Concerning one mechanism of "cumulative" meson production

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Institute of Theoretical and Experimental Physics
(Submitted November 15, 1974)
ZhETF Pis. Red. **21**, No. 1, 88–91 (January 5, 1975)

It is shown that the mechanism of high-energy pion production ($E_\pi > E_d/2$) by deuterons, wherein the pion produced by one of the nucleons acquires additional energy by scattering from the second nucleon, plays an important role at nonzero components $k_{\pi\perp}$.

The production of π^- mesons by accelerated deuterium nuclei was observed in the experiments of [1,2], and the pion energy greatly exceeded half the kinetic energy of the deuteron ($x_d > 0.5$). Calculations[2] have shown that the contribution of the simplest mechanism, the impulse approximation with allowance for the Fermi motion of the electrons in the deuteron (see Fig. 1), is insufficient to explain this effect.

In this paper we consider the mechanism of cumulative meson production by deuterons on nucleons, wherein the pion produced by one of the deuteron nucleons acquires additional energy as a result of scattering by another nucleon (Fig. 2). We consider the case $E \gg m$, where E is the energy per nucleon of the deuteron and m is the mass of the nucleon. It is convenient to change over to the deuteron rest system, in which the cumulative π mesons with $k_\perp \lesssim m$ are emitted in the rear hemisphere,[3] and the kinematic boundary for the pions produced in NN collisions takes the form $k(1+\cos\theta) \leqslant 2m$, whereas in Nd interactions we have $k(1+\cos\theta) \leqslant 2m$ (θ is the angle between the momenta of the pion and the incident nucleons, $\theta = 0$ for pions emitted backward; we neglect the π-meson mass). It is easy to verify that if no allowance is made for the Fermi motion of the nucleons in the deuteron then the allowed region for the pions expands as a result of rescattering by a second immobile nucleon: $k \leqslant m/2[1-\sin(\theta/2)]$. The ratio of the pion and deuteron momenta in the deuteron rest system is $x_d = k(1+\cos\theta)/2m$ and can reach values

$$x_d^{max} = \frac{1}{2}(1 + \sin{}^{\theta}/_{2}). \tag{1}$$

Since $k_\perp = k\sin\theta$, the boundary of the allowed region lies farther the larger $k_\perp$. At $k_\perp = 0$ and $E \gg m$, the limit of the region does not change in comparison with that obtained for the reaction $NN \to \pi \ldots$.

Inside the allowed region, and sufficiently far from its boundary, one can neglect the Fermi motion of the nucleons in the deuteron when calculating the differen-

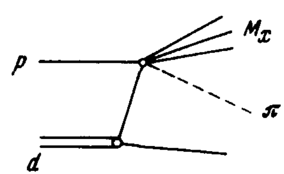

FIG. 1.

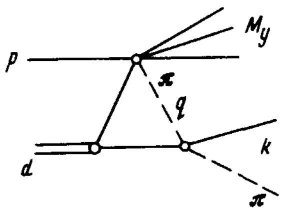

FIG. 2.

tial cross section for pion production. Taking into account only the contribution of the real pion in the intermediate state to the matrix element corresponding to Fig. 2, and neglecting the dependence on the mass of the virtual nucleon in $pN \to \pi\ldots$, we obtain:

$$k\frac{d^3\sigma}{d^3k}(x_d, k_\perp)\Big|_{dp\to\pi^-\ldots} = \int q\frac{d^3\sigma}{d^3q}(y, q_\perp)\Big|_{Np\to\pi\ldots}\frac{d\sigma}{d\Omega}(s_1, t_1)\Big|_{\pi N\to\pi N} \times \frac{s_1\, dy\, dq_\perp^2}{8\pi R^2\Delta q[(q_\perp^2 - q_\perp^{-2})(q_\perp^{+2} - q_\perp^2)]^{1/2}} \tag{2}$$

Here $\Delta = k(1+\cos\theta) - m$, q pertain to the intermediate pion,

$$q_\perp^\pm = \frac{m}{\Delta}\{yk_\perp \pm y^{1/2}[ym(2k-m) - 2\Delta k]^{1/2}\},$$

$$s_1 = m^2 + 2mq,\ t_1 = -2m(q-k),$$

$$q = (q_\parallel^2 + q_\perp^2)^{1/2};\quad q_\parallel = \frac{q_\perp^2 - m^2y^2}{2my}.$$

The integration region in (2) is

$$q_\perp^- < q_\perp < q_\perp^+,\quad \frac{2\Delta k}{m(2k-m)} < y < 1,\quad y = 1 - \frac{M_y^2}{2mE}$$

(see Fig. 2), R is the radius of the deuteron: $1/R^2 = \int p(4p)^2 p\, dp$ where $\rho(p^2)$ is the form factor of the deuteron. In the Gaussian parametrization we have $R^2 = 66\ \mathrm{GeV}^{-2}$.[4] We see that at $x_d \approx 0.5$ ($\Delta = 0$) we have $0 < y < 1$, i.e., practically all the values of M_y^2 make a contribution. When calculating the quantity

$$\eta(xd, k_\perp) = \frac{(d^3\sigma/d^3k)_{dp\to\pi^-\ldots}}{(d^3\sigma/d^3k)_{pp\to\pi^-\ldots}}\Bigg|_{x_d = x_p}$$

it must be borne in mind that three different processes contribute to the $dp \to \pi^-$ reaction: $pp \to \pi^-\ldots$ with subsequent scattering $\pi^-n \to \pi^-n$; $np \to \pi^-\ldots$ with the scattering $\pi^-p \to \pi^-p$, and also $pp \to \pi^0\ldots$ with charge exchange $\pi^0 n \to \pi^- p$. Since the fragmentation $n \to \pi^-$ (or, equivalently, $p \to \pi^+$) is 4—5 times more probable than $p \to \pi^-$,[5-7] and $p \to \pi^0$ [7] is 1.5 times more probable than $p \to \pi^-$, it is clear that allowance for the reactions $np \to \pi^-\ldots$ and $pp \to \pi^0\ldots$ is very important in the calculation of η.

Near the boundary of the allowed region, and outside the limits of this region, it is necessary to take into account the Fermi motion of the nucleons in the deuteron. Let

$$x_d = \frac{1}{2}(1 + \sin\frac{\theta}{2}) + \epsilon;\quad 0 \leqslant \epsilon << 1.$$

For the contribution made to the cross section by the diagram of Fig. 2, we obtain at $\theta \gg m/E,\ mR^{-1}$:

$$k\frac{d^3\sigma}{d^3k} \approx \frac{1}{16mk_\perp}\int q\frac{d^3\sigma}{d^3q}(y; q_\perp)\Big|_{Np\to\pi\ldots} s_1\frac{d\sigma}{d\Omega}(s_1, t_1)\Big|_{\pi N\to\pi N}\psi^2(p) \times\left(\frac{m\sin\theta/2}{2(p - p_{min}) - q_\parallel'}\right)^{1/2}\frac{1}{q^2}dq_\parallel'\, dq_\perp\, dp \tag{3}$$

$\psi(p) = \int_{p^2}^\infty \phi(p')dp'^2$, where $\phi(p)$ is the wave function of the deuteron in the momentum representation, $\int\phi^2(p)d^3p = 1$;

$$\psi^2(p) = \frac{1}{R}\left(\frac{2}{\pi}\right)^{3/2} e^{-2R^2p^2}$$

for a Gaussian parameterization, and $y = 1 - [1 - \sin(\theta/2)]q_\parallel'/m$.

The integration region in (3) is given by:

$$0 \leqslant q_\parallel' \leqslant 2(p - p_{min}),\quad q_\perp^- < q_\perp < q_\perp^+,$$

$$q_\parallel' = q_\parallel - q_\parallel^\circ + (q_\perp - q_\perp^\circ)\frac{\cos\theta/2}{1 - \sin\theta/2} - \frac{p}{1 - \sin\theta/2};$$

$$q_\parallel^\circ = \frac{m\sin\theta/2}{1 - \sin\theta/2};\quad q_\perp^\circ = \frac{m\cos\theta/2}{1 - \sin\theta/2}.$$

$$q_\perp^\pm \approx (\sin\theta/2 + 2\epsilon)^{-1}[k\sin\theta \pm (2m\sin\theta/2)^{1/2}(p - p_{min})^{1/2}],$$

$$p > p_{min} = \frac{4m\epsilon}{1 + \cos\theta}$$

As expected, the miminum value of the Fermi momentum is characterized by the fraction ϵ going to the forbidden region.

At $\theta = 0$, in the sense of the dependence on the Fermi momentum, the mechanism of Fig. 2 has no advantages over the impulse approximation: $p_{min} = 2m\epsilon = 2k - m$. This means that measurement of the effect at $\theta = 0$ would make it possible to separate the high-momentum components of the wave function of the deuteron up to $p \sim m$. Calculation by means of formulas (2) and (3)[8] shows that the mechanism with rescattering of the pion leads to a value $\eta \approx 10^{-2}$ at $x_d \approx 0.6$ and $k_\perp = 0.5\ \mathrm{GeV}/c$, which is somewhat smaller than in the experiment of[1,2]. A detailed calculation of the effect will be presented in a more comprehensive article. It must be borne in mind that at finite energies the kinematic boundaries differ noticeably in form from the asymptotic boundary (at $E \gg m$), namely:

$$k < \frac{m}{b^2 + b\cos\theta}$$

in the reaction $pN \to \pi^-\ldots$;

$$k < \frac{4m}{3b^2 - 1 + 2b\cos\theta},$$

in $pd \to \pi\ldots$, and

$$k < \frac{m}{1 + b^2 - \sqrt{1 + b^2 - 2b\cos\theta}}$$

in the process with rescattering by an immobile nucleon, where $b^2=(E+m)/(E-m)$. It is easy to verify that when the energy is decreased the kinematic boundaries for the processes $pd\to\pi\ldots$ and the process with rescattering by the immobile nucleon come closer together, i.e., the latter becomes more appreciable.

We note in conclusion the following feature of the considered mechanism: at fixed $x_d>0.5$, the effect increases with increasing k, since the boundary of the allowed region is approached from the outside. This phenomenon is in qualitative agreement with experiment.[1,2]

The authors are grateful to V.M. Lobashev and I.S. Shapiro for interest in the work and for useful discussions.

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