Production of high-energy pions in interactions of relativistic deuterons with protons and nuclei

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It is shown that experimental data on the production of fast pions on nuclei can be explained, in order of magnitude, within the framework of the impulse approximation. The effect of relativization of the deuteron wave function is explained.

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Experimental papers dealing with inclusive spectra of high-energy protons produced in collisions of deuterons with protons and nuclei have recently been published.[1–3] The pion energy exceeded the kinetic energy per deuteron nucleon. The purpose of the present paper is to compare the experimental data of[1–3] with the results obtained in the impulse approximation (see the diagram in Fig. 1) for the reactions $d+p(A)\to\pi^-(0°)+\cdots$. Using a nonrelativistic and relativistic description of the wave function (WF) of the deuteron in ρ-space.[4–6]

The invariant cross section of the inclusive production of pions in the reaction $d+p\to\pi^-(0°)+\cdots$ is given by

$$\frac{1}{p_\pi}\frac{d^2\sigma}{d\Omega dp_\pi}=\frac{4}{\pi}\sigma_{pp}\int\int\left(|a|^2+|b|^2\right)\frac{I_{Np}}{I_{dp}}\frac{E_N}{E_{N'}}\rho(x,p_\perp^\pi)\,dz\,p'^2dp',\qquad(1)$$

where σ_{pp} is the total pp-scattering cross section,

$$I_{Np}/I_{dp}=\sqrt{\frac{(pp_N)^2-m^2p_N^2}{(pp_d)^2-m^2m_d^2}}$$

is a kinematic factor that takes into account the redefinition of the flux density, $\rho(x,p_\perp^\pi)$ is the spectral density of the single-particle distribution in the reaction $p+p\to\pi^-+\cdots$, $x=p_\parallel^\pi/(p_{max}^\pi)_p$, $p_\parallel^\pi(p_\perp^\pi)$ is the longitudinal (transverse) momentum of the pion, $(p_{max}^\pi)_p$ is the maximum momentum of the pion in the reaction $N+p\to\pi^-+\cdots$, $p'(E_{N'})$ is the momentum (energy) of the nucleon N' (see Fig. 1), z is the cosine of the angle between the momenta of N' and the deuteron, Q is the nucleon momentum in the deuteron rest system, and $a(Q)$ and $b(Q)$ are the momentum representations of the deuteron WF for the s and d waves.

The relativization of the deuteron WF was effected by expansion in irreducible representations of the homogeneous Lorentz group with the aid of the transformation of the transition to the light cone (the ρ-representation).[4,6–8] At large distances (or for nonrelativistic momenta), the function in the ρ-representation coincides with the usual one. At distances smaller than or of the order of $1/m$ (or else for $Q\gtrsim m$), the WF of the representation is Fourier-conjugate not to the momenta but to the rapidities. The relativistic WF was obtained from the usual WF in the coordinate representation, in which the radius vector $\mathbf{r}$ was identified with the relativistic variable $\boldsymbol{\rho}$.

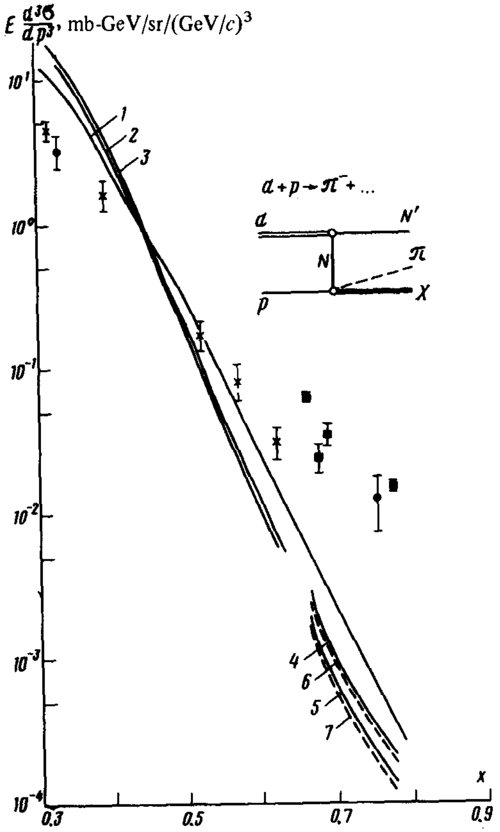

FIG. 1. Invariant cross section of π^- production in the reaction $d+p\to\pi^-(0°)+\cdots$ as a function of $x=p^\pi/p^\pi_{max}$. The points were taken from[12]: crosses—at $p_d=16.8$ GeV/c, circles—at $p_d=12$ GeV/c, squares—for the reaction $d+N_{Cu}\to\pi^-(0°)+\cdots$ at $7<p_d<10$ GeV/c. The curves are the results of the theoretical calculations: 1) at $p_d=5.8$ GeV/c, 2) at $p_d=12$ GeV/c, 3) at $p_d=16.8$ GeV/c for the Fourier transform of the deuteron WF,[10], 4 and 5) for the Fourier transform of the deuteron WF from[10] and[11], respectively, 6 and 7) for the ρ-transformation of the same functions.

It was assumed in (1) that the cross sections for π^- production by the proton and the neutron of the deuteron are equal, and the parametrization from[2,9] was used for $\rho(x,p_\perp^\pi)$. The curves of Fig. 1 are the results of the calculation of the cross section (1) as a function of x for different values of p_d. We used WF with[10] and without[11] a hard core. For x from 0.67 to 0.78, the data are those of[12] for the reaction $d+N_{Cu}\to\pi^-(0°)+\cdots$.[1)] It is seen that the effect of relativization of the deuteron WF in ρ-space ($\sim 20\%$) is comparable with the difference between the different types of WF ($\approx 50\%$), in analogy with the results of[7] for elastic backward pd scattering at high energies. At $0.6<x<0.8$, the smallest values of Q corresponding to the effective region of integration in (1) are small ($Q\gtrsim 0.4m$), and therefore the effect due to relativization of the WF does not exceed the effect due to parametrization. At large x ($x\lesssim 1$), the minimal Q increases ($Q\gtrsim 1.5m$), and the role of the relativization effect increases. Thus, at $x=0.97$ ($p_d=10.29$, $p_\pi=7.02$ GeV/c)[2)] the cross section (1) for WF with hard core is 3.6 times larger for nonrelativistic than for relativistic parametrization. For a soft core this ratio is 0.5. The cross section (1) for WF with hard core is larger by 7.8 times than for the soft core for the Fourier transformation, but the difference is small ($\sim 12\%$) in the case of the ρ-transformation.

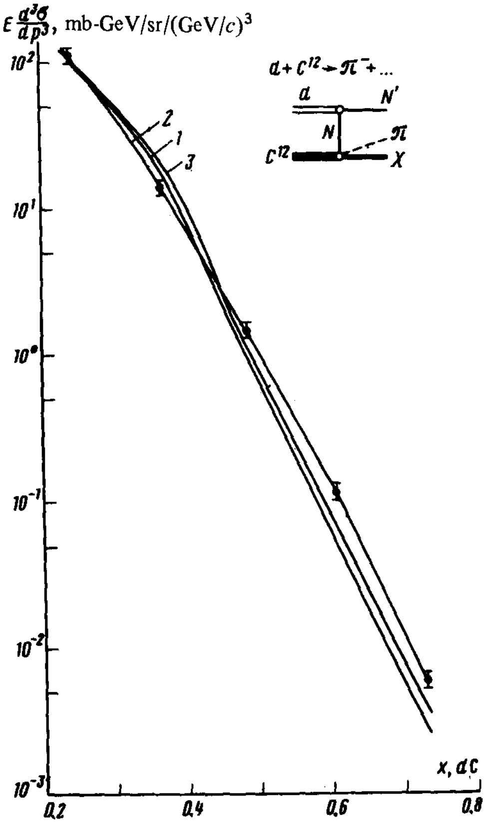

FIG. 2. Invariant cross section of the process $d+C^{12} \to \pi^-(0°)+\cdots$. Theoretical curves: 1) with allowance for cutoff in $p_\perp^\pi$, 3) without allowance in cutoff in $p_\perp^\pi$ for the deuteron WF.[10] Curve 2 is drawn through the experimental points.[3]

To calculate the cross sections of $d+A \to \pi^-(0°)+\cdots$, we used parametrization of the lower block of the diagram of Fig. 2, which agrees with the experimental data on the reaction $p+A \to \pi^-(0°)+\cdots$.[3] It follows from Fig. 2 that the considered model describes well the experimental data. In a somewhat different model, an analogous agreement was obtained in[3].

Figure 3 shows the ratios of the invariant cross sections of the processes $d+A \to \pi^-(0°)+\cdots$ and $p+A \to \pi^-(0°)+\cdots$. The curve was obtained from the experimental data[3] on the reaction $d+C^{12} \to \pi^-+\cdots$ at T_d=4.2 GeV under the assumption of scaling for the cross section of $p+C^{12} \to \pi^-+\cdots$. It follows from Fig. 3 that the experimental data of these two groups do not contradict each other. This result confirms the universal dependence, noted in[3], of the cross section of inclusive pion production from nuclei on the target atomic number A. Thus, the impulse approximation should agree, in order of magnitude, also with the data of[2] for Cu^{64}, but this contradicts the conclusion of[9] that a discrepancy by more than two orders of magnitude exists between the two. We note that the difference between our calculations and those of[9] lies also in the fact that they use experimental data not only on the cross section of the reaction $p+p \to \pi^-+\cdots$, but also $p+A \to \pi^-+\cdots$. The results presented here were

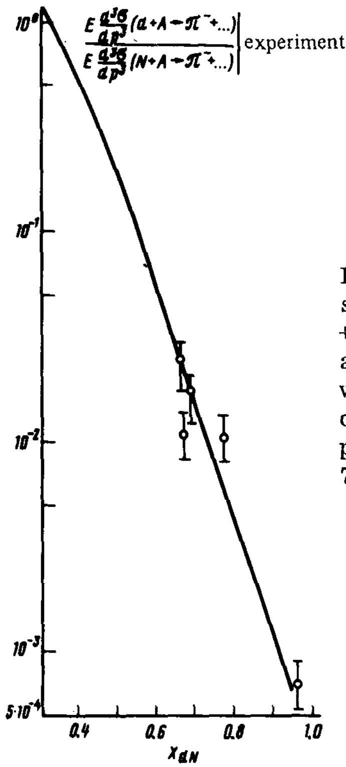

FIG. 3. Ratio of the invariant cross sections of the reactions $d+A \to \pi^-(0°) + \cdots$ and $p+A \to \pi^-(0°) + \cdots$ at $p_d = p_N$ and at equal momenta p_π. The curve was obtained from the experimental data[3] for C^{12} at $p_d = 5.8$ GeV/c. The points were taken from[2] for Cu^{64} at $7 < p_d < 10$ GeV/c.

obtained with allowance for the departure from the mass shell of the nucleon N (allowance for the exponential factor discussed in[9] 3) decreases the theoretical cross sections of that paper and of[2,9] by more than two orders). The departure from the mass shell for the intermediate nucleon N was not taken into account by us, owing to the lack of an acceptable theoretical parametrization of such a departure for the reaction $N+p(A) \to \pi^- + \cdots$. Allowance for this departure is important, since the squared 4-momentum of N in the effective integration region reaches values $p_N^2 \cong -m^2$. Thus, this model does not claim a rigorous quantitative description of the experimental data. Our analysis indicates, nevertheless, that an appreciable fraction of the experimental cross section and its dependence on x is accounted for adequately by this model even at $x > 0.5$, i.e., in the region where the quasi-free kinematics is incorrect.

We note at the same time that agreement under the "ordinary" assumptions concerning the deuteron WF with the experimental data for nuclei (Fig. 2) and the discrepancy with the data for the proton, especially at $x > 0.6$ (Fig. 1), is not quite understandable, since the effective A are approximately equal in reactions on nuclei and on protons.4) Allowance for the rescattering of the pions by the nucleons[13] does not explain this discrepancy. All this points to the need for supplementary experiments on free protons at large x, which could possibly help refine the mechanism of the reactions. A detailed exposition of the results presented above will be published in another article.

[1)] No explanation is given in[12] of the procedure used to obtain the cross section of the reaction $d+N_{Cu}\to\pi^-+\cdots$ from the experimental data on $d+Cu\to\pi^-+\cdots$. To find the connection between these two processes it is necessary, in the least, to specify concretely the mechanism whereby ultrafast pions are produced by free nucleons from nuclei, since the pion in the reaction $d+Cu\to\pi^-+\cdots$ acquires energy from both the deuteron and the nucleus.

[2)] The corresponding value of the cross section (1) is not given in[12].

[3)] Introduction of this factor at large departures from the mass shell does not seem physically justified to us.

[4)] The effective Q are somewhat smaller in reactions on nuclei.

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