INVESTIGATION OF THE INTERACTION OF $3 \times 10^{11}-6 \times 10^{12}$ eV *NUCLEONS AT ALTITUDES OF* 6–12 km

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The spectra of nucleons at altitudes of 12, 9, and 6.4 km are obtained in the energy range between 3×10^{11} and 6×10^{12} eV. The mean free path in air for nucleon absorption at the indicated energies is determined. An estimate of the mean fraction of energy retained by the nucleon after the interaction, (40^{+7}_{-13}) %, is found by comparing the absorption mean free path and the inelastic interaction range for nucleons in air.

1. INTRODUCTION

THE spectra of nuclear active particles with energy greater than 10^{11} eV at high altitudes were investigated in [1,2]. The results of the investigations, which used different apparatus, differ greatly. Thus, the integral spectrum of the nuclear-active particles, measured with the aid of emulsions [1], can be described by a power law with exponent $\gamma = 2.1 \pm 0.1$, whereas measurements with the aid of ionization chambers [2] give $\gamma = 1.6 \pm 0.1$.

It was assumed at one time [3] that the nucleon retains in the mean 70% of the initial energy after interaction with the air nucleus. This opinion was based essentially on a comparison of the mean free path for inelastic interaction and the free path for the absorption of nucleons in air, the former quantity being assumed equal to 70 g/cm^2. Our own measurements [4] have shown that at $\sim 10^{12}$ eV the range for inelastic interaction of nucleons in carbon (a substance close in atomic number to air) amounts to 92^{+12}_{-8} g/cm^2. A range of the same order was obtained for inelastic interaction in carbon in an accelerator at a proton energy of 24 BeV [5]. In this connection, the need arises for reviewing the question of the fraction of the energy retained by the nucleon after the interaction. A comparison of the absorption range measured in the present work with the previously obtained interaction range [4] enables us to estimate the fraction of the retained energy.

The work was performed with the aid of ionization chambers. The apparatus made it possible to separate each nuclear interaction event in the material of the apparatus, unlike the situation in [2], where the nuclear interactions were separated statistically as the difference of the counting rates of the apparatus with and without absorber. The experiment was carried out in an airplane at altitudes of 12, 9, and 6.4 km, corresponding to atmosphere depths of 197, 311, and 455 g/cm^2, respectively.

Favoring the measurements at higher altitudes is the larger fraction of the nucleons in the flux of nuclear-active particles, their considerable intensity, and the low accompaniment of other nuclear-active particles and soft-component particles.

2. APPARATUS AND METHODOLOGICAL PROBLEMS

The apparatus with the aid of which the measurements were made is shown schematically in Fig. 1.

It contains three rows of ionization chambers I–III, covered with lead absorbers. An aluminum detector is located between chamber rows I and II. The apparatus registered the electron-photon cascades from the π^0 mesons produced upon interaction of the nucleons in the detector, and also the cascades due to the cosmic ray soft-component particles reaching the array from the atmosphere. These cascades were separated with the aid of

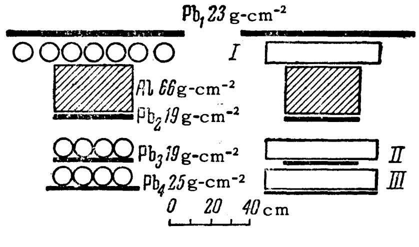

FIG. 1. Diagram of the array (in two projections).

chamber row I. The cascades from the soft-component particles were multiplied in absorbers Pb_1, Pb_2, and Pb_3, and were marked by ionization in all three rows of chambers. The cascades initiated by the nuclear interactions in the detector were multiplied in absorbers Pb_2 and Pb_3 and registered by the chambers of rows II and III. These cascades did not produce ionization in the chambers of row I and by the same token could be separated from the total number of cascades. In one series of flights, a graphite block 32.5 g/cm^2 thick was placed over the array to determine the mean free path for the inelastic nucleon interaction. The selection of the cascades which produced no ionization in the chambers of row I excluded the nucleons which experienced interaction in the graphite block, and was taken into account in the determination of the absolute nucleon fluxes.

The ionization chambers used in the array were round, 10 cm in diameter and 55 cm long. Chambers of row I had iron walls 1 mm thick, while those of rows II and III were made of copper 2 mm thick. The central electrode was a copper tube 6 mm in diameter. The chambers were filled with chemically pure argon to a pressure of 6 atm.

The electronic circuitry made it possible to register pulses in an approximately 300-fold range. The pulses from the chamber anodes, amplified by a factor 1.5×10^3, were applied to the electrodes of the oscilloscope tubes. The total ionization in chambers of row I, the total ionization in chambers of row II, and the ionization in each chamber of row III were registered. The driven sweep of the oscilloscope was triggered whenever more than 200 electrons passed through the chambers of row II simultaneously with more than 400 electrons in the chambers of row III. The chambers of row I did not trigger the array.

The error in the ionization measurement, determined from measurements of photographs of calibrated pulses fed to the input of the amplification channels, was approximately 6%.

The energy of the electron-photon cascades was determined from the ionization produced by the cascade particles in the chambers of row III. The conversion from the number of particles to the energy of the registered cascades was in accordance with the cascade theory. The cascades generated in the aluminum detector passed on the average a thickness of matter equivalent to eight radiation units. For the broad energy interval from 10 to 300 BeV, cascades at such a depth are near the maximum of their development [6], where the number of particles n in the cascade is linearly connected with the cascade energy $E_{e.p.}$.

Table I lists the ratio of the number of particles n_2 in the chambers of row II to the number of particles n_3 in the chambers of row III, for cascades striking the array from the atmosphere in the absence of the detector. Such cascades covered seven and ten radiation units in the lead absorbers, respectively. The data listed in Table I indicate that in the entire energy interval under consideration the cascades are near the maximum of their development at such a depth. In determining the number of particles in the cascade, we took account of the transition effect in the walls of the chamber, in accordance with [7]. The energy of the electron-photon cascade $E_{e.p.}$ in BeV is connected with the number of particles at the maximum development of the cascade by the relation

$$E_{e.p.} = 0.1n. \qquad (1)$$

In the case of nuclear interactions in the detector, the energy of the electron-photon cascade represents the energy E_{π^0} of all the π^0 mesons produced. The energy of the nucleons interacting in the detector was determined from the condition that the pions carry away 60% of the initial energy of the nucleon, as will be shown below. The fluctuations in the fraction of the energy transferred to the pions was calculated from formula (7) with $\sigma = 0.25$.

When taking account of the successive interactions of the nucleon, and also the interactions of the secondary $\pi^\pm$ mesons, the energy of the incident nucleon E_n was connected with the energy E_{π^0} of the π^0 mesons produced by it by the relation

$$E_n = 3.4E_{\pi^0}. \qquad (2)$$

The geometrical factor of the array was calculated

Table I. Values of n_2/n_3

Altitude in kilometers	Number of particles in the cascade				
	800—1100	1100—1600	1600—2200	2200—4800	4800—16000
12	0.94±0.04	1.12±0.06	1.02±0.05	1.03±0.05	1.11±0.13
9	1.01±0.03	1.11±0.04	1.07±0.07	1.18±0.09	1.10±0.14

for a nucleon intensity vs. zenith angle relation of the type $J(\theta) \sim \cos^k\theta$, where in accordance with [2] k was assumed equal to 2, 3, and 4 for altitudes 12, 9, and 6.4 km, respectively.

The mean free path for the inelastic interaction of the nucleons in the aluminum, necessary to determine the fraction of the nucleons interacting in the array, was assumed equal to 114 g/cm^2 [5].

3. ENERGY SPECTRA OF NUCLEONS AT ALTITUDES 12, 9, AND 6.4 km

The presence of an energy threshold for the array leads to a decrease in the registration efficiency of cascades whose energy is close to the threshold. In order to exclude the influence of the energy threshold of the array, we selected the cascades whose energy exceeded the threshold value by a factor 2.5.

Figure 2 shows the integral spectra of the nucleons at altitudes 12, 9, and 6.4 km. The energy relationships of the intensity of the nucleons can be represented in the form of a power law $N(>E) \sim E^{-\gamma}$, where the exponents are 1.90 ± 0.10, 1.92 ± 0.15, and 1.82 ± 0.26 for altitudes of 12, 9, and 6.4 km, respectively.

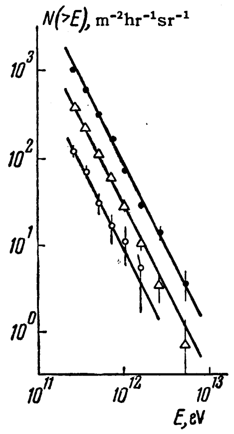

FIG. 2. Integral energy spectra of nucleons at different altitudes: •—12 km, △—9 km, o—6.4 km.

A variety of causes can lead to systematic errors in the measurement of the energy spectrum of the nucleons. One such cause is the soft-component particles accompanying the nucleons.

The upper row of the chambers registered the ionization produced by the electron-photon cascade, provided its energy exceeded 5 BeV. Because the fraction of the nucleons that have an accompaniment can increase with the nucleon energy, the exclusion of such nucleons by selecting the interactions not accompanied by ionization in chambers of row I leads to a "steepening" of the spectrum. The fraction of the nucleons with accompaniment was calculated by starting from the known average values of the perpendicular π^0 meson moments [8], which initiate the accompaniment cascade, with allowance for the lateral energy dissipation during the development of the cascade [9]. The results of the calculations have shown that at 3×10^{12} eV the fraction of the nucleons reaching the array in an accompaniment of an electron-photon component with energy larger than 5 BeV amounts to 7, 11, and 15% at altitudes 12, 9, and 6.4 km, respectively. At 3×10^{11} eV, this fraction is less than 1%. Allowance for the nucleons with accompaniment can decrease the power exponent γ of the energy spectrum of the nucleons by several percent.

No account was taken in the foregoing considerations of other processes where photons are produced, except for the decay of π^0 mesons. The presence of other photon sources, for example the decay of the excited state of the nucleon, can lead to an increase in the fraction of the nucleons that have an accompaniment and perhaps to a more appreciable distortion of the form of the spectrum.

The lower limit of the exponent of the energy distribution of the nucleons can be obtained by considering the spectra of all the cascades registered by the array. Inasmuch as the spectrum of the cascades from the soft-component particles is less steep than the nucleon spectrum [2], the spectral exponent of the nucleons should certainly be larger than the exponent of the summary spectrum.

In order to emphasize the role of the nuclear interactions that have a narrower lateral ionization distribution, we selected the cascades by the ionization which they produced in one chamber of row III. The values of the exponent γ obtained in this manner for the energy spectrum of the cascades are 1.82 ± 0.10, 1.81 ± 0.14, and 1.73 ± 0.22 for the altitudes 12, 9, and 6.4 km, respectively.

Another effect distorting the form of the energy spectrum of the nucleons consists of "additional counts" of electron-photon cascades from the soft-component particles. The chambers of row I did not completely subtend the solid angle determined by the chambers of rows II and III. As a result of this, the soft-component particles arriving in the array at large zenith angles did not produce ionization in the chambers of row I. The "added count" of such background events leads to a reduction in the exponent of the energy spectrum of the nucleons. The intensity of the background events was calculated from the known intensity of the cascades due to the soft-component particles with account of the array geometry, and amounted to 8, 13, and 16% of the nucleon counting rate at altitudes 12, 9, and 6.4 km respectively, with nucleon energy 5×10^{11} eV. The intensity of the background events which was obtained is apparently overestimated, owing to the fact that the soft-component particles, which arrive at the array in groups, can cause operation of the chambers of row I even when incident at large zenith angle. The maximum value of the exponent of the nucleon spectrum, γ_{max}, obtained by introducing an overestimate correction for the background events, is 2.03 ± 0.1 at 12 km.

The question as to what is the fraction of $\pi^{\pm}$ mesons in the flux of nuclear active particles could not be resolved experimentally in this investigation. The $\pi^{\pm}$ meson flux can be calculated by starting from data on the muon flux at sea level [10]. The calculation was made by the method proposed by Grigorov [3], under the assumption that the range for the interaction of the nucleons in air is 95 g/cm^2 [4], and the range for absorption is 120 g/cm^2. According to the calculations, the flux of $\pi^{\pm}$ mesons with energy 5×10^{11} eV is approximately 4, 8, and 12% of the flux of nucleons of the same energy at altitudes 12, 9, and 6.4 km, respectively. We disregarded in the calculation the possibility of "regeneration" of pions by the $\pi^{\pm}$ mesons [11]. If such a regeneration does take place, then the fraction of the $\pi^{\pm}$ mesons could increase to 15, 21, and 26% respectively for the altitudes indicated.

Inasmuch as the flux of high-energy nuclei ($Z \gtrsim 2$) is negligible at depths of 200—450 g/cm^2, the fraction of the nucleons in the flux of nuclear-active particles at altitudes 12, 9, and 6.4 km is predominant.

4. MEAN FREE PATH FOR THE ABSORPTION OF NUCLEONS IN AIR

The mean free path for the absorption of nucleons in air can be determined from the ratio of the nucleon fluxes I_1/I_2 at two depths of the atmosphere P_1 and P_2:

$$L = (P_2 - P_1)/\ln(I_1/I_2). \qquad (3)$$

To determine the mean free path we used the ratios of the nucleon fluxes I_{12}/I_9 at depths of 197 and 311 g/cm^2 and the flux ratio $I_{12}/I_{6.4}$ at depths 197 and 455 g/cm^2. The ratio of the nucleon fluxes and the free path for the absorption calculated by means of equation (3) are listed in Table II. The decrease in the efficiency for the registration of nucleons, the energy of which is close to the threshold energy of the array, cannot influence the measurement of the absorption free path of such nucleons, since the drop in the efficiency will be the same at different altitudes. Therefore the absorption free path was determined also for nucleons whose energy is close to threshold (see Table II, $\overline{E}$ = 300 BeV).

An account of the regeneration of the $\pi^{\pm}$ mesons, which we dealt with above, leads to a decrease in the nucleon absorption free path. Thus, for example, when we take this process into account by the method proposed by Grigorov [11], the absorption free path for nucleons with average energy 600 BeV becomes equal to 112 ± 4 g/cm^2.

In order to estimate the influence of the soft-component nucleon accompaniment, we determined the absorption mean free path of all the cascades selected by the ionization they produced in one chamber of row III. For nucleons with average energy 300 BeV, the range turned out to be equal to 125 ± 5 g/cm^2. Because the soft component is absorbed more weakly than the nucleons between the altitudes at which the experiment was carried out [2], the obtained value of the free path is the upper limit of the nucleon absorption free path.

The results listed in Table II show that when the energy varies from 300 to 2400 BeV, the mean free path for the absorption of nucleons in air remains constant at approximately 120 g/cm^2, within the limits of statistical error. A comparison of the results of this experiment with the results obtained at lower energies [12-14] leads to the conclusion that the nucleon absorption free path remains constant in the energy range 10^{10}—10^{12} eV.

5. AVERAGE FRACTION OF THE ENERGY RETAINED BY THE NUCLEON AFTER THE INTERACTION

A comparison of the mean free paths for absorption L and for the inelastic interaction λ of

Table II

	Average nucleon energy, BeV			
	300	600	1200	2400
I_{12}/I_9	2.61 ± 0.09	2.62 ± 0.12	2.75 ± 0.23	2.48 ± 0.42
$I_{12}/I_{6.4}$	6.81 ± 0.84	8.41 ± 1.26	10.2 ± 3.0	
L (12; 9), g-cm^{-2}	119 ± 4	119 ± 5	113 ± 10	125 ± 22
L (12; 6.4), g-cm^{-2}	125 ± 6	121 ± 8	111 ± 15	
L_{av}, g-cm^{-2}	121 ± 3	120 ± 4	112 ± 8	125 ± 22

nucleons in air makes it possible to estimate the average fraction of the energy $\overline{\Delta}$ retained by the nucleon after the interaction. The connection between L and λ can be represented in the form[15]

$$1 - \lambda/L = \int_0^1 \Delta^\gamma f(\Delta)\, d\Delta. \tag{4}$$

In this expression $f(\Delta)$ is a function describing the fluctuations in the fraction of the energy retained by the nucleon after interaction, and γ is the exponent of the integral spectrum of the nucleons.

The mean free path for inelastic interaction of the nucleons was determined earlier for carbon [4] and amounts to $\lambda_C = 92^{+12}_{-8}$ g/cm² at an average nucleon energy 600 BeV. Taking account of the difference between the atomic weights of carbon and the elements contained in the air increases this quantity to a value $\lambda_{air} = 95^{+12}_{-8}$ g/cm². Substituting in (4) the value $\lambda = 95^{+12}_{-8}$ g/cm² and the values $L = 121 \pm 3$ g/cm² and $\gamma = 1.90 \pm 0.1$ obtained in the present work, we get

$$\int_0^1 \Delta^{1.9} f(\Delta)\, d\Delta = 0.21^{+0.07}_{-0.13}. \tag{5}$$

Relation (5) together with the normalization condition

$$\int_0^1 f(\Delta)\, d\Delta = 1 \tag{6}$$

imposes certain limitations on the form of the function $f(\Delta)$. Thus, for example, the function $f(\Delta) = \text{const}$ cannot be used for the description of the fluctuations in the energy loss, since it does not satisfy relation (5).

To estimate the effective fluctuations on the average fraction of the retained energy $\overline{\Delta}$, the function $f(\Delta)$ was taken in the form of a Gaussian distribution

$$f(\Delta) \sim \exp[-(\Delta_0 - \Delta)^2/2\sigma^2]. \tag{7}$$

The distribution half-width was taken as $\sigma = 0.25$ in accordance with [8]. The value of the most probable fraction of the retained energy, determined by numerical integration of (5), amounts in this case to $\Delta_0 = 0.35$.

The average fraction of the retained energy, defined as

$$\overline{\Delta} = \int_0^1 \Delta \exp[-(\Delta_0 - \Delta)^2/2\sigma^2] d\Delta, \tag{8}$$

turned out to be $0.40^{+0.07}_{-0.13}$.

The average fraction of the retained energy has little dependence on the distribution half-width σ. Thus, when σ is doubled the value of $\overline{\Delta}$ decreases merely to 0.38. On the other hand, decreasing σ to zero, when $f(\Delta)$ assumes the form of a δ function, the average fraction of the retained energy is 0.44.

6. CONCLUSION

The measurements of the nucleon fluxes in the atmosphere lead to the following conclusions:

1. The integral spectra of the nucleons at altitudes of 12, 9, and 6.4 km in the energy region 3×10^{11}—6×10^{12} eV can be described by a single power law of the form $N(>E) \sim E^{-\gamma}$ with $\gamma = 1.90 \pm 0.10$.

2. The mean free path for the absorption of nucleons with energy 3×10^{11} eV in air amounts to $L = 121 \pm 3$ g/cm².

3. The average fraction of the energy retained by the nucleon after interaction with a nucleus is $0.40^{+0.07}_{-0.13}$.

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