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Differential Cross Section for Charged A_1 Photoproduction Using the Regge Exchange Formalism*

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The Regge-pole formalism is applied to the calculation of the differential cross section for A_1^+ photoproduction in the region $|t_{\min}|<-t<10\mu^2$. The ρ, A_1, A_1-daughter, A_2, and π trajectory contributions are considered, and use is made of chiral dynamics to estimate the unknown coupling constants. We find that the π and the A_2 trajectories provide the dominant contributions.

I. INTRODUCTION

This work was motivated by an experiment on A_1 photoproduction now in progress at the University of Rochester.[1] We present a calculation of the differential cross section for charged A_1 photoproduction for the small momentum transfer region $(-t<10\mu^2)$ making the following assumptions: (1) The ρ, A_1, A_1-daughter, A_2, and π trajectories provide the dominant contributions for $-t<10\mu^2$; (2) the residues can be approximated from the Feynman amplitude residues; (3) the coupling constants $g_{iA_1\gamma}$ (where $i=\pi$, ρ, A_1) and g_{iNN} (where $i=\rho$, A_1) can be estimated using "chiral dynamics"[2]; (4) the A_1-daughter residue is given by the conspiracy relation[3] $g_{00}^- + \frac{1}{2}ig_{10}^- \to \sqrt{t}$, as $t\to 0$.

The approach is first to estimate the relative contributions to the differential cross section of each of the parity-conserving helicity amplitudes in the t channel $(N\bar{N}\to\gamma A_1)$. To do this we examine the kinematic singularities prescribed by Hara and Wang[4] and consider the Regge behavior s^{α_i} of each of the trajectories contributing to the amplitude. To the important amplitudes in the region[5] $-t_{\min}<-t<10\mu^2$ (essentially the helicity-nonflip amplitudes) we apply the Reggeization procedure of Gell-Mann *et al.*[6] We approximate the residues by comparison with the t-channel Feynman amplitude residues—in which the unknown coupling constants have been estimated using chiral dynamics. We estimate the $g_{A_2A_1\gamma}$ from the $A_2\to\rho\pi$ width and the g_{A2NN} from some recent work on the A_2 trajectory in π photoproduction.[7]

Our results indicate that of the trajectories considered, the π and the possibly the A_2 provide the dominant contribution to $d\sigma/dt$ at small momentum transfers. The A_2 contribution depends critically on the g_{A_2NN} and the $g_{A_2A_1\gamma}$ coupling constants. The results which we present can be easily modified for other values of these couplings.

II. FORMALISM

We are interested in the differential cross section for the s-channel process $\gamma N\to NA_1$. The t-channel process $N\bar{N}\to\gamma A_1$ we designate by $a+b\to c+d$, where a, b, c, and d also represent the helicities of the particles in this channel. The kinematic-singularity-free parity-conserving t-channel amplitudes $g_{\lambda\mu}^{\pm}$ are as follows:

$$g_{\lambda\mu}^{\pm}(t,s)=f_{\lambda\mu}^{\pm}(t,s)K_{\lambda\mu}^{\pm}(t)\,, \tag{2.1}$$

where

$$f_{\lambda\mu}^{\pm}(t,s)=\bar{f}_{cd;ab}\pm(-)^{\lambda+\lambda_m}\eta_c\eta_d(-)^{S_c+S_d}\bar{f}_{-c-d;ab} \tag{2.2}$$

and

$$\bar{f}_{cd;ab}\equiv(\cos\tfrac{1}{2}\theta_t)^{-|\lambda+\mu|}(\sin\tfrac{1}{2}\theta_t)^{-|\lambda-\mu|}f_{cd;ab}; \tag{2.3}$$

$$\lambda=a-b,\quad \mu=c-d,\quad \lambda_m=\max(|\lambda|,|\mu|)\,. \tag{2.4}$$

$K_{\lambda\mu}^{\pm}(t)$ is a factor containing the kinematic singularities in t as prescribed by Hara and Wang.[4] The unpolarized differential cross section for $\gamma N\to NA_1$ is

$$\frac{d\sigma}{dt}=\frac{1}{16p_i^2s}\sum_{c,d,a,b}|f_{cd;ab}(t,s)|^2. \tag{2.5}$$

We list the 12 independent t-channel amplitudes $f_{\lambda\mu}^{\pm}$ in Table I, together with the possible trajectory contributions consistent with assumption (1). We also indicate the behavior near $t=0$ as determined from Wang's kinematic factor and the $t\approx t_{\min}$ dependence of the $\cos\frac{1}{2}\theta_t\sin\frac{1}{2}\theta_t$ factor which multiplies $f_{\lambda\mu}^{\pm}$ in $d\sigma/dt$.

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[1] Preliminary data are not yet available. The group working on this experiment includes H. Behrend, F. Lobkowicz, A. Wehmann, and E. Thorndike.

[2] See the Lagrangians given in Eqs. (2.10) and Ref. 10.

[3] See G. Cohen-Tannoudji, A. Morel, and H. Navelet, Ann. Phys. (N. Y.) **46**, 239 (1968).

[4] L. L. Wang, Phys. Rev. **142**, 1187 (1966); **153**, 1664, (1967); Y. Hara, *ibid.* **136**, B507 (1964); see also J. D. Jackson and G. E. Hite, *ibid.* **169**, 1248 (1968).

[5] $t_{\min}$ is the value of t for which $|\cos\theta_t|=1$; $t_{\min}\approx -M^2M_A{}^4/s^2$.

[6] M. Gell-Mann, M. L. Goldberger, F. E. Low, E. Marx, and F. Zachariasen, Phys. Rev. **133**, B145 (1964).

[7] K. Vasavada and K. Raman, Phys. Rev. Letters **21**, 577 (1968).

TABLE I. The parity conserving amplitudes and their behavior for small t. A_1-D is the A_1 daughter trajectory and π_c is the trajectory conspiring with the pion; M_A, M, and μ are the masses of the A_1, nucleon, and pion, respectively.

Amplitude	Dominant parity	Trajectory contributions	Behavior near $t=0$ (from $K_{\lambda\mu}^{\pm}$)	Behavior of $\cos\theta_t \sin\theta_t$ for $t\approx t_{\min}$	Estimated behavior for small t
f_{00}^{+}	$(-)^J$	ρ, A_2	const	const	$\sim s^{\alpha_\rho}, s^{\alpha_{A2}}$
f_{00}^{-}	$(-)^{J+1}$	π, A_1-D	$\left(\frac{M_A^2}{t}\right)^{1/2}+c\left(\frac{t}{\mu^2}\right)^{1/2}$	const	$\sim\left(\frac{M_A^2}{t}\right)^{1/2} s^{\alpha_{A1}-1}+c\left(\frac{t}{\mu^2}\right)^{1/2} s^{\alpha_\pi}$
f_{10}^{+}	$(-)^J$	ρ, A_2	const	$\left(\frac{t-t_{\min}}{M^2}\right)^{1/2}\frac{s}{s_0}$	$\sim\left(\frac{t-t_{\min}}{M^2}\right)^{1/2} s^{\alpha_{\rho,A2}}$
f_{10}^{-}	$(-)^{J+1}$	A_1	$\left(\frac{M_A^2}{t}\right)^{1/2}$	$\left(\frac{t-t_{\min}}{M^2}\right)^{1/2}\frac{s}{s_0}$	$\sim\left[\frac{(t-t_{\min})M_A^2}{M^2 t}\right]^{1/2} s^{\alpha_{A1}}$
$f_{0\text{-}1}^{+}$	$(-)^J$	ρ, A_2	const	$\left(\frac{t-t_{\min}}{M^2}\right)^{1/2}\frac{s}{s_0}$	$\sim\left(\frac{t-t_{\min}}{M^2}\right)^{1/2} s^{\alpha_{\rho,A2}}$
$f_{0\text{-}1}^{-}$	$(-)^{J+1}$	π	$\left(\frac{\mu^2}{t}\right)^{1/2}$	$\left(\frac{t-t_{\min}}{M^2}\right)^{1/2}\frac{s}{s_0}$	$\sim\left[\frac{(t-t_{\min})}{M^2 t}\mu^2\right]^{1/2} s^{\alpha_\pi}$
$f_{1\text{-}1}^{+}$	$(-)^J$	ρ, A_2, π_c	$\left(\frac{t}{M^2}\right)^{1/2}+c'\left(\frac{\mu^2}{t}\right)^{1/2}$	const	$\sim\left(\frac{t}{M^2}\right)^{1/2} s^{\alpha_{\rho,A2}-1}+c'\left(\frac{\mu^2}{t}\right)^{1/2} s^{\alpha_\pi-2}$
$f_{1\text{-}1}^{-}$	$(-)^{J+1}$	A_1	const	const	$\sim s^{\alpha_{A1}-1}$
$f_{0\text{-}2}^{+}$	$(-)^J$	ρ, A_2	const	$\frac{t-t_{\min}}{M^2}\left(\frac{s}{s_0}\right)^2$	$\sim\frac{t-t_{\min}}{M^2} s^{\alpha_{\rho,A2}}$
$f_{0\text{-}2}^{-}$	$(-)^{J+1}$	π	$\left(\frac{\mu^2}{t}\right)^{1/2}$	$\frac{t-t_{\min}}{M^2}\left(\frac{s}{s_0}\right)^2$	$\sim\frac{t-t_{\min}}{M^2}\left(\frac{\mu^2}{t}\right)^{1/2} s^{\alpha_\pi}$
$f_{1\text{-}2}^{+}$	$(-)^J$	ρ, A_2, π_c	$\left(\frac{t}{M^2}\right)^{1/2}+c''\left(\frac{\mu^2}{t}\right)^{1/2}$	$\left(\frac{t-t_{\min}}{M^2}\right)^{1/2}\frac{s}{s_0}$	$\sim\left(\frac{t-t_{\min}}{M^2}\right)^{1/2}\left[\left(\frac{t}{M^2}\right)^{1/2} s^{\alpha_{\rho,A2}-1}+c''\left(\frac{\mu^2}{t}\right)^{1/2} s^{\alpha_\pi-2}\right]$
$f_{1\text{-}2}^{-}$	$(-)^{J+1}$	A_1	const	$\left(\frac{t-t_{\min}}{M^2}\right)^{1/2}\frac{s}{s_0}$	$\sim\left(\frac{t-t_{\min}}{M^2}\right)^{1/2} s^{\alpha_{A1}-1}$

The conspiracy relations for A_1 photoproduction are[3]

$$f_{00}^{-}+\tfrac{1}{2}if_{10}^{-}\to\sqrt{t}, \tag{2.6a}$$

$$f_{02}^{-}+if_{12}^{+}\to\sqrt{t}, \tag{2.6b}$$

and

$$f_{01}^{-}+if_{11}^{+}\to\sqrt{t}. \tag{2.6c}$$

Since the scalar particle does not contribute to the f_{10}^{-} amplitude, a conspiracy of the type (2.6a) is not possible for the pion. [In this case the pion would conspire with a Regge pole which has $\alpha(0)=\alpha_\pi(0)-1$.] In Table I we have assumed the conspiracy relation (2.6c) for the pion. (In this case the pion conspires with a Regge pole which has the same spin but opposite parity at $t=0$.)

Using the Regge behavior, $s^{\alpha_i(t\approx 0)-\lambda_m}$, for contributions from the ith trajectory, we estimate the contribution of $f_{\lambda\mu}^{\pm}$ to $d\sigma/dt$ near $t\approx t_{\min}$. (See the last column of Table I.) This preliminary examination indicates that $f_{00}^{\pm}$, f_{10}^{+}, and possibly $f_{0\text{-}1}^{\pm}$ will dominate the cross section for small t.

The π contribution to $f_{0\text{-}1}^{-}$ can be neglected because it is zero at $t=t_{\min}$ and because it is roughly μ^2/M^2 smaller than the π contribution to $|f_{00}^{-}|^2$ for small t.[8]

The A_2 contributions to f_{10}^{+} and $f_{0\text{-}1}^{+}$ can present special problems since we have no information about the helicity-flip couplings. However, these contributions will be multiplied by $\sin^2\theta_t$ in $d\sigma/dt$ and will therefore be zero at $t=t_{\min}$. If the helicity-flip couplings are comparable to the nonflip couplings, the A_2 contributions to f_{10}^{+} and $f_{0\text{-}1}^{+}$ will be at least an order of magnitude smaller than the A_2 contribution to f_{00}^{+} for the range of t which we are considering.

To get some feeling for the size of the ρ contributions, we have assumed $\mathcal{L}_{\rho A_1\gamma}=g_{\rho A_1\gamma}\epsilon^{\mu\alpha\beta\gamma}(\partial_\alpha A_\alpha)A_{1\beta}{}^i\rho_\mu{}^j\epsilon_{3ij}$

[8] The Feynman-diagram calculation (assuming the "chiral dynamics") gives zero for this amplitude.

and $\mathcal{L}_{\rho NN}=ig_V\bar{N}\gamma_\mu\boldsymbol{\tau}N\cdot\boldsymbol{\rho}^\mu+ig_T\partial_\nu(\bar{N}\sigma^{\mu\nu}\boldsymbol{\tau}N\cdot\boldsymbol{\rho}_\mu)$ and estimated the ρ contribution to $f_{10}{}^+$ using a rather large value of $g_{\rho A1\gamma}(=1)$; $g_V=\frac{1}{2}$ and $g_T=\frac{1}{2}(\mu_p-\mu_n)$. We found that this contribution to $d\sigma/dt$ was approximately 10^{-2} that of the pion contribution to $f_{00}{}^-$; the ρ contribution to $f_{00}{}^+$ was of the same order when compared to the pion contribution.

Therefore, neglecting the $f_{0\text{-}1}{}^\pm$ and $f_{10}{}^+$ amplitudes, we assume

$$d\sigma/dt\approx(1/16\pi p_i{}^2s)\times(|f_{00}{}^+|^2+|f_{00}{}^-|^2+\tfrac{1}{4}\sin^2\theta_t|f_{10}{}^-|^2)\,,\quad(2.7)$$

where

$$f_{00}{}^+(t,s)\approx\pi\frac{(1+e^{-i\pi\alpha_{A2}(t)})}{2\sin(\pi\alpha_{A2})}(2\alpha_{A2}+1)\times\frac{\beta_{00}{}^{A2}(t)\alpha_{A2}(t)}{2K_{00}{}^+(t)}\bar{E}_{00}{}^{+\alpha_{A2}}(\cos\theta_t)\,,\quad(2.8\text{a})$$

$$f_{00}{}^-(t,s)\approx\pi\frac{(1+e^{-i\pi\alpha_\pi(t)})}{2\sin(\pi\alpha_\pi)}(2\alpha_\pi+1)\frac{\beta_{00}{}^\pi(t)}{K_{00}{}^-(t)}\bar{E}_{00}{}^{+\alpha_\pi}(\cos\theta_t)+\pi\frac{(1+e^{-i\pi\alpha_{A1\text{-}D}(t)})}{2\sin(\pi\alpha_{A1\text{-}D})}(2\alpha_{A1\text{-}D}+1)\times\frac{\beta_{00}{}^{A1\text{-}D}(t)}{K_{00}{}^-(t)}\bar{E}_{00}{}^{+\alpha_{A1\text{-}D}}(\cos\theta_t)\,,\quad(2.8\text{b})$$

and

$$f_{10}{}^-(t,s)\approx\pi\frac{(1-e^{-i\pi\alpha_{A1}(t)})}{2\sin(\pi\alpha_{A1})}(2\alpha_{A1}+1)\frac{\beta_{10}{}^{A1}(t)}{K_{10}{}^-(t)}\times[\alpha_{A1}(\alpha_{A1}+1)]^{1/2}\bar{E}_{01}{}^{+\alpha_{A1}}(\cos\theta_t)\,.\quad(2.8\text{c})$$

α_π, α_{A2}, α_{A1}, and $\alpha_{A1\text{-}D}$ represent the trajectories of π, A_2, A_1, and the daughter of A_1, respectively. The $\bar{E}_{\lambda\mu}{}^{+\alpha}$ are normalized such that, asymptotically,

$$\bar{E}_{00}{}^{+\alpha}\equiv\left(\frac{p_tp_t'}{s_0}\right)^\alpha E_{00}{}^\alpha\to\frac{\Gamma(\alpha+\frac{1}{2})}{\pi^{1/2}\Gamma(\alpha+1)}\left(\frac{s}{s_0}\right)^\alpha\quad(2.9\text{a})$$

and

$$\bar{E}_{01}{}^{+\alpha}\equiv\left(\frac{p_tp_t'}{s_0}\right)^{\alpha-1}\times E_{01}{}^\alpha\to\frac{2\alpha\Gamma(\alpha+\frac{1}{2})}{[\pi\alpha(\alpha+1)]^{1/2}\Gamma(\alpha+1)}\left(\frac{s}{s_0}\right)^{\alpha-1}.\quad(2.9\text{b})$$

We take s_0 to be 1 GeV^2.

We now redefine the residue factors $\beta_{\lambda\mu}{}^\alpha/K_{\lambda\mu}{}^\pm$ to be $\gamma_{\lambda\mu}{}^\alpha(t)$ and approximate the $\gamma_{\lambda\mu}{}^\alpha$ by the Feynman amplitude residues at t equal to the exchanged mass squared. We also require that the $\gamma_{\lambda\mu}{}^\alpha$ contain Wang's kinematic singularity factors.[9]

[9] Some factors of $(t-M_A{}^2)$ which would be obtained from Wang's formulas are not necessary in this case.

To calculate the Feynman amplitudes for π, A_1, and A_2 exchange, we use the following Lagrangians[10]:

$$\mathcal{L}_{\pi NN}=ig_{\pi NN}\bar{N}\gamma_5\boldsymbol{\tau}N\cdot\boldsymbol{\pi}\,,\quad(2.10\text{a})$$

$$\mathcal{L}_{A1NN}=ig_A\bar{N}\gamma_\mu\gamma_5(\tfrac{1}{2}\boldsymbol{\tau})N\cdot\mathbf{A}_1{}^\mu\,,\quad(2.10\text{b})$$

$$\mathcal{L}_{A_2NN}=iM^{-2}g_{A_2NN}\bar{N}\boldsymbol{\tau}(\partial_\mu\partial_\nu N)\cdot\mathbf{T}^{\mu\nu}\,,\quad(2.10\text{c})$$

$$\mathcal{L}_{\pi A1\gamma}=eM_A\epsilon_{3ij}\left[M_A{}^{-2}A^\mu\partial^\nu\pi^i(\partial_\mu A_{1\nu}{}^j-\partial_\nu A_{1\mu}{}^j)-\frac{(1-\delta)}{M_A{}^2}F^{\mu\nu}\partial_\mu\pi^iA_{1\nu}{}^j+A_\mu\pi^iA_1{}^{j\mu}\right],\quad(2.10\text{d})$$

$$\mathcal{L}_{A_1A_1\gamma}=\tfrac{1}{2}e(1+\delta)\epsilon_{3ij}(\partial_\mu A_\nu-\partial_\nu A_\mu)A_1{}^{i\mu}A_1{}^{j\nu}\,,\quad(2.10\text{e})$$

and

$$\mathcal{L}_{A_2A_1\gamma}=(f_2/M_A)\epsilon^{\alpha\beta\gamma\mu}(\partial_\beta A_\alpha)(\partial_\gamma A_1{}^{i\nu})T_{\mu\nu}{}^j\epsilon_{ij3}\,.\quad(2.10\text{f})$$

N, π, $A_{1\mu}$, A_μ, and $T_{\mu\nu}$ are the nucleon, pion, A_1, photon, and A_2 fields, respectively; i is the isospin index. M, M_A, and μ are the masses of the N, A_1, and π, respectively.

Using Eqs. (2.8) and comparing the residues with the Feynman exchange amplitudes, we obtain

$$\gamma_{00}{}^{+\alpha_{A2}}=\tfrac{4}{5}\sqrt{2}g_{A2NN}f_2\left(\frac{M_A}{M^2}\right)\frac{d\alpha_{A2}}{dt}\frac{(t-4M^2)^{1/2}}{(t-M_A{}^2)}s_0{}^2,\quad(2.11\text{a})$$

$$\gamma_{00}{}^{-\alpha_\pi}=eM_AMg_{\pi NN}(t)\frac{d\alpha_\pi}{dt}\left(\frac{t}{2M^2}\right)^{1/2},\quad(2.11\text{b})$$

$$\gamma_{10}{}^{-\alpha_{A1}}=\tfrac{1}{2}\sqrt{2}g_A\times e(1+\delta)\frac{d\alpha_{A1}}{dt}(M_A{}^2-t)\left(\frac{t-4M^2}{t}\right)^{1/2}.\quad(2.11\text{c})$$

We determine the A_1 daughter residues from the conspiracy condition (2.6a). Thus

$$\gamma_{00}{}^{-\alpha_{A1\text{-}D}}=\tfrac{1}{2}\sqrt{2}g_A\times e(1+\delta)\frac{d\alpha_{A1}}{dt}\frac{(M_A{}^2-t)^2}{M_A{}^2}\left(\frac{M^2}{t}\right)^{1/2}\frac{P_{\alpha A1(0)}{}'(0)}{P_{\alpha A1(0)-1}(0)}.\quad(2.12)$$

For $g_{\pi NN}(t)$ we assume the form[11] $g_{\pi NN}[1+\bar{\lambda}(\mu^2-t)/\mu^2]^{-1}$, with $g_{\pi NN}{}^2/4\pi=14$ and $\bar{\lambda}=0.1$. This form gives a good fit to the ρ-production differential cross section

[10] For a derivation of (2.10d) and (2.10e), see J. Wess and B. Zumino, Phys. Rev. **163**, 1727 (1967), and H. Schnitzer and S. Weinberg, *ibid.* **164**, 1828 (1967).

[11] This general form has also been used by U. Amaldi and F. Selleri, Nuovo Cimento **31**, 360 (1964).

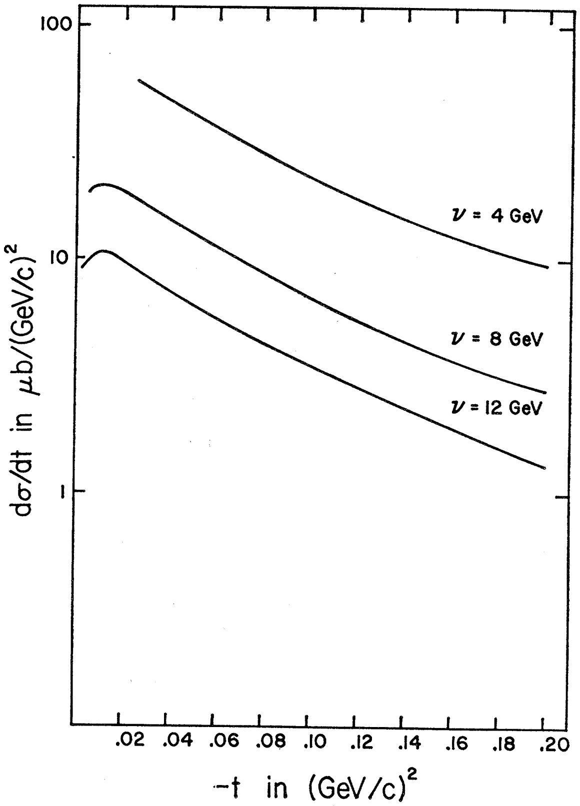

FIG. 1. Unpolarized differential cross section for $\gamma N \to NA_1$ with $g_{A_2NN}=0.5$.

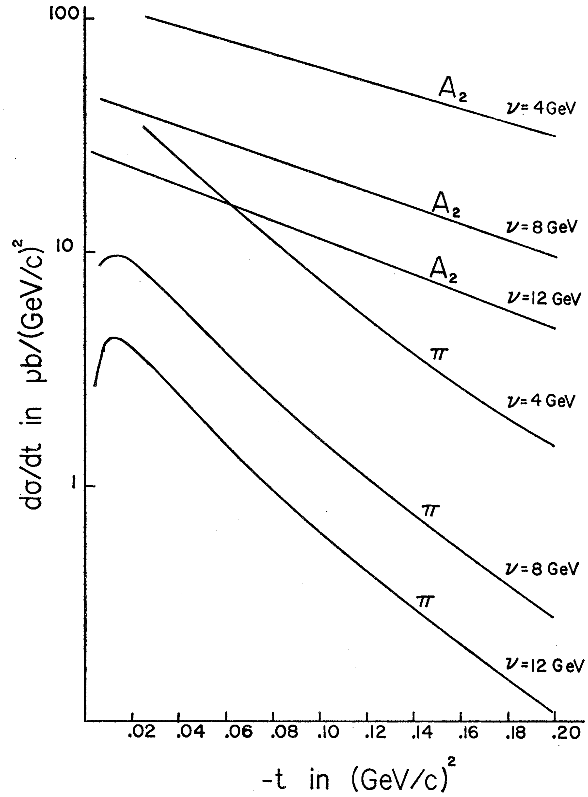

FIG. 2. Pion and the A_2 trajectory contributions to the differential cross section for $\gamma N \to NA_1$; $g_{A_2NN}=1$.

for $\pi N \to \rho N$ at incident pion momenta of 4 and 8 GeV/c.[12–14]

The f_2 was estimated by first relating the $A_2A_1\gamma$ coupling to the $A_2\pi\gamma$ coupling using partial conservation of axial-vector current (PCAC). With the substitution $\gamma_\mu \to e\rho_\mu/g_\rho$, the f_2 can be estimated from the $A_2 \to \rho\pi$ width. [In carrying out this procedure we assumed only the $A_2A_1\gamma$ coupling given in (2.10f). There are three independent $A_2A_1\gamma$ couplings which should be used, and our estimate of f_2 is lacking in this respect.] Using $g_\rho^2/4\pi=2.4$ and $\Gamma(A_2\to\rho\pi)\approx 19$ MeV, we obtain an estimate for f_2 of about 1. For $g_A=(G_A/G_V)M_A^2/M^2$, we use 13.2 and for δ we use -0.3.[15]

Using the results of Vasavada and Raman[7] on the A_2 trajectory in π photoproduction, we estimate g_{A2NN} to be approximately 0.5. This was done by comparing the Feynman amplitude residue for A_2 exchange in $N\bar{N}\to\gamma\pi$ [using (2.10c)] to the residue factor of Ref. 7 at $t=M_{A2}^2$. A rather large uncertainty in g_{A2NN} ($\approx\pm0.4$) is introduced because we are forced to compare residues at $t=M_{A2}^2$ where Ref. 7 obtains a small slope for the A_2 trajectory, and where the results of Ref. 7 are least accurate. For this reason and because of the crude estimate for f_2, we present the π and A_2 contributions to the differential cross section separately.

For the Regge trajectories we use $\alpha_\pi(t)=(t-\mu^2)/s_0$, $\alpha_{A1}(t)=\alpha_{A1}(0)+t/s_0$, $\alpha_\rho(t)=0.54+0.46t/M_\rho^2$, $\alpha_{A2}(t)=0.34+1.66t/M_{A2}^2$, and $\alpha_{A1\text{-}D}(t)\approx\alpha_{A1}(0)-1$.

III. RESULTS AND CONCLUSIONS

Figure 1 shows the differential cross section for incident photon energies of 4, 8, and 12 GeV and $-t_{\min}<-t<10\mu^2$. For this calculation we used $g_{A2NN}=0.5$ and $f_2=1$. We find the A_1 and A_1 daughter contributions to be negligible so that, in effect, $d\sigma/dt$ is given by the π and the A_2 trajectory contributions. Several values of $\alpha_{A1}(0)$ between -0.1 and -0.4 were tried and little variation in the A_1 and A_1 daughter contributions was observed.[16]

[12] The $\pi N\to\rho N$ differential cross section was calculated in the same manner as described in this paper assuming that the π and the A_1 trajectory contributions dominate the cross section at small momentum transfers. The experimental results used were those of Ref. 13.

[13] For the 8-GeV/c data we used the results of W. Selove, F. Forman, and H. Yuta, Phys. Rev. Letters **21**, 952 (1968); for the 4-GeV/c data we used the results of the Notre Dame, Purdue, and SLAC Collaboration, Phys. Rev. **176**, 1651 (1968). This form for $g_{\pi NN}(t)$ was used rather than $g_{\pi NN}[1+\lambda(\mu^2-t)/\mu^2]$ (see Ref. 14) since the latter did not fit the ρ-production data.

[14] See, e.g., R. J. N. Phillips, Nucl. Phys. **B2**, 394 (1967); J. S. Ball, W. Frazer, and M. Jacob, Phys. Rev. Letters **20**, 518 (1968).

[15] H. J. Schnitzer and S. Weinberg, Phys. Rev. **164**, 1828 (1967).

[16] Except at $t\approx0$ (and therefore only observable when $t_{\min}\approx0$), the A_1 and A_1 daughter contributions were about two orders of magnitude smaller than the π contribution.

Since the A_2 couplings are rather crudely estimated, we have plotted the A_2 and the π contributions to $d\sigma/dt$ separately in Fig. 2 using $g_{A2NN}=1$ and $f_2=1$. The differential cross section in this model for different values of the A_2 couplings can be determined from Fig. 2.

From the differential cross sections shown in Fig. 1, we estimate total cross sections of about 5, 2, and 1 μb for incident photon energies of 4, 8, and 12 GeV, respectively. Total cross sections of about 16, 7, and 3 μb (for $\nu=4$, 8, and 12 GeV, respectively) would be indicated for $g_{A2NN}=1$ and $f_2=1$.

We would like to reemphasize our assumptions (Sec. I) and point out again that our estimates of g_{A2NN} and f_2 have been made with some reservations. When experimental cross sections are available it may be possible to say something further about the unknown couplings using a model such as the one presented here.

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Regge Model in High-Energy Lepton Processes*

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The application of Regge-model ideas to high-energy semileptonic reactions is taken up in some detail for the process $\nu+p\rightarrow\mu^-+p+\pi^+$ (and its electroproduction analogs), and, qualitatively, for more complicated processes of the sort $\nu+p\rightarrow\mu^-+p+X_1+X_2+\ldots$.

I. INTRODUCTION

ON the standard assumption of locality for the weak couplings of lepton pairs,[1] high-energy neutrino processes acquire a structure which is well suited to the testing of Regge-model notions.[2] In the simplest inelastic reaction, $l+N\rightarrow l+N+\pi$, rather detailed features of the theory become accessible for test in a striking way. This is particularly true for the neutrino reaction $\nu+N\rightarrow\mu+N+\pi$, which is the topic of Sec. II. Results for the corresponding electroproduction reactions (e or μ)$+N\rightarrow$ (e or μ)$+N+\pi$ are obtained in Sec. III. Certain qualitative features suggest themselves also for generalization to more complicated processes, again with definite observable consequences. These are taken up in Sec. IV.

It is a familiar implication of Regge-pole dominance[3] for strong two-body $\rightarrow$ two-body reactions that all helicity amplitudes for a given process share a common phase to leading order in energy, where this phase is determined by the signature factor of the dominant Regge trajectory. For the differential cross-section spectrum this entails the vanishing, to leading order in the energy, of correlations that are odd under reversal of all spin and momenta (e.g., correlations of the form $\boldsymbol{\sigma}\cdot\mathbf{k}_1\times\mathbf{k}_2$). Such quasi-$T$-violating effects first arise only in an energy order corresponding to interference between the leading and next ranking trajectories. It is this "phase" property of Regge theory that we shall especially focus on here. We suppose that it, along with other standard aspects on the theory, can be carried over to weak and electromagnetic analogs of two-body $\rightarrow$ two-body strong interactions, e.g., $\nu+N\rightarrow\mu+N+\pi$, $e+N\rightarrow e+N+\pi$. The experimental implications are especially rich for the neutrino-induced reactions. Here, because of the presence of parity-violating interactions, odd correlation terms formed solely out of momentum vectors (terms of the kind $\mathbf{k}_1\cdot\mathbf{k}_2\times\mathbf{k}_3$) are now permis-

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[1] General implications of locality are discussed by T. D. Lee and C. N. Yang, Phys. Rev. **126**, 2239 (1962); A Pais, Phys. Rev. Letters **9**, 117 (1962); A Pais and S. B. Treiman (unpublished). [In the last paper the factor σ on the left-hand-side of Eq. (18) should be replaced by $d^2\sigma/dsdt$.]

[2] Diffractive aspects of high-energy neutrino reactions have been discussed by C. A. Piketty and L. Stodolsky, in Proceedings of the Topical Conference on Weak Interactions, CERN, 1969 (unpublished).

[3] For definiteness we consider the Regge model to be a Regge-*pole* model. In what follows the, reader will find comments at appropriate places concerning the extent to which statements are actually independent of specific *pole* properties.