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Nucleon Exchange and Decay Angular Dependence in High Energy Nucleon Diffraction Dissociation

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ABSTRACT

Discrepancies between recent data on $NN \to (N\pi)N$ and Drell-Hiida-Deck (DHD) type models in the nucleon exchange sector of phase space are resolved by interpreting the DHD model in terms of infinite momentum frame perturbation theory rather than the conventional covariant perturbation theory. The physical motivation of this choice is briefly discussed.

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New high statistics data from Fermilab[1], Serpukhov[2], and the ISR[3] on the reaction $NN \to (N\pi)N$ have revealed contributions to the production mechanism that were not previously apparent. In terms of Drell-Hiida-Deck (DHD) -- type exchange models[4], this means that the usual pion exchange and resonance contributions[5] should be accompanied by both the nucleon exchange and direct nucleon production amplitudes[6] and by absorptive corrections.[7] It has appeared however, that calculations taking into account both the virtual nucleon's spin and s-channel helicity conservation (SCHC) in high energy elastic scattering according to covariant perturbation theory result in cross sections that qualitatively disagree with the observed data in particular regions of phase space.[6] I will show that the DHD-type calculation should be performed using infinite momentum frame (IMF) or "old fashioned" perturbation theory, in which case the calculations agree very well with the data. Similar results for the reaction $\pi p \to (3\pi)p$ have been noted by Pumplin.[7]

The notation pertaining to the reaction $np \to (p\pi^-)p$ is established in Fig. 1, where the wavy lines denote high energy elastic scattering, thus allowing neglect of the spin of the target and recoil protons. Covariant matrix elements for the three graphs are

$$M_\pi = \bar{u}(q_1,\lambda)\, i\gamma_5\, u(Q_1, \tfrac{1}{2})\, A_\pi(s_2,t)\, F_\pi(t_1), \tag{1}$$

$$M_N = \bar{u}(q_1,\lambda)\, (A + \not{q}_2 B)\, (\not{p}_\alpha + m)\, i\gamma_5\, u(Q_1, \tfrac{1}{2})\, F_N(u_1), \tag{2}$$

$$M_D = \bar{u}(q_1,\lambda)\, i\gamma_5\, (\not{p}_\beta + m)\, (A + \not{q}_2 B)\, u(Q_1, \tfrac{1}{2})\, F_D(s_1), \tag{3}$$

where $\lambda = \pm\frac{1}{2}$ and parity allows restricting the beam helicity to $+\frac{1}{2}$, and

$$F_\pi(t_1) = \sqrt{2}\, g\, e^{b_\pi(t_1-\mu^2)}/(t_1-\mu^2)\,,$$

$$F_N(u_1) = \sqrt{2}\, g\, e^{b_N(u_1-m^2)}/(u_1-m^2)\,,$$

$$F_D(s_1) = \sqrt{2}\, g\, e^{b_D(s_1-m^2)}/(s_1-m^2)\,,$$

with m the nucleon mass, μ the pion mass and $g^2/4\pi \simeq 14.3$. Use of more complicated form factors in the nucleon propagators does not qualitatively alter the results.[6] Also $A_\pi \sim i\sigma_{\pi p}\, e^{B_\pi t}\, s_2$, and A and B are the invariant amplitudes for spin 0 - spin 1/2 elastic scattering and are related to s-channel helicity amplitudes for large s by

$$f^{(s)}_{++}(s,t) \sim A(s,t) + \frac{\nu}{1-\frac{t}{4m^2}}\, B(s,t)$$

$$f^{(s)}_{+-}(s,t) \sim \sqrt{-t}\; A(s,t),$$

where $\nu = (s-u)/2m$. Assuming SCHC for the high energy elastic scattering means $f^{(s)}_{+-} = 0$ and only $B \sim i\sigma_{pp}\, e^{B_p t}$ contributes to M_N and M_D in this approximation. The amplitudes M_N and M_D tend to cancel due to the opposite signed propagators in F_N and F_D,[8] but this cancellation is not exact and qualitatively M_π and $M_N + M_D$ dominate different regions of phase space. For example, in the t-channel helicity frame[9] ($\hat{z} = \hat{Q}_1$, $\hat{y} = \hat{q}_2 \times \hat{Q}_1$, and $\cos\theta_t$, ϕ_t determine $\hat{q}_1$) the pion and nucleon propagators generally force M_π and $M_N + M_D$ to be large for $\cos\theta_t \sim 1$ and -1, respectively. The double differential cross section $d^2\sigma/d\cos\theta_t\, d\phi_t$ shown[1] in Fig. 2(a) clearly supports such an interpretation. The cuts $M < 1.3\ \mathrm{GeV}/c^2$ and $0.02 < -t < 0.15\ (\mathrm{GeV}/c)^2$ are taken to avoid any resonances. The model results shown in Fig. 2(b) are obtained by evaluating (1) - (3) with $\sigma_{\pi p}$, σ_{pp}, B_π, B_p taken from elastic scattering data, $b_\pi = 3.9\ \mathrm{GeV}^{-2}$, and $b_N = b_D = 2.9\ \mathrm{GeV}^{-2}$, and the model results are scaled in order to match the maximum height in Fig. 2(a). I have verified by explicit calculation that this scale factor can be accomodated by including absorption without qualitatively changing the angular distributions. The values for b_π, b_N, and b_D were chosen to achieve agreement with the projection $d\sigma/d\cos\theta_t$ (not shown). Clearly, for $\cos\theta_t > 0$, where M_π dominates, the model agrees very well with the data. However, for $\cos\theta_t < 0$, where $M_N + M_D$ dominates, the model is in qualitative disagreement with the data.[8] In particular $d\sigma/d\phi_t$ for $\cos\theta_t \sim -1$ has the wrong shape in the model.

It is possible to resolve this dilemma within the framework of DHD-type models by considering more carefully the covariant amplitudes M_N and M_D. Let us concentrate on M_N for definiteness. Recall that the covariant propagator $(\not{p}_\alpha - m)^{-1}$ contains both particle and anti-particle states. In fact, (2) can be rewritten as

$$M_N = \bar{u}(q_1, \lambda)\, \not{q}_2\, B(s_3, t) \sum_{\lambda'} \left[\frac{u(\tilde{p}_\alpha, \lambda)\, \bar{u}(\tilde{p}_\alpha, \lambda')}{2E_\alpha (p_{\alpha 0} - E_\alpha)} + \frac{\nu(\tilde{p}_\alpha, \lambda')\bar{\nu}(\tilde{p}_\alpha, \lambda')}{2E_\alpha (p_{\alpha 0} + E_\alpha)} \right]$$

$$\times\, i\gamma_5\, u(Q_1, \tfrac{1}{2})\, \sqrt{2}\; g\, e^{b_N(u_1 - m^2)} \,, \qquad (4)$$

where $\tilde{p}_\alpha = (E_\alpha, \vec{p}_\alpha)$, $E_\alpha^2 = \vec{p}_\alpha^{\,2} + m^2$, $p_{\alpha 0} = Q_{10} - k_0$. The two parts in (4) correspond to the diagrams in Fig. 3(a) and 3(b), respectively. Here, as in "old-fashioned" perturbation theory, intermediate particles are on mass-shell, but energy is not conserved at vertices. Clearly, on physical grounds where one imagines elastic rescattering of the dissociation products, only the particle contribution to M_N should be retained. Denote this by $M_N^{(a)}$. Similar considerations apply to M_D, leading to a term $M_D^{(a)}$. As the beam energy Q_{10} approaches infinity, $2E_\alpha (p_{\alpha 0} - E_\alpha) \to u_1 - m^2$ and $2E_\alpha (p_{\alpha 0} + E_\alpha) \to Q_{10}^2$, so $M_N^{(a)}$ and $M_D^{(a)}$ are dominant in the IMF. Note that similar considerations do not change M_π. Since energy is not conserved in the subprocess $p(\tilde{p}_\alpha) + p(Q_2) \to p(q_1) + p(q_2)$, the expression

$$f^{c}_{\lambda'\lambda}(s_3, t) = \bar{u}(q_1, \lambda)\, \not{q}_2\, B(s_3, t)\, u(\tilde{p}_\alpha, \lambda') \,,$$

is not helicity conserving in the center of momentum frame c where $\vec{q}_1 + \vec{q}_2 = 0$. Therefore, we should write

$$f^{c}_{++}(s_3, t) = i\,\sigma_{pp}\, s_3\, e^{B_p t} ,$$

and transform f^{c}_{++} to the t-channel helicity frame with Wigner rotations on the helicities,[10]

$$f^{t}_{\lambda'\lambda} = i\, d^{1/2}_{\lambda\lambda'}(\omega - \omega')\, \sigma_{pp}\, s_3\, e^{B_p t} ,$$

$$M_N^{(a)} = \sum_{\lambda'} f^{t}_{\lambda'\lambda}\, \bar{u}(\tilde{p}_\alpha, \lambda')\, i\gamma_5\, u(Q_1, \tfrac{1}{2})\, F_N(u_1) , \tag{5}$$

where ω and ω' are the Wigner rotation angles. After calculating a similar expression for $M_D^{(a)}$, the results shown in Fig. 2(c) are obtained, with $b_\pi = 3.5\ \mathrm{GeV}^{-2}$ and $b_N = b_D = 1.5\ \mathrm{GeV}^{-2}$. The model results are now in excellent qualitative agreement with the data in Fig. 2(a).

The original work of Good and Walker[11] was based on the idea that at high energies the scattered wave can, through diffraction, acquire components corresponding to dissociation products of the beam. Clearly the IMF is a preferred theoretical frame for discussing such reactions, since in this frame the components are "frozen" and can be probed by the Pomeron, similar to the way photons probe for partons in deep-inelastic scattering. Equation (5) is just the leading term in an IMF perturbation series, and differs from (2) by neglect of antiparticle contributions which are not relevant at high energies. The calculation of absorption terms in the IMF is in progress and will allow a more detailed comparison of the model with the data, particularly the t-dependence.

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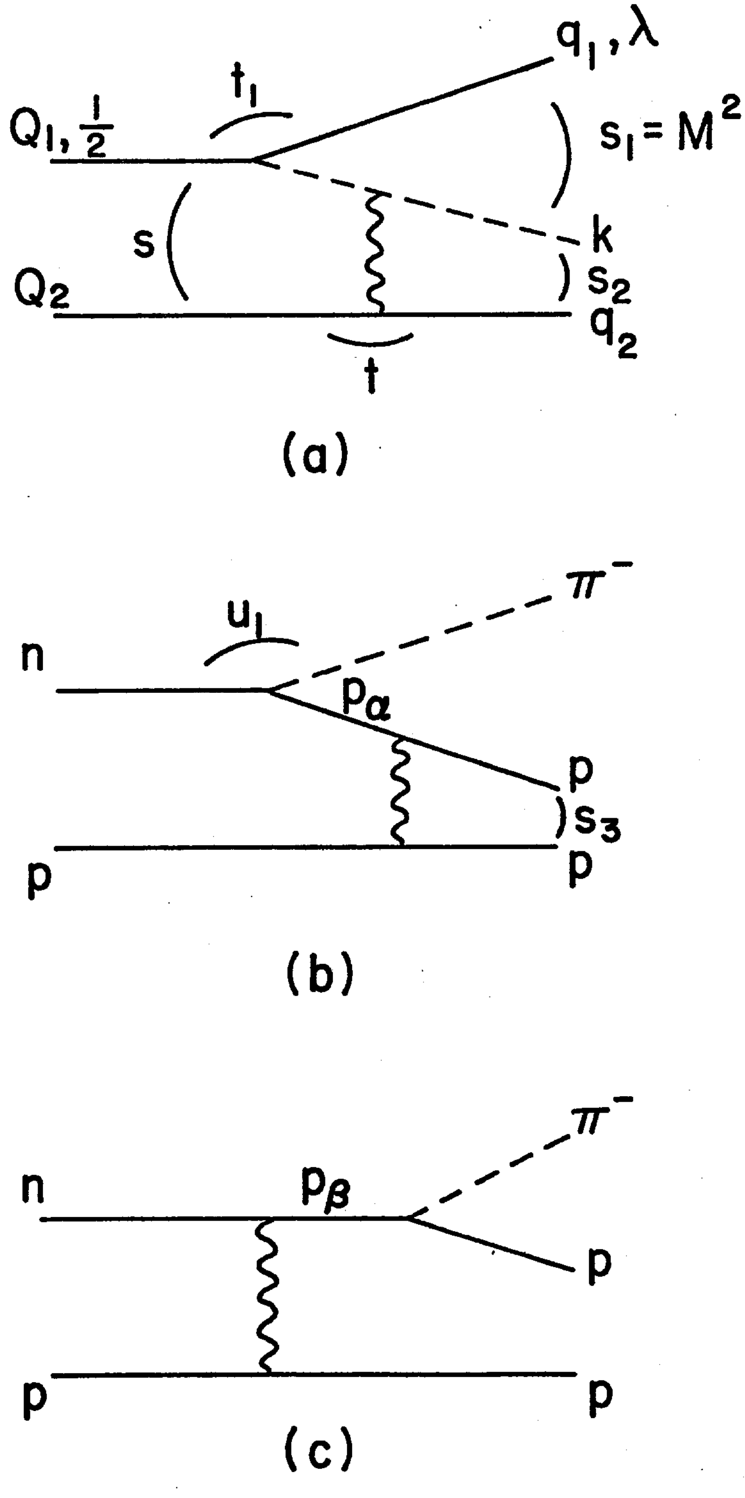
FIGURE CAPTIONS

Fig. 1: DHD-Type graphs for (a) pion exchange, (b) nucleon exchange, and (c) direct nucleon production. The particle momenta and relevant kinematic variables are noted.

Fig. 2: (a) Fermilab-Northwestern-Rochester-SLAC data on $np \to (p\pi^-)p$ for $M < 1.3$, $0.02 < -t < 0.15$,[1] (b) standard DHD model, and (c) IMF model.

Fig. 3: (a) The particle exchange process relevant to IMF calculations; (b) the antiparticle exchange process that should be omitted.



$Q_1, \frac{1}{2}$
t_1
q_1, λ
$s_1 = M^2$
s
k
s_2
Q_2
q_2
t
(a)
π^-
u_1
n
p_α
p
s_3
p
p
(b)
π^-
n
p_β
p
p
p
(c)

Fig. 1

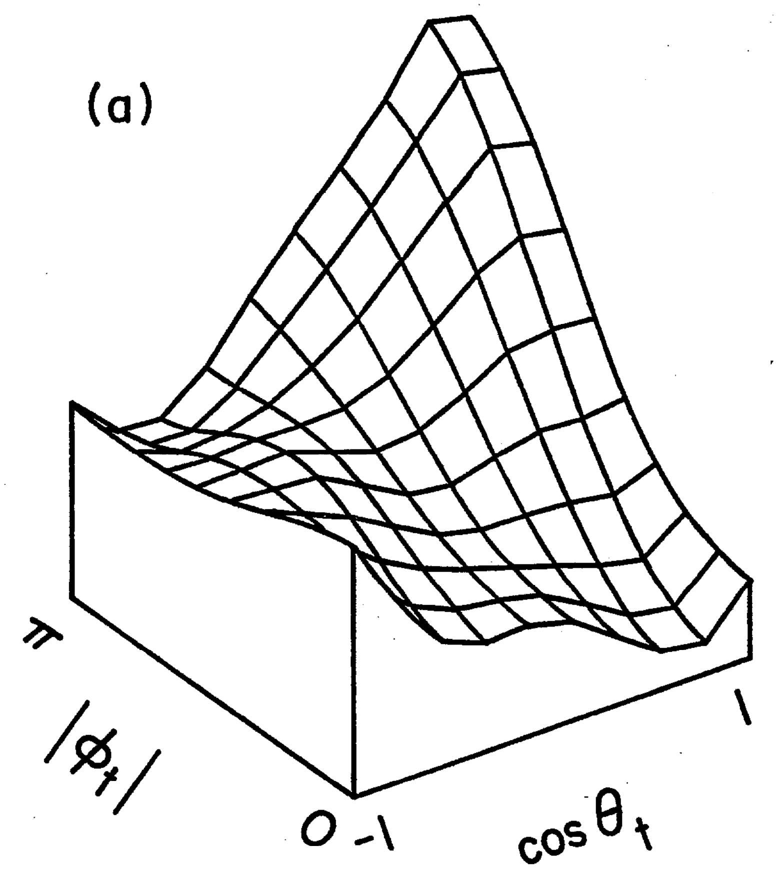


Fig. 2(a)

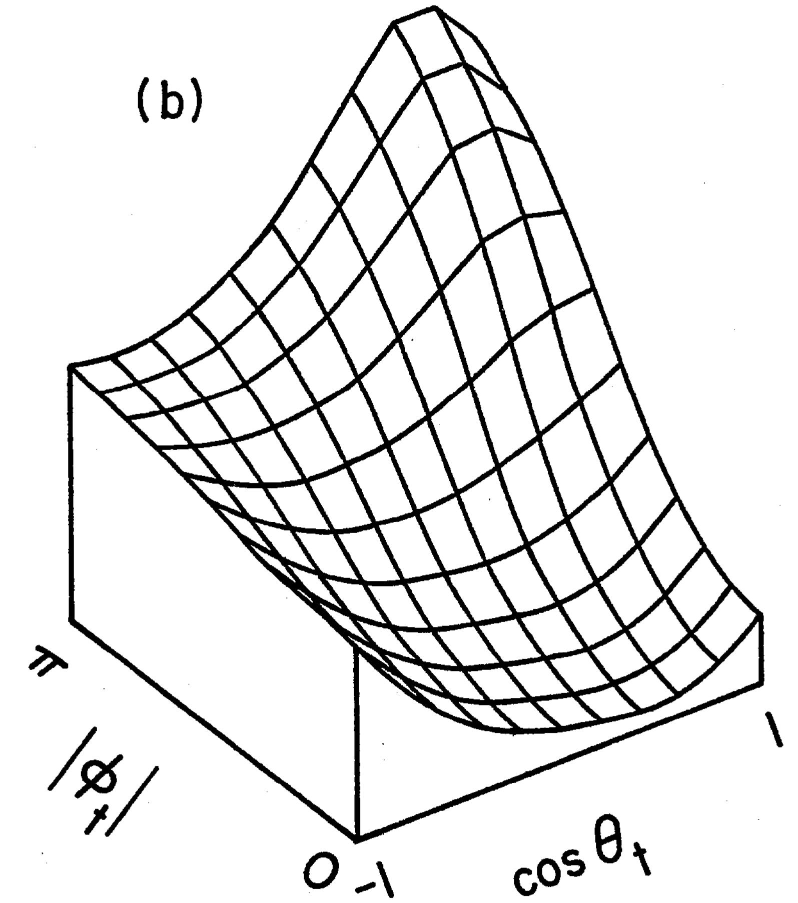


Fig. 2(b)

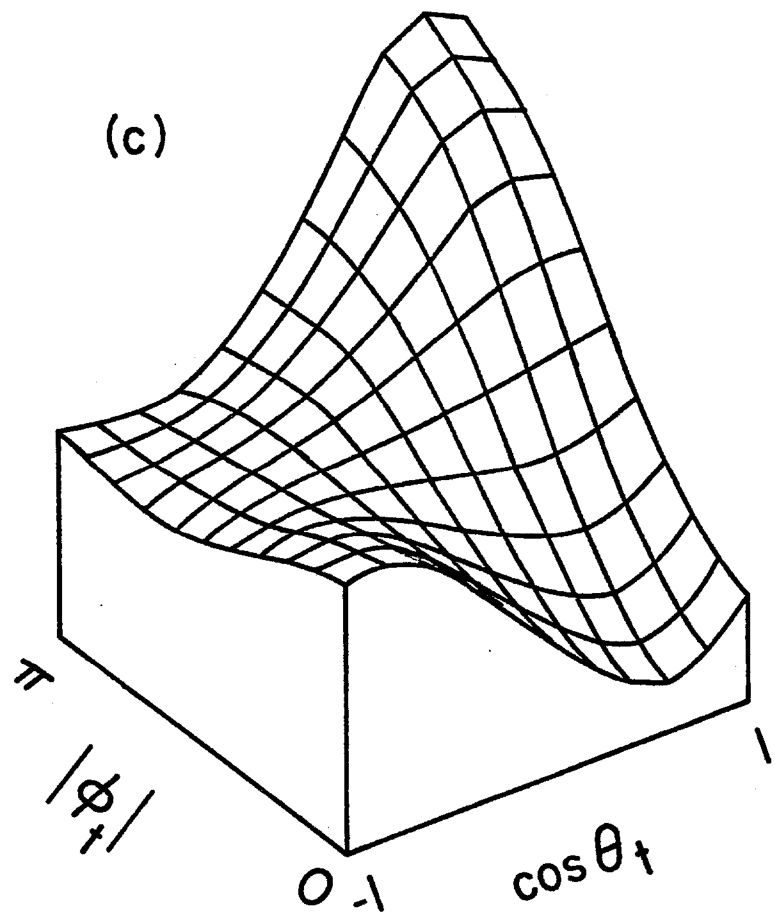


Fig. 2(c)

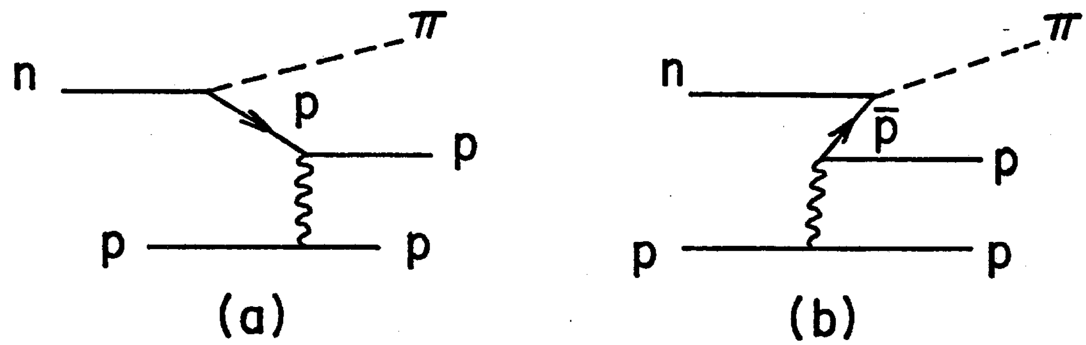


Fig. 3