AN EXPLANATION OF SOME INCONSISTENCIES IN THE DATA ON COSMIC RAYS WITH ENERGIES ABOVE 10^{11} eV, BASED ON THE ASSUMPTION OF THE EXISTENCE OF A PASSIVE NUCLEON STATE

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It is shown that a number of inconsistencies in the experimental data on interaction between cosmic ray nucleons with energies $\geq 10^{11}$ eV can be removed if it be assumed that after interaction the nucleon goes over to a passive state, in which the nuclear interaction cross section is smaller than the normal cross section. Analysis of the experimental data pertaining to a broad energy range from 10^{11} to 10^{16} eV yields a single lifetime for baryons in the passive state. The value obtained is $\sim 10^{-10}$ sec which is the time characteristic of processes connected with change of parity in weak interactions. Estimates of the transition probability and cross section for baryon interaction in the passive state are discussed.

THE accumulating experimental material on the fluxes and the character of the interaction of the particles of cosmic rays with energies 10^{11} eV and higher has recently added to the number of contradictions between the data of different experiments. The first such contradiction arose in 1955, following the measurement by Vishnevskiĭ [1] of the range for absorption of nuclear-particles in a dense medium—water. Extensive use of the calorimeter introduced by N. L. Gribov[2] has led to an entire group of results that differ substantially from the data obtained by other methods. Critical discussions, and in many cases also repetition of the measurements, disclose no radical errors in the formulation of the various experiments.

In this paper we propose and discuss a physical hypothesis which eliminates the main contradictions to a great degree.

Let us list the main items which are contradictory to one degree or another within the framework of the presently assumed notions.

1. The difference between the range for absorption of nuclear-active particles, predominantly nucleons, with energy $\sim 10^{11}$ eV in air and in water.

Numerous measurements[3] of the range of absorption in air give a value $\lambda_{abs} = 120-130\ g/cm^2$, whereas in water, a medium very close in its nuclear composition to air, the measurements[1] yielded $\lambda_{abs} = 180-200\ g/cm^2$. The absorption curve at small thicknesses, even if the density effect is excluded, has a very complicated character (see Fig. 1).

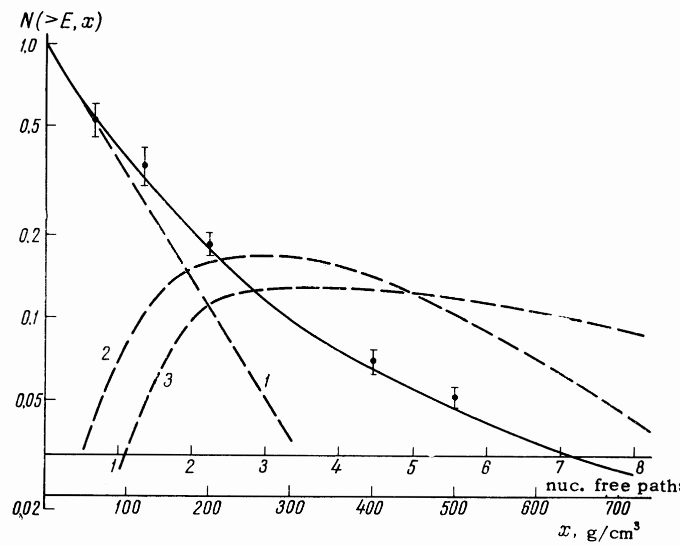

FIG. 1. Absorption of nucleons with energy $\sim 10^{11}$ eV in water: continuous curve—calculation, points—experimental data of[1]. Dashed curves: 1—$N_1(x)$, 2—$N_2(x)$, 3—$N_3(x)$. The calculations were made using $\lambda_{int} = 90\ g/cm^2$, and $\alpha = l_{nuc}/l_S = 0.4$.

2. The difference in the nucleon fluxes measured with an ionization calorimeter—installation with a "thick" filter (several nuclear ranges, where successive interactions of the primary nucleons should take place)—and instruments with "thin" filters, where practically only one interation is probable.

Thus, according to calorimetric data[2] the particle flux at 3260 m altitude (pressure 690 g/cm^2) in the energy interval $2 \times 10^{11}-2 \times 10^{12}$ eV turns out to be several times smaller than the flux obtained in measurements with a thin filter,[4] and

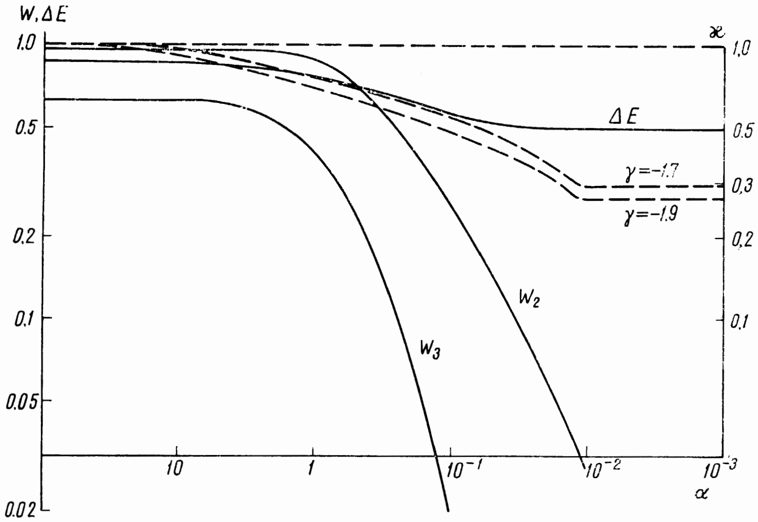

FIG. 2. Calculated data concerning energy measurement with an instrument having an absorber of thickness P = 5 nuclear free paths.

the exponent of the energy spectrum is larger by 0.1–0.2 (see Fig. 2). The latest measurements of the spectrum of the primary radiation with a calorimeter installed on an artificial satellite "Proton 1"[5] also yield a proton intensity lower than that measured earlier from the bursts generated in thin filters at 200 g/cm^2 pressure,[4] or from the electron-photon cascades generated in emulsions at high altitudes in the stratosphere.[6, 7] We note also the extremely low flux of nucleons having no shower accompaniment, measured with the aid of a calorimeter on mountains.[8] The authors were forced to deduce from this that the range for the interaction of nucleons in the atmosphere increases with energy, a deduction that contradicts many data.[9-11]

3. The difference in the data on the inelasticity coefficient K in interaction between 10^{11}–10^{12} eV nucleons and light nuclei.

When working with calorimeters, the experimentally measured quantity is the energy of the electron–photon component, produced during the interaction, i.e., $K_{\pi 0}$. Calorimetric measurements give for interactions in graphite[12] a mean value $K_{\pi 0} = 0.33 \pm 0.05$. Similar measurements observe 10–20% of events[13, 14] in which $K_{\pi 0} \sim 0.8$, and in most cases 50–60% of the energy of the primary particle is carried away by a single π^0 meson with the highest energy.

A similar value was obtained for $K_{\pi 0}$ in the case of interactions with iron nuclei.[15] The corresponding total coefficient is close to unity, for example in [12] $K = 0.65 \pm 0.10$. This coefficient, however, includes estimates of the energy of the charged pions obtained from the magnitude of the transverse momentum, which are much less accurate.

Use of a cloud chamber[16] yields with greatest accuracy, in our opinion, the mirror inelasticity coefficient K_3. Its mean value is $\overline{K}_3 = 0.41 \pm 0.04$. The peak of the distribution of K lies near a value 0.2. Cases with $K > 0.8$ are extremely rare. The average value of $\overline{K}_{\pi 0}$ amounts to ~ 0.15. A nearly equal picture is obtained also in emulsion investigations for particles with energy $\sim 10^{14}$ eV.[10]

A study of the passage through the atmosphere of nucleons with energy 10^{11}–10^{13} eV and of the production of pions by them makes it possible to determine certain effective characteristics of the interactions. Thus, the results of [4] yield

$$\int_0^1 (1-K)^{1.7} W(1-K)\, d(1-K) = 0.24^{+0.07}_{-0.09} = (1-0.56)^{1.7},$$

$$\int_0^1 K_{\pi^0}{}^{1.7} W(K_{\pi^0})\, d(K_{\pi^0}) = 0.08 \pm 0.02 = 0.22^{1.7},$$

$$\int_0^1 \left(\frac{E_m}{E_0}\right) W\left(\frac{E_m}{E_0}\right) d\left(\frac{E_m}{E_0}\right) = 0.033 \pm 0.007 = 0.14^{1.7} \quad (1)$$

(here E_0 is the energy of the primary particle, E_m is the energy of the most energetic π^0 meson, and W is the distribution function). The obtained characteristics are in good agreement with the results of chamber and photoemulsion measurements, and contradict the calorimetric data. For example, the effective value of $K_{\pi 0}$ as measured with a calorimeter[14] is

$$\int_0^1 K_{\pi^0}{}^{1.9} W(K_{\pi^0})\, dK_{\pi^0} = 0.20 = 0.42^{1.9}.$$

4. The difference in the estimate of the energy of the nuclear-active component of an extensive air shower (EAS) and the resultant estimates of

the fluctuations in the development of the EAS.

We refer here, primarily, to observation in calorimetric measurements[14, 18] of so-called young air showers. These showers arise in interactions in which the π^0 mesons obtain the overwhelming fraction of the energy. The fraction of the energy of the nuclear-active component in such showers is 10–20%,[14, 18] i.e., the shower develops further practically like a pure electromagnetic cascade. According to an estimate made in [17], such showers, with extreme fluctuations in the altitude variation, amount to not less than 50% of all the EAS. The existence of showers with extremely large fluctuations cannot be deduced from the analysis of fluctuations of the ratio N_μ/N_e for showers[19] and Cerenkov bursts of EAS[20], and from the altitude variation.[21]

5. Anomalies in the spectrum of extensive air showers relative to the number of particles N in the region $N = 10^5–10^8$.[22]

Whereas an increase in the exponent of the spectrum in the interval $N = 10^7–10^6$ can be attributed to a hypothetical change of the primary spectrum, the value $\gamma = 1.5$ in the region $N = 10^5–10^6$ is to some degree in contradiction to data on the primary spectrum.

6. Certain peculiarities in the flux of charged particles deep under the earth.

According to [23,24], at a depth of approximately 7500 meters water equivalent (m.w.e.) of the "normal scale" ($z = 11$, $\rho = 2.65$ g/cm^3), the vertical flux amounts to 1.5×10^{-10} particles/cm^2-sec-sr. This flux can be attributed to muons with energy $\sim 10^{13}$ eV. However, the latest data[25] disclose an unexpectedly broad angular distribution of the charged particles, and to explain this distribution it must be assumed that high-energy neutrinos generate muons with a cross section greatly exceeding the expected value. We note also the appreciable probability of observing underground showers of particles and muon groups,[25] and of showers at large zenith angles at sea level.[26]

The hypothesis that eliminates the foregoing contradictions and explains many results from a unified point of view is simple: during the time of interaction the nucleon goes over into a passive state, in which its interaction with the matter has a cross section much smaller than usual. The baryon stays in this state for a certain time τ that varies relativistically with the energy. After the lapse of the time τ, the nucleon goes over into the normal state and interacts with the nuclei at the normal nuclear cross section. The lifetime and the interaction cross section in the passive state (S) should be determined experimentally.

A theoretical analysis of the question, carried out by Feĭnberg,[27] leads to the conclusion that the cross section decreases for the electromagnetic interaction, and points to the possibility of a similar effect in strong interactions if the energy is sufficiently high.

1. ABSORPTION OF NUCLEONS IN MATTER

Thus, we shall assume, in analyzing the problem, that the nucleon, while retaining a fraction Δ of its energy in the interaction, turns into a passive S-particle which does not interact with the matter. The nucleon exists in such a state for a time $\tau = \tau_0 E/Mc^2$.

The interactions of the first-generation nucleons N_1 are distributed in the matter in accordance with

$$dN_1 / dx = e^{-x} \tag{2}$$

(x is measured in nuclear free paths). The variation of the number S_1 of "passive" first-generation particles is

$$dS_1 / dx = e^{-x} - S_1 / \rho c\tau. \tag{3}$$

The solution of the problem is determined by the value of the parameter $d = 1/\rho c\tau$, which is equal to the ratio of the geometrical length corresponding to the nuclear free path of the nucleon l_{nuc} to the baryon free path in the S state l_S. The value of α varies in inverse proportion to the particle energy.

For the nucleons and S-particles of the second generation we have

$$\frac{dN_2}{dx} = \alpha S_1 - N_2, \quad \frac{dS_2}{dx} = N_2 - \alpha_2 S_2$$

and analogously for the succeeding generations.

The problem is similar to that of the radioactive family, and the solutions can be readily obtained. We write out the expressions for N_2 and N_3, assuming that $\alpha_2 = 2\alpha$, which corresponds to $\Delta = 0.5$:

$$N_2(x) = \frac{\alpha}{1-\alpha}(e^{-\alpha x} - e^{-x}) - \frac{\alpha}{1-\alpha} x e^{-x},$$

$$N_3(x) = \frac{2\alpha}{(1-\alpha)^3} e^{-\alpha x} - \frac{2}{(1-\alpha)(1-2\alpha)} e^{-2\alpha x}$$

$$+ \frac{\alpha^2}{(1-\alpha)(1-2\alpha)} x e^{-x} + \frac{\alpha^2}{(1-\alpha)(1-2\alpha)} x^2 e^{-x}$$

$$+ \frac{\alpha[(1-\alpha)^3 - (1-2\alpha)^3]}{(1-\alpha)^3(1-2\alpha)^3} e^{-x}.$$

If the nucleon retains after the interaction a fraction of energy Δ, and the incident nucleons have a power-law energy spectrum of the form $N(>E) \sim E^{-\gamma}$ at a depth x, then the flux of nucleons with energies smaller than a given value is given by the expression

$$N(>E,x) = N_1(x) + \Delta^{\gamma} N_2(x) + \Delta^{2\gamma} N_3(x) + \ldots \quad (4)$$

We note that the absorption curve is approximated by e^{-x} for small thicknesses and by $e^{-\alpha x}$ for moderately large ones.

In Fig. 1 we compare the results of the calculations, for which in accord with experiment[4, 16] we have assumed $\Delta = 0.5$, with the experimental data[1] on the absorption of nucleons in water. The initial section of the curve shows that the free path for the interaction in water is close to 90 g/cm^2, and that

$$\alpha = \frac{90}{180-200} = 0.5 - 0.4.$$

The energy of the nucleons observed in the experiment[1] is estimated at $\sim 10^{11}$ eV. From this we obtain (E is in electron volts)

$$\alpha = 4\cdot 10^{-2}(10^{12}/E), \quad l_S = 20(E/10^{12})\,[\mathrm{m}].$$

The uncertainty in the determination of l_S from Vishnevskiĭ's experimental data is governed by the accuracy with which the energy of the particles is estimated, and amounts apparently to approximately 2–3.

At an energy $\sim 10^{11}$ eV, the lifetime of the particles in the passive state, determined from the free path, is $\sim 10^{-8}$ sec. If the rest mass of the S-particles is close to that of the nucleons, then the lifetime for the particle at rest is $\sim 10^{-10}$ sec, i.e., a time characteristic of processes connected with the change of strangeness in weak interactions.

2. MEASUREMENT OF NUCLEON ENERGY WITH A CALORIMETER

It is easy to calculate the probability of realization of the i-th interaction of the nucleon in an absorber of thickness P nuclear free paths

$$W_i(P) = \int_0^P N_i(x)\,dx.$$

Integration yields

$$W_2(P) = 1 - \frac{1}{(1-\alpha)^2} e^{-\alpha P} + \frac{\alpha(2-\alpha)}{(1-\alpha)^2} e^{-P} + \frac{\alpha}{1-\alpha} P e^{-P},$$

$$\begin{aligned} W_3(P) = {} & \frac{2}{(1-\alpha)^3}(1-e^{-\alpha P}) \\ & - \frac{1}{(1-\alpha)(1-2\alpha)^2}(1-e^{-2\alpha P}) \\ & + \frac{2\alpha^2(2-3\alpha)}{(1-\alpha)^2(1-2\alpha)^2}[1-e^{-P}(P+1)] \\ & + \frac{\alpha^2}{(1-\alpha)^3(1-2\alpha)}[2-e^{-P}(P^2+2P+2)] \\ & + \frac{\alpha[(1-\alpha)^3-(1-2\alpha)^3]}{(1-\alpha)^3(1-2\alpha)^3}(1-e^{-P}). \end{aligned}$$

The value of W_3 was obtained for $\alpha_2 = 2\alpha$, corresponding to reduction of the nucleon energy to one half by the interaction. Figure 2 shows the values of W_2 and W_3 for a characteristic absorber thickness $P = 5$ nuclear free paths as a function of the quantity $\alpha = mc^2/E\rho c\tau_0$.

Figure 2 shows also the dependence of the fraction of the energy ΔE released by the nucleon in the absorber on α. We see that α changes by a factor of 2 when the energy changes by approximately three orders of magnitude. This leads to a distorted energy spectrum of the nucleons if this spectrum is measured with the aid of apparatus with a thick filter.

Figure 2 shows the coefficients $\kappa = (N(>E)E^{\gamma})_{\mathrm{meas}}/(N>E)E^{\gamma})_{\mathrm{true}}$ characterizing the variation of the integral spectra of the nucleons. The calculations were made for power-law spectra with exponents $\gamma = -1.7$ and $\gamma = -1.9$. We see that in the interval $10 > \alpha > 10^{-2}$ the exponent increased by 0.1–0.2, and after reaching a plateau in the region of small α, the measured flux is smaller than the true one by a factor 3–4.

We have used these calculations for comparison with the already mentioned nucleon fluxes at 3260 m altitude, measured with a calorimeter and with apparatus with a thick absorber. For the Moscow State University calorimeter[2] the density is $\rho \approx 4.8/200 \approx 1/42$ nuclear free path per cm.

Figure 3 shows a comparison of the spectra. The thin-absorber nucleon spectra presented come from two sources: measurements in the atmosphere,[4] and calculations from data obtained by the Moscow State University group[14] on the in-

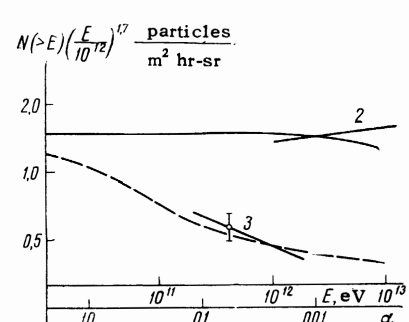

FIG. 3. Energy spectrum of nucleons at 795 g/cm^2 pressure. Curves 1 and 2 were obtained with a thin absorber in[4] and [14] respectively; curve 3–experiment with thick absorber [2], dashed curve–calculation for calorimeter.

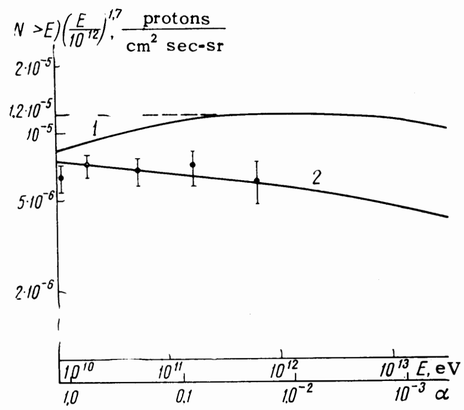

FIG. 4. Energy spectrum of primary protons. Curve 1—from [4], curve 2—calculation for calorimeter with P = 3 nuclear free paths, $\rho = 1/23$, points—data of "Proton-1" satellite.

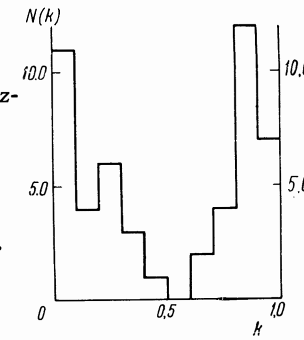

FIG. 5. Experimental [14] ionization ratio $k = I_I/I_I + I_{II})$ under a "thin" (I_I) and "thick" (I_{II}) absorber for particles with energy ~ 10^{12} eV (total number of events to the left and to the right is 25).

tensity of the ionization bursts under 60 g/cm^2 absorbers. For the calculation we used data on the burst spectra, with allowance for the structures. It was assumed that in an absorber of thickness 60 g/cm^2 the electron-photon component receives 25% of the primary-particle energy (pion interactions are taken into account). The normalization to the absolute flux is in this case in accordance with Fig. 5 of [14]. We see that within the 20–30% measurement accuracy quoted by the authors of the cited papers, the data obtained with the thin absorber agree with one another, and the results obtained with a thick absorber lie well on the calculated curve.

Figure 4 shows a similar comparison of data on the primary proton spectrum. The results for the primary spectrum, obtained in [4] from a set of measurements with a thin absorber (assuming the nuclear composition of primary cosmic rays given in the review[28]), are compared with measurement data obtained with the "Proton-1" satellite. The amount of matter in the "proton-1" calorimeter corresponded to three nuclear free paths of iron at a density $\rho = 1/23$ nuclear free paths per cm. We see that in this case, too, there is good agreement between the calculations and the experimental data.

In concluding this section we note that correct allowance for the fraction of the energy registered by the calorimeter in the case of a steeply decreasing nucleon spectrum traveling without a shower accompaniment, at mountain altitudes, greatly increases the flux of such nucleons and voids the conclusion drawn by Grigorov[8] that the free path for the interaction of the nucleons in the atmosphere is greatly altered in the energy interval 10^{11}–10^{13} eV.

3. INELASTICITY COEFFICIENT IN THE INTERACTION OF HIGH-ENERGY NUCLEONS

We analyze further the fraction of the energy transferred in the interaction from the nucleon to the secondary particles. We shall first consider the typical results of the experiments of Grigorov and his co-workers,[8,14] who have concluded from their experiments that an interaction exists with "catastrophic" losses, in which up to 80% of the nucleon energy is transferred to the π^0 mesons.

The experiments were carried out with an installation containing two graphite absorbers, I and II, of 60 and 210 g/cm^2 respectively. The density of the matter in the instrument was $\rho = 1/65$ nuclear free paths per centimeter. The nucleon energy was $\gtrsim 10^{12}$ eV. A histogram of the ionization ratios I_I and I_{II} measured under the first and second absorbers, taken from [14], is shown in Fig. 5.

The probabilities of the first interactions in absorbers I and II are respectively $W_I = 0.51$ and $W_{II} = 0.48$. Thus, the first interactions in the absorbers have practically equal probabilities. The second-interaction probabilities for the experimentally obtained particles with energy $\approx 10^{12}$ eV, for which $\alpha = 4 \times 10^{-2}$, are 0.01 and 0.06. Thus, only approximately 10% of the nucleons interacting in the upper absorber will give rise to secondary interactions in the lower absorber.

An elementary balance for the energy transferred to the electron-photon component, for those cases when the first interaction occurs in the upper absorber, gives an average ratio $k = I_I/(I_I + I_{II}) = 0.73$ and describes satisfactorily the right-side group of events in Fig. 5 both with respect to the average ionization ratio and with respect to the existence of approximately 10% of events with an ionization ratio $k \sim 0.6$.

The left-side group of events, which includes cases when the first interaction occurs in the lower absorber, explains the peak of the ionization ratio at 0.0–0.1. The group of events with ionization ratio ~ 0.25 can be attributed to the penetration of the energy of the particles accompanying the nucleon through the upper lead absorber, since the events selected in the experiment were those in which, first, $I_u/I_{thr} \leq 0.5$ in the upper trays and, second, $I_I \geq 0.05\ I_{thr}$.

Thus, the experimental data of Grigorov et al.[14] can be interpreted without resorting to the conclusion that "catastrophic losses" of energy take place.

The data of [13] can be interpreted in similar fashion. The fraction of the energy transferred to the π^0 mesons decreases to 0.3–0.4, and the energy of the maximum π^0-meson energy is decreased to 0.20–0.30 of the nucleon energy. These values do not contradict the measurements stratosphere[4] and the cloud-chamber data,[16] and can be attributed to fluctuations in the energy distribution during the decay of isobars with mass close to two nucleon masses (see Fig. 2 of [13]).

In [12], where a calorimeter was used, it was found that the average energy fraction $K_{\pi 0}$ transferred to the π^0 mesons in interactions of particles with energies close to 3×10^{11} eV with carbon nuclei is 0.33 ± 0.05. A close value, 0.37 ± 0.04, was obtained[15] in measurements of interactions with iron nuclei. From the point of view developed here, these values simply reflect the symmetry in the production of π^0 and $\pi^{\pm}$ mesons.

If we recognize further that approximately half the nucleon energy is released in the calorimeter, then the calorimetrically measured $K_{\pi 0}$ and the "effective" $K_{\pi 0}$ are in good agreement with the results obtained in the cloud chamber[16] and in the atmosphere.[4]

The estimate of σ, the variance of $K_{\pi 0}$, is likewise altered. Using the formulas given in [14], we obtain

$$\left(1+\left(\frac{\sigma}{K_{\pi^0}}\right)^2\right)^{1/2}=\frac{0.42}{0.33}=1.25,\quad \frac{\sigma}{K_{\pi^0}}=0.7,$$

i.e., the same value as obtained from measurements in the atmosphere.[4]

Thus, the proposed hypothesis explains the extreme measured values of $K_{\pi 0}$, i.e., those with the maximum deviations. The intermediate measurement results can, naturally, not be explained. These are, for example, the results given by a calorimeter with a Cerenkov counter,[29] namely that $K_{\pi 0}$ remains constant at 0.22 ± 0.02 in the energy interval $E_0 = 1 \times 10^{11}–7 \times 10^{11}$, and also the measurement results[30] in which the distribution of the inelasticity coefficient in interactions caused by neutral primary particles (presumably neutrons) differs from the similar distribution for charged primary particles. It is concluded from this that events with large $K_{\pi 0}$ are due to the interaction of charged pions. This point of view is different from the point of view of N. L. Grigorov, who states that interactions with catastrophic losses are due to nucleons.

4. YOUNG ATMOSPHERIC SHOWERS

From the point of view of the hypothesis considered, a young atmospheric shower is an event in which the nucleon in the shower incident on the array is in a passive state. It is easy to estimate the fraction of such showers when these showers are registered by an instrument installed at a pressure 700 g/cm^2 (the experimental conditions of [14, 18]). We have

Particle energy, eV:	10^{13}	$2\cdot10^{13}$	$5\cdot10^{13}$	10^{14}
$\alpha = l_{nuc}/l_S$:	3.4	2.0	0.8	0.4
Fraction of showers with S-particles, per cent:	3.0	13	50	67

The only nuclear active particles in a young air shower are charged pions, which furthermore transfer part of their energy in the atmosphere to the electron-photon component. The average measured ratio of the energy of the nuclear-active particles to the energy of the π^0 mesons can amount to approximately unity. This value is somewhat higher than that observed in experiment[14, 18], but the experimental selection of events makes an exact quantitative comparison difficult.

In deeper layers of the atmosphere, the nucleon goes over into the normal state and becomes the leading particle of the shower. This eliminates the contradiction in the estimate of the fluctuations in the altitude variation of EAS.

5. PASSAGE OF HIGH-ENERGY NUCLEONS THROUGH THE ATMOSPHERE AND FORMATION OF EAS

We must now take into consideration the fact that the density of the atmosphere varies in proportion to the depth:

$$\rho = \rho_0 x$$

(here ρ_0 is the atmosphere at a depth equal to one nuclear free path, $\rho_0 = 1/8500$ nuclear free paths per meter). Then

$$\alpha=\frac{1}{\rho_0 c\tau}\,\frac{1}{x}=\frac{\beta}{x},\quad \beta=\frac{1}{\rho_0 c\tau_0 E/Mc^2}=4\cdot10^2\left(\frac{10^{12}}{E}\right)$$

(E is in electron volts). Thus

$$dS_1 / dx = e^{-x} - S_1\beta / x. \quad (5)$$

The solution of Eq. (5) can be readily obtained by the method of successive generations:

$$S_1(x) = e^{-x} \sum_{i=1}^{\infty} \frac{x^i}{i!} a_i, \quad a_i = \prod_{h=1}^{i} \frac{1}{1+\beta/k}. \quad (6)$$

The solution of the equation for N_2 is

$$N_2(x) = \beta e^{-x} \sum_{i=1}^{\infty} \frac{x^i}{ii!} a_i. \quad (7)$$

The results of the calculations are shown in Fig. 6.

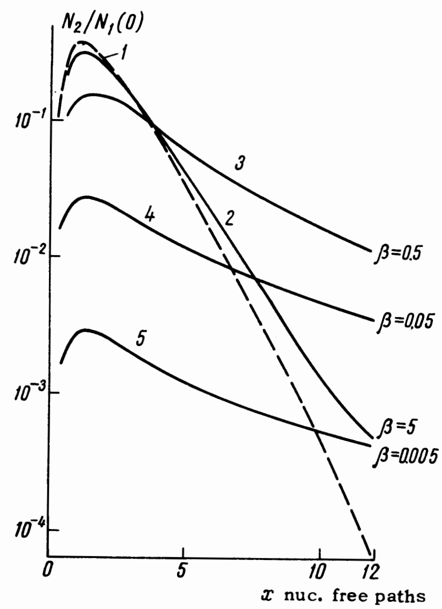

FIG. 6. Flux of second-generation nucleons in the atmosphere. Curve 1–without account of transition of the nucleons into the passive state, curve 2–$\beta = 1/\rho_0 c\tau = 5$, 3–$\beta = 0.5$, 4–$\beta = 0.05$, 5–$\beta = 0.005$.

For comparison with experiment, let us calculate also $W_2(P)$, the probability of realization of a second nucleon interaction in the layer of the atmosphere (P = 11 nuclear free paths), and $\overline{X}_2(P)$, the average depth of the point at which the second interaction of the nucleon takes place in the atmosphere, as functions of β:

$$W_2(P) = \int_0^P N_2(x)\,dx = \beta \sum_{i=1}^{\infty} \frac{a_i}{ii!} \int_0^P e^{-x} x^i dx,$$

$$\overline{X}_2(P) = \int_0^P x N_2(x)\,dx = \beta \sum_{i=1}^{\infty} \frac{a_i}{ii!} \int_0^P e^{-x} x^{i+1}\,dx. \quad (8)$$

Thus, the particle-number spectrum of the EAS will not duplicate the energy spectrum of the primary nucleons, for two reasons:

1) A change takes place in the fraction of the energy ϵ lost by the nucleon in the atmosphere:

$$\varepsilon = 0.5\,W_1 + (0.5)^2 W_2 + \ldots;$$

2) a change takes place in the height at which the second interaction of the nucleon takes place.

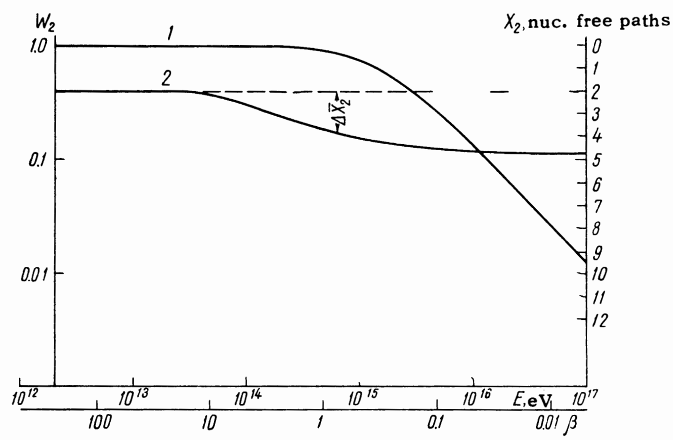

FIG. 7. Calculated data on the passage of second-generation nucleons through the atmosphere: curve 1–probability W_2 of realizing interaction of a second-generation nucleon, curve 2–average depth $\overline{X}_2$ for this interaction (calculation for P = 11 nuclear free paths).

Figure 7 shows that the average depth of the second interaction begins to increase from $\overline{X}_2 = 2$ at $\beta \sim 10$ and again reaches a plateau at a value $\overline{X}_2 = 4.8$ for $\beta < 0.5$.

We assume that the number N of shower particles is proportional to the energy lost by the nucleon in the atmosphere. Let us calculate further the variation of the average depth of energy release

$$\overline{X} = \frac{W_1\overline{X}_1 + 0.5W_2\overline{X}_2}{W_1 + 0.5W_2}.$$

The change in the number of particles of the shower with changing $\overline{X}$ is taken into account by using the experimental coefficient of absorption of the EAS in the atmosphere, as determined by measuring the intensity of the showers at sea level and on mountains.[31]

The results of the calculation for a power-law spectrum with $\gamma = 1.7$ are shown in Fig. 8. We see that the calculation agrees with experiment.[22] This shows that in estimating the lifetime of nucleons in the passive state it is possible to start from data on the interaction of the particles in a rather wide range of energies, and not only from the results of the experiments of V. F. Vishnevskiĭ.[1]

The analyzed experimental data indicate that at energies 10^{11} eV and higher the probability that the

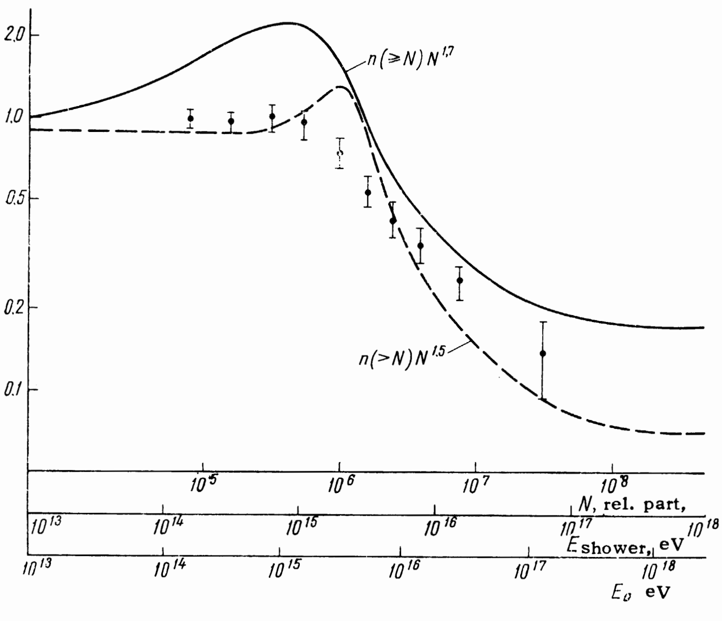

FIG. 8. Particle-number spectrum of EAS at sea level (N = number of particles). Curves–calculated spectra for a power-law primary spectrum with $\gamma = 1.7$, points–experiment[22].

nucleon goes into the passive state after the interaction is close to unity. One cannot exclude, of course, the possibility of the nucleon having a probability of several times ten percent of remaining in the normal state after the interaction.

It follows from the same results that the cross section for the interaction of the baryon in the passive state should not be more than $^1/_{10}$–$^1/_5$ of normal.

6. FLUX OF HIGH ENERGY PARTICLES UNDER THICK LAYERS OF MATTER

The intensity of the particle flux under thick layers of matter constitutes a radical criterion for estimating the cross section for the interaction of passive baryons. Using formulas (6) and (7), we can calculate the energy spectra for S_1 particles and N_2 second-generation nucleons at sea level. We have started in this calculation from the spectrum of the primary cosmic rays, given in Clark's review paper[32], and corrected in the energy region $\sim 10^{14}$ eV in accord with [4].

The results of the calculations are shown in Fig. 9. At energies above 10^{15} eV, the intensity of the flux of the S-particles is only several times smaller than the intensity of the primary rays. The flux of second-generation nucleons in the energy region 10^{14}–10^{16} also turns out to be much higher than the flux calculated without account of the transition of the nucleons into the passive state. It is easy to see that the angular distribution of such particles at sea level will be relatively flat. These results make it possible again to estimate the probability of observing EAS at large zenith angles.

The absorption of S particles in the ground is determined by the expression

$$S(E_1, x) = S(E, x_0)\, e^{-\alpha(x-x_0)}, \tag{9}$$

where x_0 is the sea level. If the absorption takes place in the "normal scale," then $\alpha = 1.5$

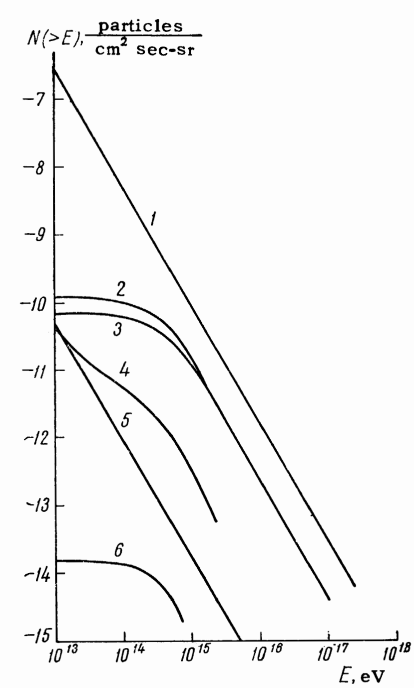

FIG. 9. Integral energy spectra of nucleons and S-particles: curve 1–spectrum of primary cosmic rays[32], 2–spectrum of S-particles at sea level, 3–spectrum of S-particles at depth 7500 m.w.e., 4–spectrum of nucleons N_2 at sea level, 5–spectrum of nucleons at sea level without account of transition to the passive state, 6–spectrum of nucleons N_2 at depth 7500 m.w.e.

$\times 10^{-5}(10^{15}/E)$ (E is in electron volts). The second-generation nucleon flux is given by the expression

$$N_2(E, x) = \alpha S(E, x), \tag{10}$$

which shows that the nucleons are in equilibrium with the S-particles. Figure 9 shows the integral energy spectra of the S-particles and nucleons at a depth of 7500 meters water equivalent in the "normal scale."

If we bear in mind the fact that the primary-nucleon flux data and the value of $\alpha(E)$ used in the calculations have an accuracy not better than 200% and that we do not know the fraction of the neutral S-particles in the flux, then the agreement between the calculations and the experiments[23, 24, 25] is good enough. This explains likewise the high intensity of the showers under thick layers of ground.

These results, when taken literally, signify that the cross section for the interaction of nucleons in the passive state does not exceed 10^{-3} of the normal cross section. It would be premature, however, to insist on this estimate, since an appreciable fraction of the particle flux at large depths underground can be due to muons.

The results allow us to assume that the existence of a passive baryon state is a likely hypothesis, and at any rate is worthy of careful attention.

Together with analyzing from this new point of view other experimental data on high-energy cosmic rays and nucleons accelerated to ~30 GeV, it is most interesting to plan experiments to explain the physical nature of the passive baryons.

The probability of realizing at different energies the transition of the interacting nucleon into the passive state, the cross section for the nuclear interaction of the passive baryon, the question whether other particles are emitted during the transition to the normal state, the masses and the exact lifetimes of the baryons in the passive state, and their radiative losses, are all imminent questions.

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