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ON THE MECHANISM OF INTERACTION OF FAST PROTONS WITH NUCLEI

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Abstract: The paper discusses the results of the publications concerned with the interaction of 9 GeV protons with photoemulsion nuclei. The comparison drawn with recourse to data on nucleon-nucleon collisions warrants the conclusion that the cascade mechanism of interaction with nuclei is valid.

The mechanism of interaction with nuclei of fast nucleons in cosmic rays has been the subject of many experimental and theoretical investigations. Two alternative schemes have been suggested for explaining the experiments: the cascade mechanism of consecutive nucleon-nucleon collisions and the tunnel mechanism, i.e., the simultaneous interaction of an incident particle with a group of nucleons of the nucleus in a tube of nuclear substance along the path of the particle. Accelerators yielding particles of energy ≈ 10 eV made a definite solution of this problem possible for this energy region, since our knowledge of the energy of an incident particle eliminates quite a few difficulties.

In ref. [1]) it was concluded, on the strength of the analysis of the fission by 8.7 GeV protons of a group of light nuclei of photoemulsion (C, N, O) as well as silver and bromium nuclei, that the cascade mechanism of nucleon-nucleon interactions actually occurs in experiment. In this investigation the angular and momentum spectra of nuclear fission products were determined and the particles identified by their masses. This made it possible to determine the average number of consecutive collisions equal to 2 for the averaged nuclei of photoemulsion ($\bar{A} \approx 30$) or to 1.4 for light nuclei ($A = 14$). The energy spent in the generation of mesons and the fission of the medium nuclei was found equal to 5.1 ± 0.8 GeV, and the energy carried away by the fast nucleon equal to 3.0 ± 0.5 GeV. This means that their sum 8.1 ± 1 GeV agrees with the energy of the initial proton. Accordingly, the fraction of energy lost by the proton in a single collision with the nucleon of the nucleus was found equal to 0.4 ± 0.1; in later work [2, 3]) concerned with the study of proton-nucleon collisions, the figures coincided: 0.39 ± 0.02.

† Reported at the Conference on Physics of Elementary Particles Uhzgorod, May 18, 1960.

The tunnel mechanism contradicts experimental results, as is shown in ref. [1]), since this mechanism ought to give a larger number of fast particles and an essentially broader angular distribution. The authors of ref. [3]) also concerned with the interaction of 8.7 GeV protons with nuclei also arrive at the conclusion that their results do not contradict the cascade mechanism.

The authors of ref. [4]) also lay emphasis on the cascade mechanism, but conclude that the broadening of angular distributions with increasing multiplicity of fast particle generation corresponds to a pattern of interaction intermediate between the concepts of consecutive and simultaneous interactions of the initial nucleon with the nucleons of a nucleon †.

E. Friedländer, on the other hand, who also dealt with the interaction between nuclei in photoemulsion and 9 GeV protons [5]) infers that experiment fully agrees with the tunnel mechanism. It seems worthwhile therefore to discuss the experimental data and conclusions of ref. [4]).

(i) Only a particular kind of events with a number of relativistic particles was selected. The momenta of the particles were not measured and the speed of the centre of gravity γ_c, indispensable for finding the number of nucleons in the tunnel, was determined only by the emission angles of the particles, which is not reliable.

(ii) The histograms in fig. 5, making it possible, in the author's opinion, to classify interactions with different magnitudes ν, where ν is the number of nucleons of the nucleus in the tunnel, give no errors along the ordinate-axis representing the distribution function $\phi[\xi(\nu)]$ of the events; yet these errors are rather large since only 300 events are divided into two groups, 10 intervals of ν in each. The function $\xi(\nu)$ is evaluated by the Costangoli formula, which is not rigorous. Nor were the errors along the axis $\xi(\nu)$ given, which are essential in the case of narrow peaks and minima in the histogram.

(iii) The rigidity coefficient K is determined without measuring the momenta of the secondary particles under the assumption of the transversal momentum $1/P_\perp = 0.94/\mu$, (where μ is the mass of a pion, according to data on cosmic rays). This coefficient was found equal to $K = 0.33 \pm 0.02$ and it is claimed that it is in extremely good agreement with the results of ref. [5]). It is shown in refs. [1-3]), however, that the rigidity coefficient in p-n-collisions are equal to 0.4. Consequently, we cannot regard the magnitude $K = 0.3$ as reliable since if we do, we must assume that the rigidity coefficient decreases in the tunnel mechanism when free energy in c.m.s. is larger and the number $\bar{n}_s$ grows.

(iv) The tunnel mechanism and the growth of $\bar{n}_s$ with contradicts the conservation of large energy in one particle, all the more so since this particle, as is shown in ref. [1]), is a nucleon, and on the average, one nucleon per interaction

† G. B. Zhdanov, a co-author of ref. [4]), reported at the Dubna conference, May 1960, that the continuation of the investigation and the analysis of the results led to the conclusion of the soundness of the cascade mechanism.

for in the case of collision with a group of nucleons the excitation energy in the c.m.s. is larger and the velocity of the centre system is less.

(v) Throughout his argument the author neglects secondary interactions in the nucleus, though the possible path of the particles in the nucleus and the known cross sections for mesons and nucleons call for taking account of the secondary interactions. In ref. [7]) the Monte Carlo method was used for calculating the nuclear cascade and it was shown that the results of the calculation agree with the experimental data of ref. [1]).

Apart from the above comparisons, it is necessary to bear in mind that the mechanism of fast nucleon-nucleus interaction must depend on the properties of nucleon-nucleon collisions. E. Feinberg [8]) considered the conditions requiring for the introduction of the tunnel mechanism. It was assumed that the magnitude of the transversal momentum of the recoil nucleon $P_\perp \approx \mu$, where μ is the meson mass. Then the longitudinal momentum $P_\parallel$ is equal to

$$P_\parallel \approx \frac{M^2 \nu\varepsilon}{2E(E-\nu\varepsilon)} + \frac{\nu\mu^2}{2\varepsilon} + \tfrac{1}{2}[\theta_M{}^2(E-\nu\varepsilon)+\theta_M{}^2 \nu\varepsilon], \tag{1}$$

where θ_M and θ_μ are the angles of the emission of the nucleon and π-meson, ν is the number of mesons, ε is the energy of mesons and M and E are the mass and the initial energy of the nucleon. It was shown in accordance with eq. (1) in ref. [8]) that the tunnel mechanism may set in when $\theta_M \approx \theta_\mu \approx M/E$ and $\nu\varepsilon \ll E$ or $\nu\varepsilon \approx (E-\nu\varepsilon)$. If on the other hand $\theta_\mu \approx \sqrt{M/E}$ which corresponds to isotropy in the c.m.s. and

$$\nu\varepsilon > 2\frac{\mu E}{M}, \tag{2}$$

then the pattern of consecutive collisions applies. The characteristics of p-n-collisions at 9 GeV known at present [1–3]) make it possible to elucidate this; in the c.m.s. we observe a sharp anisotropy of the nucleons, while the anisotropy of the mesons is comparatively small. The experimental value is $\theta_{\mu\frac{1}{2}} \approx 16°$, while $\theta_\mu = \sqrt{M/E} = 17°$. The energy losses $\nu\varepsilon = 0.4$. This means that the inequality (2) is valid. Consequently, by comparing with experiment, we have a case when the conditions necessary for the mechanism of consecutive nucleon-nucleon collisions are fulfilled. Let us note that the experimental value $P_\perp = 0.37 \pm 0.025$ GeV is nearly three times as large as was assumed in ref. [8]) as the initial condition for introducing the tunnel model.

In view of the above it should be concluded that the inference of ref. [1]) on the validity of the cascade mechanism for nucleon-nucleus collisions is correct for the energy region 10 GeV.

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