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PRODUCTION OF PIONS BY HIGH-ENERGY COSMIC-RAY ALPHA PARTICLES

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Experimental results are compared with the hydrodynamical theory of multiple meson production. It is shown that, for showers with energy $\gtrsim$ 10 Bev per nucleon, the results of an analysis of the parameters of observed stars do not contradict the concept of an interaction between the incident α particle and nucleons filling a tunnel in the target nucleus.

IN the collisions of high-energy nucleons ($\gtrsim 10^{12}$ ev) with atomic nuclei, it is assumed that the nucleons interact with the contents of a tunnel punched by the nucleon in the target nucleus and filled with solid matter; the diameter of the tunnel equals the diameter of the nucleon,* and its length depends on the atomic number of the target nucleus and on the impact parameter. On the basis of such a model of the interaction between the nucleon and the nucleus, one can explain some experimental results for high-energy showers (jets; $\theta_{1/2} \leq 10°$).[2-4]

In the present article, analogous calculations are used for describing the interaction of high-energy α-particles ($\gtrsim 10^{10}$ ev/nucleon) with atomic nuclei. In this case, the idea of a nuclear tunnel as consisting of solid matter will be more correct, since the cross section of the tunnel punched out in the nucleus by the α particle is proportional to $A_\alpha^{2/3}$, and the number of nucleons introduced into the tunnel equals A_α.

In view of that fact, the nucleon density in the interaction volume increases, and the assumption that the time between consecutive collisions of nucleons is smaller than the duration of the interaction is, in that case, more correct.

Showers produced by α particles in a stack of stripped Ilford G-5 emulsions exposed in 1955 in Italy at the altitude of 30 km were selected for the study. In addition, a part of the showers were taken from the published articles by various authors.[5-12]. The total number of showers studied equals 67.

1. SHOWER STARS

1. According to the hydrodynamical theory of Landau-Belen'kiĭ,[13,14], the number of particles produced in an interaction of an α-particle with a nucleus is

$$N = N_\alpha (n+1)/2 \quad \text{for } n \leqslant 3.7,$$
$$N = 0.92 N_\alpha \left(n - \tfrac{1}{4}\right)^{3/4} \quad \text{for } n > 3.7,$$
$$N_\alpha = k A_\alpha^{3/4} (E_\alpha / 2M_0 c^2)^{1/4}, \tag{1}$$

where N is the sum of produced particles and nucleons involved in the collision, N_α is the same for a collision of two α particles, and $n = M_t/M_\alpha$ is the ratio of the mass of the tunnel punched out in the nucleus by the α particle to the mass of the latter. The relation between the total number of particles N and the number of charged particles n_s is given by the relation

$$N = 1.5 n_s + n + 1. \tag{2}$$

The energy of the primary α particle is equal to

$$E_\alpha = 2nM_\alpha c^2 / \tan^2 \theta_{1/2}. \tag{3}$$

From Eq. (1), using Eqs. (2) and (3), we obtain

$$\tan \theta_{1/2} = A_\alpha^2 (n+1) n^{1/2} (1.5 n_s + n + 1)^{-2} \quad \text{for } n \leqslant 3.7,$$
$$\tan \theta_{1/2} = 3.39 A_\alpha^2 (n - 0.25)^{3/2} n^{1/2} (1.5 n_s + n + 1)^{-2} \quad \text{for } n > 3.7. \tag{4}$$

In the case where the impact parameter is bigger than the difference between the radii of the target nucleus and the α particle, not the entire mass of the α particle takes part in the interaction but only part of it, $M_\alpha^*(b)$ (where b is the impact parameter). The first equation of (4) can then be written in the form

$$\tan \theta_{1/2} = A_\alpha^{*2} (n^* + 1) n^{*1/2} (1.5 n_s + M_t^* / M_\alpha + A^*/4)^{-2},$$
$$n^* = M_t^* / M_\alpha^* \leqslant 3.7. \tag{4'}$$

A_α^*, M_t^*, M_α^* are calculated as the corresponding fractions of the spherical volumes for their partial overlapping; the density of the nuclear matter is assumed to be constant. Formulae (4) and (4′) give the relation between the angle $\theta_{1/2}$, from

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*One should distinguish between a tunnel in solid nuclear matter from one in the structure of a nucleus;[1] the diameter of the latter is slightly greater than the diameter of the nucleon.

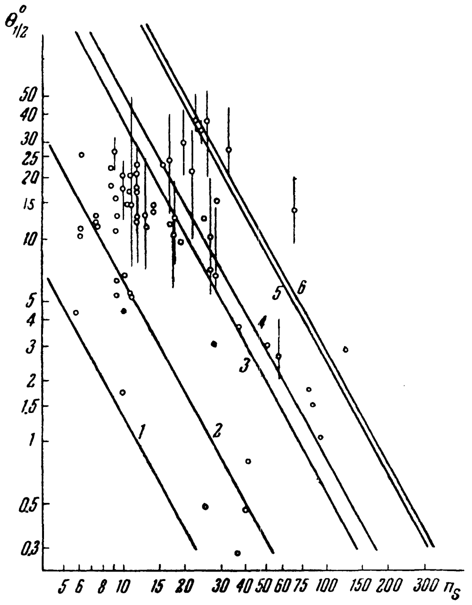

FIG. 1

which the energy of the α particle is determined, and n_s.

The dependence of $\theta_{1/2}$ on n_s for different lengths of tunnels is given in Fig. 1. The smallest possible multiplicity corresponds to the case of a collision between an α particle and a peripherical nucleon of the nucleus, or to a collision of an α particle with a hydrogen nucleus; in both cases the tunnel is punched out by the nucleon in the incident α particle. Averaging over the diameter of the α particle, we obtain $M_t^0/M_0 = 1.6$, where M_t^0 is the mass of the tunnel punched out by the nucleon in the helium nucleus. The dependence of $\theta_{1/2}$ on n_s for that case is given by curve 1. Curve 2 corresponds to the average value of the tunnel length produced by the α particle in a mean light nucleus of emulsion ($\overline{A} = 14$); $n^* = 1.35$. Curve 3 gives the dependence of $\theta_{1/2}$ on n_s for the maximum tunnel length produced by an α particle in an average light nucleus of the emulsion; $n = 2$. Curve 4 gives this dependence for $n^* = 2.77$, which corresponds to the value of the average tunnel length produced by α particles in medium-heavy nuclei of the emulsion ($\overline{A} = 94$). Curves 5 and 6 correspond to a central collision of an α particle with a silver nucleus ($n = 4.41$) and a nucleus of iodine ($n = 4.57$; this corresponds to the maximum tunnel length in photographic emulsion). It should be noted that, for the above selection of tunnel lengths, the experimental points should be grouped in the region between curves 1 and 6. It can be seen from Fig. 1 that this is actually the case.

The errors shown take into account the possible forward-backward asymmetry in the distribution of particles in c.m.s.[15] The errors due to measurement inaccuracy are not given, since the fluctuations are much larger and include these.

2. In heavy nuclei of the emulsion, the maximum tunnel length punched out by the α particle in a nucleus equals 4.57; the maximum length of the tunnel in light elements equals 2.00. It is clear that, for peripheral collisions with a heavy nucleus, the length of the tunnel may be the same as in collisions involving light nuclei of the emulsion. We shall find the ratio N_1 of the number of cases of interaction of α particles with the nuclear matter in a tunnel, the length of which varies from 2.0 to 4.57, to the number of cases of interactions N_2 with tunnels smaller than the maximum tunnel length in light elements.

Assuming the cross section of interaction of α-particles with nuclei being equal to[16]

$$\sigma_i = \pi (R_i + R_\alpha - 2\Delta R), \tag{5}$$

where R_i is the radius of the target nucleus and R_α the radius of the α particle ($R_i = 1.4 \times 10^{-13} A_i^{1/3}$, $\Delta R = 0.85 \times 10^{-13}$ cm), and taking into account the composition of the emulsion, we find that $N_1/N_2 = 0.6$. The experimental value of this ratio for various energies of the primary α particle, is given in Table I. The data of the table are in good agreement with the calculations.

TABLE I

E, Bev/nucleon	N_1/N_2
$E > 10$	$0.46^{+0.40}_{-0.17}$
$E > 50$	$0.54^{+0.88}_{-0.38}$
$E > 100$	$0.79^{+0.43}_{-0.54}$

It is interesting to compare the results obtained with an analogous calculation carried out for showers produced by nucleons.[15] For this case $(N_1/N_2)_{\text{nucleon}} = 1.45$ and the experimental ratio equals 5.39 ± 0.30 for energies larger than 50 Bev, and 2.92 ± 0.31 for energies > 100 Bev. The observed discrepancy cannot be explained by fluctuations of multiplicity and of the angle $\theta_{1/2}$. The experimental results for showers produced by α particles are therefore in much better agreement with the calculation than for showers produced by nucleons. It should be noted that the conclusion about a purely multiple character of meson production for a given shower cannot be made only on the basis of the fact that a point corresponding to the shower falls into the region of $\theta_{1/2}$ predicted by the hydrodynamical theory. Thus, for instance, the R-star of Kaplon et al.[5] falls on curve 4 (Fig. 1), although, according to the authors, it is produced not in a purely multiple process.

The above analysis points rather towards the meson production being not purely multiple, though predominantly so. A certain contribution of a plural process cannot be excluded. In order to establish the purely multiple character of meson production, it is necessary to carry out additional detailed study of showers.

2. HEAVILY IONIZING STARS

1. Experimental distribution of showers with respect to the number of grey-black tracks N_h is given in Fig. 2 (histogram 1). The distribution has a maximum in the region $3 \leq N_h \leq 5$ and gives one or two cases per interval for $N_h > 6$. The maximum value of N_h observed experimentally equals 26.

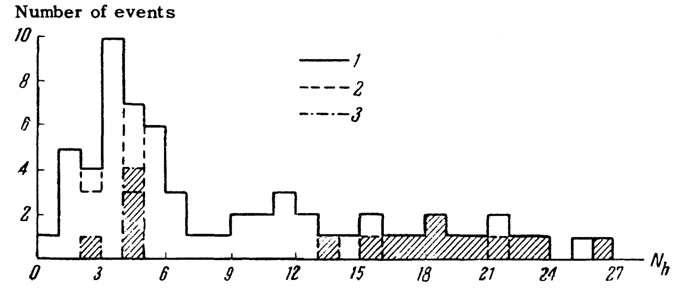

FIG. 2

For total disintegration of light nuclei, the greatest value of N_h equals 8. The ratio of the number of cases with $N_h > 8$ to those with $N_h \leq 8$ equals $n_1(N_h > 8)/n_2(N_h \leq 8) = 0.64$.

It should be noted that Rao et al.[17] found that the mean energy of α particles producing showers equals 10 Bev per nucleon. An analogous ratio found from their data equals 0.6.

Taking the cross section for the interaction of α particles and nuclei according to Eq. (5), we obtain the ratio of the number of interactions with heavy nuclei n_H to the number of interactions with light nuclei of the emulsion n_L equal to 1.87, which is as expected since the cases with $N_h \leq 8$ include the disintegration of both heavy and light nuclei. In the explanation of heavy ionizing stars produced by high-energy α particles, as well as in the explanation of relativistic showers, there is consequently no contradiction between experiment and the idea of the interaction of α particles with a part of the nucleus or with a tunnel punched by the particle in it. The shape of the tunnel is of no importance, the main feature being the fact that the residual nucleus carries away a small fraction of the energy of the primary particle.

2. We shall find the ratio of the number of events $N_h > 8$ to the number of events $N_h \leq 8$ for various values of the primary α particles. The results of such operations are given in Table II.

TABLE II

E, Bev/ nucleon	$n_1(N_h>8)/n_2(N_h\leqslant 8)$	$n_1(N_h>8)/n_H$
$\overline{E}=10$	0.6	0.58
$E>10$	0.64 ± 0.01	0.60 ± 0.01
$E>50$	$0.50^{+0.04}_{-0.09}$	$0.51^{+0.03}_{-0.07}$
$E>100$	$0.43^{+0.14}_{-0.05}$	$0.46^{+0.10}_{-0.04}$

It can be seen that, with increasing energy, the fraction of events with $N_h > 8$ decreases and the maximum value of the ratio $n_1(N_h > 8)/n_2(N_h \leq 8)$ is about 0.6. This means that the tunnel model is the more correct the larger the energy of the primary α particle. In the interaction of α particles with light nuclei of the emulsion, $N_h \leq 8$; for peripheral collisions of α particles with heavy nuclei where a tunnel of roughly the same length as in light elements is punched in the nucleus, we also find $N_h < 8$.[18] Consequently, the value $N_h > 8$ is left for the fraction of central and close to central collisions of the α particle with heavy nuclei where the tunnel has maximum length.[17] In other words, the ratio $n_1(N_h > 8)/n_2(N_h \leq 8)$ should not be of greater order of magnitude than 0.6, the value of N_1/N_2. The data of Table II fully confirm this conclusion.

With increasing energy of the α particle, the energy transfer to the residual nucleus (according to the tunnel-effect model) decreases. In consequence, the fraction of cases with $N_h > 8$ will decrease. This conclusion is also confirmed by the results of Table II (column 3), where the ratio of the number of cases with $N_h > 8$ to the number n_H of expected events of collision of α particles with heavy emulsion nuclei is calculated, assuming the validity of Eq. (5).

3. Aside from the general distribution of all showers with respect to N_h, the distribution of showers in which the tunnel length is smaller and larger than the maximum tunnel length in light nuclei is given in Fig. 2, histograms 2 and 3 respectively. It can be seen that histogram 3 begins with $N_h > 13$, and histogram 2 has a maximum for $N_h = 3$ and is practically cut off at $N_h = 12$.

We shall calculate the average value $\overline{N}_h$ as a function of the tunnel length and the energy of the primary α particle. The result is given in Table III. It can be seen that, according to all that was said above, the average value of $\overline{N}_h$ for

TABLE III. Dependence of the number of grey and black tracks on tunnel length and the energy of the primary α particle

E, Bev/nucleon	N_h $(n \leqslant 2)$	N_h $(n > 2)$
$E > 10$	6.1 ± 2.9	14.3 ± 4.3
$E > 50$	5.3 ± 2.4	12.7 ± 3.8
$E > 100$	2.6 ± 1.5	18.1 ± 1.1

showers with large tunnel length is larger by more than a factor of 2 than the value of $\overline{N}_h$ for showers with small tunnel length; with increasing energy of the primary α particle, this relation becomes more pronounced.

4. Calculating $\overline{N}_h$ in the same manner as was done for showers produced by nucleons,[1] we obtain, for the case of a central collision of the α particle with the average heavy nucleus of the emulsion, $\overline{N}_h = 4.5$, which is considerably smaller than the experimental value. Consequently, the assumption that, in the case of interaction of a high energy particle with heavy nuclei, N_h is determined only by the change of the surface energy of the nucleus and the friction in the tunnel is not correct. In that case, in fact, only about 20% of the nucleons contained in the tunnel are emitted. The redistribution of the residual nucleons in the new nucleus is accompanied by more far-reaching changes than those which are taken into account by the variation of the surface and friction in the tunnel.

CONCLUSIONS

An analysis of the number of particles in showers produced by helium nuclei with energies $\gtrsim 10$ Bev per nucleon is in agreement with the tunnel-effect model of the interaction between the incident α particle and continuous nuclear matter.

The energy threshold of the application of such a model of interaction between high-energy α particles and nuclei which in the limiting case is not bigger than 50 Bev/nucleon, is markedly lower than that in the interactions between a nucleon and the nucleus. This can be explained by the fact that, in the case where the primary particle is an atomic nucleus with atomic weight A, $A^{1/3}$ times more nucleons are introduced into the tunnel as compared with the events in which the primary particle is a nucleon. One should therefore expect a better agreement between the theory of multiple meson production and the experiment for showers produced by nuclei heavier than the helium nucleus.

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