INVESTIGATION OF INTERACTION AT EXTREMELY HIGH-ENERGIES USING THE ANALYSIS OF EXTENSIVE AIR SHOWERS*

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In the present paper we wish to summarize the conclusions, which, in our opinion, can be drawn on the basis of the data obtained in investigation of extensive air showers.

One can obtain the following characteristics of the processes at extremely high energies.

1) The interaction cross section, $\sigma = const/R_{cmfp}$ where R_{cmfp} is the collision mean free path.

2) The energy distribution of secondary particles:

$$\frac{dN_{n.a.}}{dE^{\sec}_{n.a.}} = f(E^{\sec}_{n.a.}),$$

where $dN_{n.a.}$ is the number of secondary nuclear active particles with energy between $E^{\sec}_{n.a.}$ and $E^{\sec}_{n.a.} + dE^{\sec}_{n.a.}$.

The investigation of extensive air showers can also verify our hypothesis concerning the possibility of extrapolating to extremely high energies of our conclusion which was obtained when investigating cosmic rays in the stratosphere, namely the conclusion that the predominant part of primary particle energy is transferred to some one of the secondary nuclear particles, which most probably is a nucleon [1].

3) The angular distribution of the energy fluxes of secondary particles, which are generated in the interaction of a particle of extremely high energy with the atomic nucleus of the atmosphere:

$$\frac{\sum_i^{\sec} E(\theta)}{E_{prim}} = F(\theta),$$

4) The variation of characteristics, enumerated above, with the primary particle energy

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1. Interaction cross section

a) The collision mean free path of primary particles can be obtained by means of a study of fluctuations in Cherenkov radiation of extensive air showers in the atmosphere for the showers with a given total number of particles (for the further details see the paper by Chudakov et al. submitted to this conference).

b) The collision mean free path of high energy particles can also be obtained from the ratio of the number of cases when the nuclear active particle is not accompanied by the air shower to the total number of nuclear active particles in the same energy region (for further details see paper by Grigorov et al., submitted to this conference).

Since the area covered by the ionization chamber was small and the duration of measurements was also small, we could obtain the data on the nuclear-active particles only for energy of 10^{12} *eV*. The collision mean free path was found to be < 85 g/cm^2 . The symbol < means that a part of showers generated in the upper atmosphere could not be recorded by our counters.

c) The absorption mean free path (R_{cmfp}) can be determined for the region of very high energies. Since the interaction path is shorter than the absorption path, we can determine the upper limit for the first one.

From the data obtained by Hristiansen and collaborators at sea-level and by Nicol'skij and collaborators at 3860 m it follows that the flux of nuclear active particles with energy exceeding 10^{13} *eV* is equal to 0.01 $h^{-1}m^{-2}$ and 0.1 $h^{-1}m^{-2}$ at sea-level and at 3860 *m*, respectively.

From the comparison of this data with the total number of primary cosmic ray particles having such energy (36 $h^{-1}m^{-2}$) it follows that the absorption mean free path is equal to 120 g/cm^2 .

d) Already in 1949 one of us (G. T. Z.) suggested to use the data on the altitude dependence of extensive air showers for the determination of the upper limit for the collision mean free path.

At present [2] it is known that the altitude dependence of extensive air showers in the energy interval of from 10^{14} *eV* to 10^{18} *eV* is characterised by a path $\Lambda = (90 \div 140)$ g/cm^2 . It follows from this that the interaction mean free path of primary cosmic ray particles with the nuclei of nitrogen atoms is undoubtedly less than Λ .

Since the collision mean free path within the interval of $(10^{10} \div 10^{11})$ *eV* and the absorption mean free path in the interval of $(10^{11} \div 10^{13})$ *eV* are practically constant, we suggest that for the purpose of further analysis it is reasonable to assume that the collision mean free path of protons with nitrogen nuclei is constant and equal to 70 g/cm^2 also in the region of extremely high energies.

2. Energy distribution of secondary particles

Let us assume that the fluctuations in energy losses in interactions are small. If the mean path between two interactions is equal to 70 g/cm^2 than the fact that the altitude dependence of the extensive air showers is characterized by the value 140 g/cm^2

can be explained by the assumption that the path of each individual cascade is practically equal to 200 *g/cm²*.

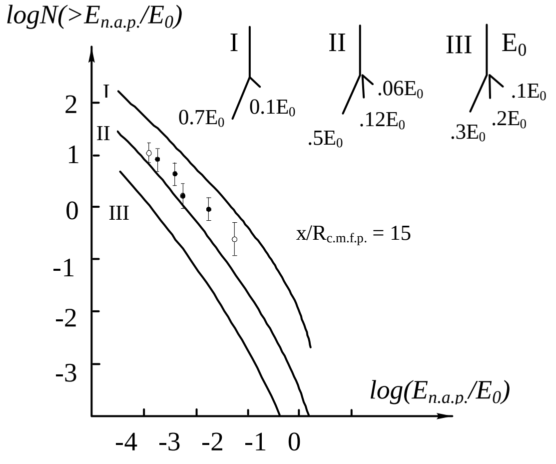

Fig. 1

Thus, the part of the energy which the nuclear active particle loses in one interaction is given by the ratio of the collision mean free path to the mean free path to the absorption of an individual cascade. This is 70/200 = 0.35.

In order to obtain more detailed information about the character of the interaction acts, J. P. Ivanenko and E. V. Gorchakov have calculated the energy spectra of the nuclear-active particles using the method of successive generations [3].

The Fig. 1 shows some results of these calculations, as well as some experimental data obtained by Hristiansen et al.

From the figure can be seen that the curve corresponding to the case when one of the secondary particles retains about 50% of the primary particle energy gives the best agreement.

However, if the fluctuations of the values of the energy losses in the interaction acts are large (as it is supposed in the paper by Grigorov et al.) then the energy losses will be greater.

3. Angular distribution of secondary particle energy fluxes in the interaction act.

V. I. Zacepin carried out the calculations of the lateral distribution of particles basing on assumptions on angular dependence of the fluxes of energy of the secondary particle.

The idea of these calculations is that the shower caused by a primary particle with energy *E* is equal to the sums of showers produced by all the secondary particles generated in the first interaction act.

It is known from experiments on extensive air showers that the lateral distribution $\rho(r)$ does not depend on the primary energy and that in the region 1 *m* < *r* < 10 *m* of the shower the particle density is inversely proportional to the distance from the axis: $\rho(r) \sim 1/r$.

Therefore, in order to determine the lateral distribution of the particles of showers generated by the primary particle with energy *E* (according to the above assumptions) it is necessary to sum the extensive air showers generated by the secondaries.

The axis of these extensive air showers are distributed according to $F(\theta)$.

Calculations show that independent from the assumptions about the type of the function $F(\theta)$ for the agreement with the experimental data it is necessary to assume that the angle $\theta_{\frac{1}{2}}$, including a half of the energy fluxes of secondary particles is always approximately the same, i. e., 10^{-4} *rad* for primary particles with energy 10^{14} *eV*.

If the lateral distribution for distances shorter than 1 *m* is also inversely proportional to the distance, than this angle should be less than 10^{-4} *rad*.

Besides, in the above analysis the deviation of the secondaries from the deviation of the primaries has been taken into account only in the first act.

Therefore $\theta_{\frac{1}{2}}$ is apparently substantially less than 10^{-4} and, consequently, on the average $P_t < 10^9$ *eV/c* .

In principle similar estimates of the transverse momenta can be made by the comparison of the lateral distribution and of the absorption of the extensive air showers.

The absorption of an individual shower in a thin layer of air is determined by the energy spectrum of the soft component alone, because it is known that no small energy electrons are generated in nuclear collisions. Thus, the mean value of the exponent of the energy spectrum *s* can be obtained.

The lateral distribution of electrons is also determined by *s* alone, if the angular divergence of nuclear active particles is sufficiently small.

The experimental data ensure a satisfactory explanation of the mean absorption and of the mean lateral distribution by the single parameter *s*. Therefore P_t is sufficiently small to give no observable influence on the lateral distribution of the electrons.

4. The variation of characteristics of primary particles

The investigation of characteristics of the separate individual showers including the measurements of total number of particles in them enables us to study the dependence of their characteristics on the energy of primary particles.

Some preliminary results which were obtained both in our experiments and in experiments of other authors indicate the change of properties of showers with the change of the number of shower particles. It is quite possible that this means that our conclusion concerning the conservation of a greater part of primary energy on a single particle ceases to hold when we go over to extremely high energies.

References

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