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THE INTERACTION OF FAST PARTICLES WITH NUCLEI

K. D. TOLSTOV

Joint Institute for Nuclear Research, Dubna, USSR

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Abstract: It is shown that the dispersion of proton momenta in inelastic p-N-collisions for 9 GeV and π^--N-collisions for 7 GeV as well as data on inelastic collisions with proton nuclei for 9 to 27 GeV agree with the mechanism of successive collisions of an incident particle with the nucleons in the nucleus. The methods and conclusions of refs. [10,13]) which deal with collisions with nuclei are discussed for comparison. It is shown that several negligences in these papers affect the conclusion on the validity of the tunnel mechanism and the difference in the inelasticity coefficients in the interval of 2 to 27 GeV. For example, in refs. [10,13]) the authors have omitted a rather essential geometric factor taking into account the probability for finding an electron pair when the tracks of the relativistic particles are continued towards the primary beam by Kings's method.

The energy dependence of the primary collision of an incident particle with nucleons in a nucleus is of cardinal importance in the study of the interaction of fast mesons and protons with nuclei. In the present paper this problem is considered for mesons with an energy of 7 GeV and protons in the energy interval of 9 to 30 GeV.

Two alternative schemes were proposed in many experimental and theoretical papers: (1) the cascade mechanism, i.e., successive collisions with individual nucleons; (2) the interaction of a fast particle simultaneously with a group of nucleons in the nucleus, or "tunnel model". In the latter case the incident particle, falling for example along the axis connecting the centres of two nucleons of the nucleus "knows" the presence of the second nucleon at the moment of the collision with the first. It is shown in ref. [1]) that this may be a consequence of the smallness of the dispersion of the longitudinal momentum transferred in inelastic collisions with a free nucleon, which leads, in accordance with Heisenberg's uncertainty principle, to a region of interaction larger than the nucleon diameter. To determine at which energy the tunnel mechanism may occur is therefore an important aspect of the energy dependence of nucleon-nucleus collisions. The collisions with nuclei are a means of investigating this process. As accelerators making it possible to obtain particles with energies up to 30 GeV went into operation, the unambiguous solution of the problem of the mechanism of the interaction with the nucleus became possible since the knowledge of the mass and energy of the incident particle obviates several difficulties.

Data on the interaction of 9 GeV protons with photo emulsion nuclei were obtained and analysed in refs. [2,3]). The mean number of collisions of a proton with light nuclei (C, N, O) was found 1.4, about two collisions occur on the effective nucleus of the emulsion ($A \approx 30$). One fast nucleon carries 3.0 ± 0.5 GeV. The inelasticity coefficient in the laboratory system per collision with nucleons in the nucleus is 0.4 ± 0.1. In a considerable number of cases the emergence of up to 40 charged particles, i.e. the decay of the nucleus primarily into separate nucleons, is observed. These facts as well as the number of shower particles and their angular distribution are in good agreement with the cascade mechanism and contradict the tunnel model. Comparing the experimental results obtained in their investigation of collisions of 9 GeV protons with nuclei and nucleon-nucleon collisions at 6.2 GeV/c, the authors of ref. [3a]) also drew the conclusion that the experimental facts agree better with the cascade process.

A calculation for the cascade interaction was performed in ref. [4]) by the Monte-Carlo method, and the number of shower particles, the energy and angular spectra of mesons and protons were found practically to coincide with the experimental values. Similarly, the interaction of π^--mesons with nuclear emulsion nuclei at 7 GeV was investigated in ref. [5]). The use of the average energy of mesons generated in π^--meson-nucleon collisions according to the data of ref. [6]) and the calculation by the Monte-Carlo method for their subsequent collisions with nucleons in the nucleus yielded $\xi = \log \gamma_c = 0.256$. The experimental value is according to ref. [7]) $\xi = 0.245$. This points to the cascade mechanism for meson-nucleus collisions as well (a conclusion in favour of the validity of the tunnel model is drawn in ref. [7])).

Let us analyse the evidence for the tunnel model proceeding from the value of the root-mean-square deviation of the longitudinal nucleon momentum $\sqrt{\overline{(\Delta p_{\parallel})^2}}$ in inelastic π^--N collisions for 7 GeV. According to the experimental results of ref. [6]) the quantity $\sqrt{\overline{(\Delta p_{\parallel})^2}}$ is practically independent of the number of the particles generated and on the average is in the laboratory system

$$\sqrt{\overline{(\Delta p_{\parallel})^2}} = (0.53 \pm 0.05)\mathrm{GeV}/c.$$

In accordance with this we have

$$\sqrt{\overline{(\Delta r)^2}} = (0.37 \pm 0.04)\ \mathrm{fm}.$$

Hence the interaction region is certainly less than the nuclear diameter (≈ 2 fm), i.e. there are no grounds for the tunnel model. In inelastic p-N collisions at 9 GeV the average transverse nucleon momentum is, according to refs. [8,9]) 0.37 ± 0.03 GeV/c and 0.44 ± 0.05. These quantities are nearly three times larger than those adopted in ref. [1]) ($p_{\perp} \approx \mu \approx 0.14$ GeV/c) as the initial condition for the tunnel model. Assuming a Gaussian distribution for the transverse momenta, we have

$$\sqrt{\overline{\Delta(p_{\perp})^2}} = \sqrt{\tfrac{1}{2}\pi}\,\bar{p}_{\perp} = (0.46 \pm 0.04)\mathrm{GeV}/c.$$

Hence we obtain

$$\sqrt{\overline{\Delta \bar{r}^2}} = (0.44 \pm 0.04)\ \mathrm{fm}.$$

It is very interesting to consider collisions with nucleons and nuclei for the highest energy attainable at present: 30 GeV. No results of a direct study of inelastic collisions of protons with nucleons (necessary for the analysis of the interaction with a nucleus) are known to the author. However, in ref. [10]) electron pair observations are used to compare the energy spectra of π^0-mesons generated by protons with energies of 9 and 23.5 GeV and the conclusion is drawn that the inelasticity coefficient decreases with increasing proton energy up to $\leqq 0.23 \pm 0.06$, which points to the possibility of a tunnel mechanism at 23.5 GeV. It can be shown, however, that the conclusion of ref. [10]) is obtained in a wrong way. Indeed, in the estimate of the inelasticity coefficient for 9 GeV protons the authors of ref. [10]) proceed from the data of ref. [11]) in which the portion k of the energy carried away by $\pi^{\overset{\pm}{0}}$-mesons in the collision with an average emulsion nucleus is $0.27 \pm 0.07 < k < 0.33 \pm 0.08$. This figure is less by a factor of 1.5 to 2 than that obtained in ref. [2]). A discussion with the authors showed that in ref. [11]) no account was taken of the probability W of registration of electron pairs in function of the angle φ with the primary beam (the pairs were registered by the King method [12])). To take into account this (geometric) correction it is necessary to take each pair with a weight proportional to the quantity W^{-1} where

$$W = \frac{2}{\pi} \arcsin \left(\frac{\sin \alpha_0}{\sin \varphi} \right), \tag{1}$$

where α_0 is the limiting angle of inclination of electron pairs to the emulsion plane in the King method. This correction increases the contribution of pairs with larger angles φ, i.e. pairs from softer γ-quanta. Hence the corrected spectrum of π^0-mesons will be softer and the inelasticity coefficient will decrease even more. Obviously, not everything was taken into account in the calculation of the π^0-meson energy by the observations of electron pairs. In ref. [10]) an attempt is made to obviate possible difficulties with the help of relative measurements. The ratio of the inelasticity coefficients for 9 and 23.5 GeV is considered:

$$\frac{K_{23.5}}{K_9} \leqq \frac{9}{23.5} \frac{\langle\alpha\rangle_{23.5}^{-1} \langle n_\pi \rangle_{23.5}}{\langle\alpha\rangle_9^{-1} \langle n_\pi \rangle_9}, \tag{2}$$

where $\langle n_\pi \rangle$ is the average number of mesons generated in the collision and α is the projection of the pair angle. The quantity $\langle\alpha\rangle^{-1}$ is proportional to the average energy of the π^0-mesons. However, the inequality (2) is wrong since the geometric corrections must be taken into account even in this relative calculation. Indeed, the average angle of the pairs must be calculated taking into account its "weight" in accordance with eq. (1). The quantity $1/W$ increases as the angle φ increases, i.e. softer γ-quanta corresponding to larger angles must enter with larger weights. The values of α for these γ-quanta are larger than the average $\langle\alpha\rangle$ and hence, without the geometric correction, $\langle\alpha\rangle$ is underestimated. The inverse quantity $\langle\alpha\rangle^{-1}$ is overestimated, the more as the primary beam energy is smaller, since the angles φ of emergence of the π^0-mesons increase. After taking into account the geometric corrections the quantity $\langle\alpha\rangle_9^{-1}$ in the denominator of eq. (2) decreases more strongly than $\langle\alpha\rangle_{23.5}^{-1}$ in the numerator, which leads to an increase of $K_{23.5}$. Consequently, in the calculation of the quantity $K_{23.5}$ in ref. [10]) the geometrical corrections are not taken into account twice, viz. in obtaining K_9 and in eq. (2). Therefore, the quantity $K_{23.5} \leqq 0.23$ obtained in ref. [10]) is not correct.

The interaction of a 27 GeV proton beam with emulsion nuclei was studied in ref. [13]). Let us discuss some methodical points of this investigation which seem to be wrong. In the estimate of the generated meson energy the authors of ref. [13]) do not take into account the particles whose tracks in the projection on the emulsion plane make an angle $\beta \leqq 2°$ with the direction of the proton beam. Most mesons having an angle $\varphi \approx \sqrt{2}\ \beta \approx 3°$ with the direction of the proton beam fall into this interval. According to ref. [2]), for the primary proton energy of 9 GeV there were ≈ 0.3 π-mesons among the particles with $\varphi \leqq 3°$. The number of generated mesons increases with proton energy; and the generated mesons are directed forward. Therefore, their number for $\varphi \leqq 3°$ must increase. Let us estimate this number under the assumption that in the c.m.s. the average momentum of pions is 0.5 GeV/c and the average transverse momentum 0.3 GeV/c. In case of isotropic production of mesons $\approx 10\%$, i.e. 0.5 meson gets into the interval $\varphi \leqq 3°$ in the c.m.s., if their average number from ref. [13]) is $\bar{n} = 4.6$. According to refs. [8,9]) the angular distribution of mesons in the forward hemi- sphere of the c.m.s. has a maximum in the direction of the primary beam and therefore a still larger number of them ought to be expected for $\varphi \leqq 3°$.

Then, in contrast to ref. [13]), it can be shown that at angles $\varphi > 3°$ there must be protons which strongly affect the estimate of the meson energy by the method of ref. [13]). Indeed, assume, according to ref. [13]) that 0.6 of the energy of a primary proton is spent on the average on meson generation and that energy losses have a uniform distribution. Under this assumption the nucleon in half of the collisions will preserve ≈ 0.2 of the initial energy, i.e. $\leqq 6$ GeV. The average transverse momentum of these nucleons may be assumed to be 0.5 GeV/c and therefore there must be protons with $\varphi > 5°$. This strongly affects the estimate of the average meson energy made in ref. [13]). If, indeed, the average number of shower particles $\bar{n}_s = 6.6$, among which there are, according to ref. [13]) two protons, then one of them has an energy ≈ 6 GeV and $\varphi > 3°$. Hence, the total number of shower particles, mesons and protons $\bar{n}'_{\pi,\mathrm{p}}$ with $\varphi > 3°$ is

$$\bar{n}'_\pi = \bar{n}_\pi + 1 = 5.6.$$

The average meson energy according to ref. [13]) is 2.3 GeV. However, from fig. 10 of this paper it follows that in the stars produced by mesons of such an energy the average number of shower particles $\bar{m}_\pi = 0.85$. The total number of shower particles $\bar{N}$ in the stars produced by mesons and protons $\bar{n}'_{\pi,\mathrm{p}}$ which in ref. [13]) were assumed to be all mesons is

$$\bar{n}'_{\pi,\mathrm{p}}\bar{m}_\pi = \bar{N} = 5.6 \times 0.85 = 4.8.$$

Hence, from fig. 3 of ref. [13]) it follows that the average number of shower particles

$\overline{m}_p$ in the stars produced by 6 GeV protons is

$$\overline{m}_p = 2.2.$$

Therefore we must subtract $\overline{m}_p$ from $\overline{N}$ in order to obtain the number of shower particles $\overline{N}_\pi$ in the stars produced only by mesons:

$$\overline{N}_\pi = \overline{N} - \overline{m}_p = 4.8 - 2.2 = 2.6.$$

Accordingly the average number of shower particles in one star produced by mesons is

$$\overline{N}_\pi / \overline{m}_\pi = 2.6/4.6 = 0.57.$$

Using this quantity, from fig. 10 we obtain for the average meson energy $\bar{E}_\pi$, instead of 2.3 GeV,

$$\bar{E}_\pi = 1.2 \text{ GeV}.$$

Let us consider what part of the energy K' is spent by protons of 9 or 27 GeV ðn the generation of mesons, taking into account the absorption and scattering of mesons in the nucleus.

According to ref. [2]), for 9 GeV the energy carried away by mesons is 4 ± 0.8 GeV and the nuclear decay energy is 1.05 ± 0.1 GeV.

According to ref. [14]), in inelastic proton-nucleon collisions the slow-nucleon energy is 120 ± 40 MeV and according to ref. [15]) $\approx$ 130 MeV. In ref. [2]) it is shown that the primary proton on the average undergoes about two collisions with the nucleons of the average emulsion nucleus. Accordingly, it can be assumed that the nucleons in the nucleus obtained $\approx$ 250 MeV directly from the incident proton. Consequently, due to absorption and meson collisions in the nucleus they receive the energy

$$1.05 - 0.25 = 0.8 \pm 0.1 \text{ GeV}.$$

The total energy spent on meson generation is

$$(4 \pm 0.8) + (0.8 \pm 0.1) = 4.8 \pm 0.8 \text{ GeV}.$$

Hence we obtain $K' = 0.55 \pm 0.09$.

A second way of obtaining K' is to start from the fast proton energy; after the collision with the nucleus it is 3.0 ± 0.5 GeV and hence we obtain $K' = 0.69 \pm 0.06$.

For 27 GeV the portion of energy carried away by the mesons is estimated to be 0.6 ± 0.2. The number of particles with relative ionization $I/I_0 > 1.4$ in one star produced by 9 or 27 GeV protons is 7.8 ± 0.6 and 7.2 ± 0.2. Therefore it can be assumed that the energy released in the decay of the nucleus for 27 GeV is close to its value 0.8 GeV for 9 GeV. This also follows from ref. [16]) in which it was established that the cosmic ray protons spend in the energy interval of 3 to 50 GeV the same energy on the disintegration of nuclei. Accordingly, to obtain K' for 27 GeV it is necessary to add 0.8 27 = 0.03 to the quantity K:

$$K' = K + 0.03 = 0.63 \pm 0.2.$$

TABLE 1

Proton energy (GeV)	Average number of shower particles	Average meson energy (GeV) $\bar{E}_\pi$	Average fast proton energy (GeV) $\bar{E}_p$	Average nuclear decay energy (GeV) $\bar{E}_{nucl}$	Portion of energy carried by mesons K	Average number of particles with $I/I_0 > 1.4$	Portion of energy transferred by meson taking into account nuclear decay: from $\bar{E}_\pi$ and $\bar{E}_{nucl}$	Portion of energy transferred by meson taking into account nuclear decay: from $\bar{E}_p$
9	3.2±0.2	1.0±0.2	3.0±0.5	1.05±0.1	0.46±0.09	7.8±0.6	0.55*±0.09	0.63±0.6
27	6.6±0.1	2.3±0.2			0.6±0.2	7.2±0.2	0.63*±0.2	
23.5		1.2*			≦ 0.23±0.06		≦0.26*±0.6	

Consequently, the quantities K pt 9 and 27 GeV are 0.46 ± 0.09 and 0.6 ± 0.2. respectively, and the quantities K' practically coincide. Therefore in contrast to the conclusions of ref. [13]) there is no differenco in the portion of the energy transferred to the mesons.

Let us dwell on the conclusions of ref. [13]) with respect to the mechanism of the interaction with the nucleus. Ref. [13]) points to the agreement of the expermental value of the quotient r of the average numbers of shower particles in heavy Ag, Br and light nuclei C, N, O, $r = 1.6 \pm 0.3$, and its value calculated by ref. [7]) on the basis of the hydrodynamical tunnel model of the collisions with the nucleus $r = 1.62$. The number of primary proton collisions determined from the angles of emission ei shower particles by the Castagnioli formula is obtained as $\nu_H = 2.7$ in heavy nuclei and $\nu_L \approx 1.1$ in light nuclei. It is indicated that the ratio $\nu_H/\nu_L \approx 2.5$ does not deviate from the value $(A_H/A_L)^{\frac{1}{3}} = 1.9$ given by the tunnel model. However, the agreement of the experimental meson spectrum (fig. 10 of ref. [13])) and the spectrum calculated by the statistical theory in ref. [13]) is also noted for proton-nucleon collisions. Let us note that in all these points the authors of ref. [13]) do not take into account the secondary collisions in the nucleus of the particles generated in a primary collision, which is quite essential, as is shown in refs. [4, 5]). For example, the coincidence of the number of particles from the decay of the nucleus at 9 and 27 GeV indicates that the cascade process takes place also at 27 GeV since a smaller excitation of the nucleus and a smaller number of particles from its decay should be expected with the tunnel model. The large number of shower particles for heavy nuclei, 8.2, as compared with the number for light nuclei, 5.0, also agrees with the cascade mechanism, since the proton preserving ≈ 0.5 of the initial energy after the first collision, and fast mesons before emission from the nucleus, will create more shower particles in a collision.

In conclusion let us tabulate for comparison the main results of refs. [2, 10, 13]) and some additions (symbol *) in accordance with what has been said above.

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