particles is not exact, we have not been able to make any energy comparison. The data of Perkins et al.[2] were normalized so that the scale on the x axis denotes for our data the total energy, and for those of Perkins the energy of the photons. The normalization of the y axis is at the point denoted by the black and white circle. From the figure it follows that in the energy range 2×10^{11}–2×10^{12} eV both spectra coincide within the limits of the experimental errors. Unfortunately, the data of Perkins refer to a considerably higher altitude.

Measurements of the photon spectrum by the emulsion method at mountain altitudes have been carried out by Nishimura et al.[5] These results, however, refer to higher energies. The exponent

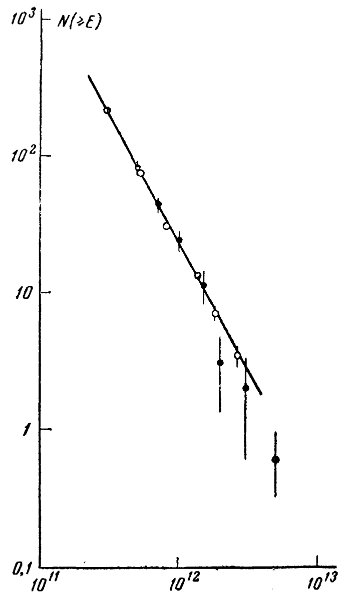

FIG. 4. Comparison of the energy spectrum of nuclear-active particles and of the energy spectrum of ionization bursts: ● – energy spectrum measured in the present experiment, ○ – integral spectrum of energy released as π^0 mesons in the graphite absorbers 60 g/cm² thick (according to [1]); the x axis represents the energy transferred to π^0 mesons in the recorded bursts, and the y axis the frequency of bursts in arbitrary units; ◑ – normalization point.

γ of the integral spectrum was found to be equal to 2.3 ± 0.2 in the energy range 2×10^{12}—2×10^{13} eV.

The spectrum of bursts in ionization chambers, produced by single nuclear-active particles, has already been obtained earlier.[1] These measurements were carried out at the same altitude as our measurements, and refer to the same energy interval (Fig. 4). The spectrum exponent in this experiment was found to equal $\gamma = 1.92 \pm 0.05$, and fully agrees with our result.

We can conclude therefore that in the energy range 2×10^{11}—2×10^{12} eV the exponents of the spectrum of nuclear-active particles, the spectrum of bursts from single nuclear-active particles in ionization chambers, and of the energy spectrum of electron-photon cascades produced in nuclear interactions coincide. This means that the mean inelasticity factor in nuclear interactions remains constant in the energy range under consideration.

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