Strong Absorptive Regge-Cut Model for Pion Photoproduction, $np \to pn$, and Related Processes*

G. L. Kane, F. Henyey, D. R. Richards, and Marc Ross
Physics Department, University of Michigan, Ann Arbor, Michigan 48104

and

G. Williamson†
Physics Department, University of California, Los Angeles, California 90024
(Received 10 August 1970)

The combined high-energy data for $\gamma p \to \pi^+ n$, $\gamma n \to \pi^- p$, $np \to pn$, $\bar{p}p \to \bar{n}n$, $\gamma p \to \pi^0 p$, and $\gamma p \to \eta p$ are successfully described in a strong absorptive (Regge-cut) model. Only the high-lying trajectories, ω, ρ, A_2, and (evasive) π and the associated cuts are necessary to understand the data. The $\pi^\pm$ photoproduction cross-section difference rules out "nonsense wrong-signature zeros." The scale of the cross sections is determined correctly by the conventional coupling strengths. The general features of pion exchange are discussed.

Using a previously proposed model,[1] we present here a description of the reactions for charged photoproduction,

$$\gamma p \to \pi^+ n, \tag{1a}$$

$$\gamma n \to \pi^- p; \tag{1b}$$

for neutral photoproduction,

$$\gamma p \to \pi^0 p, \tag{1c}$$

$$\gamma p \to \eta p, \tag{1d}$$

$$\gamma n \to \pi^0 n, \tag{1e}$$

$$\gamma n \to \eta n; \tag{1f}$$

ana for nucleon-nucleon charge exchange,

$$np \to pn, \tag{1g}$$

$$\bar{p}p \to \bar{n}n. \tag{1h}$$

The same model (hereafter referred to as HKPR) has been used to describe the forward reactions $\pi^- p \to \pi^0 n(\eta n)$, $K^- p \to K^0 n$, $K^+ n \to K^0 p$, $K_2 p \to K_1 p$, $\pi N \to K\Sigma(K\Lambda)$, $KN \to \pi\Lambda(\pi\Sigma)$,[2] and the backward reactions $\gamma p \to n\pi^+(p\pi^0)$, $\pi^\pm p \to p\pi^\pm$, $\pi^- p \to n\pi^0$, and $\pi^- p \to n\rho^0(p\rho^-)$.[3]

Our model is one of several which combine the good features of (1) Regge-pole physics and (2) absorptive effects for hadrons.[4-6] All of these models essentially agree on the form of the absorption correction, which appears in the angular momentum plane as a Regge cut associated with each Regge pole. Their major differences are (1) the form of the Regge-pole amplitude, (2) the expected size of the absorption correction associated with inelastic intermediate states, and (3) the validity of the ideas when applied to elastic scattering. In the HKPR model (1) the Regge poles have no "nonsense wrong-signature zeros." Dips are produced by another mechanism, the destructive interference between poles and their associated cuts; i.e., the dips are diffraction minima. Factorization does not relate the dip structure of different amplitudes as is the case with the "nonsense wrong-signature zero" mechanism. (2) The absorption corrections (Regge cuts) are assumed to have significant contributions from inelastic states. (3) The model is not necessarily applicable to elastic or inelastic diffractive scattering.

The general formula for the cross section for the process $a+b \to c+d$, where particles a and c move forward in the center-of-mass system and a, b, c, d, have helicities λ, μ, λ', μ', respectively, is

$$d\sigma/dt = \sum |M_{\lambda'\mu'\lambda\mu}|^2/64\pi q^2 s, \tag{2}$$

where $\sum$ is the sum over final and average over initial spins. The amplitude in our model is the sum over all Reggeon exchanges and their associated cuts: $M = \sum_j (M_j^P + M_j^C)$. The dominant exchanges are π, ρ, and A_2 for charged photoproduction and nucleon-nucleon charge exchange, and ρ and ω for neutral photoproduction. Lower-lying trajectories such as B were ignored. The s-channel helicity amplitudes for exchange of Reggeon j are[7]

$$M_{j\lambda'\mu'\lambda\mu}{}^P = (-t)^{(n+x)/2} \exp[-\tfrac{1}{2}i\pi\alpha_j{}'(t-m_j{}^2)] \frac{g(acj)_{\lambda'\lambda} g(bdj)_{\mu'\mu}}{m_j{}^2 - t} \left(\frac{s-\frac{1}{2}\sum m^2}{s_{0j}}\right)^{\alpha_j(0)+\alpha_j{}'t}, \tag{3}$$

where $n = |(\lambda-\lambda')-(\mu-\mu')|$, $x = |\lambda-\lambda'| + |\mu-\mu'| - n$, $\sum m^2$ is the sum of external masses squared, and

Table I. Vertex functions and parameter values.

Vertex Function	Parameter	Fitted Value	Expected Value
$g(np\rho^+)_{\frac{1}{2}\frac{1}{2}} = -2G_\rho^V s_{o\rho}^{\frac{1}{2}}$	G_ρ^V	2.03	2
$g(np\rho^+)_{\frac{1}{2}-\frac{1}{2}} = G_\rho^T s_{o\rho}^{\frac{1}{2}}/m_N$	G_ρ^T/G_ρ^V	6.4	3.7
$g(\gamma\pi\rho) = g_{\gamma\rho\pi} s_{o\rho}^{\frac{1}{2}}/2$	$g_{\gamma\rho\pi} = g_{\gamma\omega}g_{\omega\rho\pi}$	fixed	.26 GeV^{-1}
$g(\gamma\eta\rho) = -g(\gamma\pi\omega)$			
$g(npA_2^+)_{\frac{1}{2}\frac{1}{2}} = \sqrt{2}\, G_A^V s_{oA}$	G_A^V	.273 GeV^{-1}	near the ρ[a]
$g(npA_2^+)_{\frac{1}{2}-\frac{1}{2}} = \sqrt{2}\, G_A^T s_{oA}/2m_N$	G_A^T/G_A^V	11.6	"
$g(\gamma\pi A_2) = -g_{\gamma A\pi} s_{oA}/4\sqrt{2}$	$g_{\gamma A\pi} = g_{\gamma\rho}g_{\rho A\pi}$	fixed	1.32 GeV^{-1}
$g(pp\omega)_{\frac{1}{2}\frac{1}{2}} = -\sqrt{2}G_\omega^V s_{o\omega}^{\frac{1}{2}}$	G_ω^V	11.5	7
$g(pp\omega)_{\frac{1}{2}-\frac{1}{2}} = g_\omega^T s_{o\omega}^{\frac{1}{2}}/\sqrt{2}m_N$	G_ω^T/G_ω^V	.5	-.14
$g(\gamma\pi\omega) = g_{\gamma\omega\pi} s_{o\omega}^{\frac{1}{2}}/2$	$g_{\gamma\omega\pi} = g_{\gamma\rho}g_{\omega\rho\pi}$	.83 GeV^{-1}	.72 GeV^{-1}
$g(\gamma\eta\pi) = -g(\gamma\pi\rho)$			
$g(np\pi^+)_{\frac{1}{2}\frac{1}{2}} = 0(1/s)$		fixed	0
$g(np\pi^+)_{\frac{1}{2}-\frac{1}{2}} = \sqrt{2}\, g_{\pi NN}$	$g_{\pi NN}^2/4\pi$	fixed	14.7
$g(\gamma\pi\pi) = (8\pi\alpha)^{\frac{1}{2}}$	α	fixed	1/137

Parameter	Fitted Value	Expected Value
Regge Pole Parameters[a]		
α_π'	.9	1 ± .2
$\alpha_\rho' = \alpha_\omega'$	1.16	1 ± .2
α_A'	.8	1 ± .2
$s_{o\pi}$	.385	
$s_{o\rho}$	1.94	
s_{oA}	3.37	
$s_{o\omega}$	1.36	
Absorption Strength Parameters[b]:		
Photoproduction:		
λ^π	3.35	
$\lambda^\rho(n)$	2.0	
$\lambda^\rho(f)$	1.19	
$\lambda^A(f)$	1.19	
$\lambda^A(n)$	2.05	
$\lambda^\omega(n)$	2.71	
$\lambda^\omega(f)$	1.2	
Nucleon-nucleon charge exchange:		
$\lambda^\pi(4)$	1.81	
$\lambda^\rho(1)$	1.0	
$\lambda^\rho(4)$	1.94	
$\lambda^\rho(5)$	1.21	
$\lambda^A(1)$	1.3	
$\lambda^A(4)$	2.2	
$\lambda^A(5)$	2.2	

[a]In GeV units.

[b]Arguments n (f) refer to nucleon helicity nonflip (flip) amplitudes. Arguments 1, 4, and 5 refer to the amplitudes φ_1, φ_4, and φ_5, respectively.

m_j is the mass of the nearest particle on the trajectory $\alpha_j(t)$. The factorized residues g are defined in Table I and are assumed to be t independent. The t dependence in the numerator is that demanded by conservation of angular momentum, $(-t)^{n/2}$, and parity, $(-t)^{x/2}$. If $x > 0$, the amplitude is called "evasive."

The principal cut M_j^C associated with Reggeon j is given by HKPR[1] Eq. (A11B), multiplied by an adjustable strength parameter λ. If only elastic intermediate states contribute to the cut, $\lambda = 1$, while contributions from inelastic intermediate states make $\lambda > 1$. Complete absorption in the lowest partial wave corresponds to $\lambda \simeq 1.6$ (1.2) for πN (NN) scattering.

Data[8-18] for the six reactions a, b, c, d, g, and h were fitted by a variation of the 28 parameters listed in Table I. The linear trajectories $\alpha_j(t)$ were constrained to pass through the correct spin at $t = m_j^2$. Known couplings were not allowed to differ drastically from their accepted values. The λ's were bounded so as not to lead to gross overabsorption of low partial waves. The one exception to this constraint, λ^π for photoproduction, is discussed below.

We fit cross-section data for $p_{\mathrm{lab}} \geq 5$ GeV/c excluding points for which $\theta \gtrsim \frac{1}{4}$ rad, e.g., $|t| \gtrsim 1$ at 8 Gev/c. [These restrictions result from the high-energy nature of the model, especially omission of lower trajectories and double Reggeon exchange cuts, and from small-angle approximations. Polarized-photon asymmetry data down to 3 GeV/c were included. The normalization of the $np \to pn$ cross-section data measured by a recent zero-gradient synchrotron experiment[17] is larger by about a factor of 2 than that of Manning et al.[16] Fitting all the reactions considered here with a single set of parameters is possible only if the higher normalization is accepted. The parameter values used in obtaining the fits shown in Fig. 1 are given in Table I.

There are several qualitative features of these

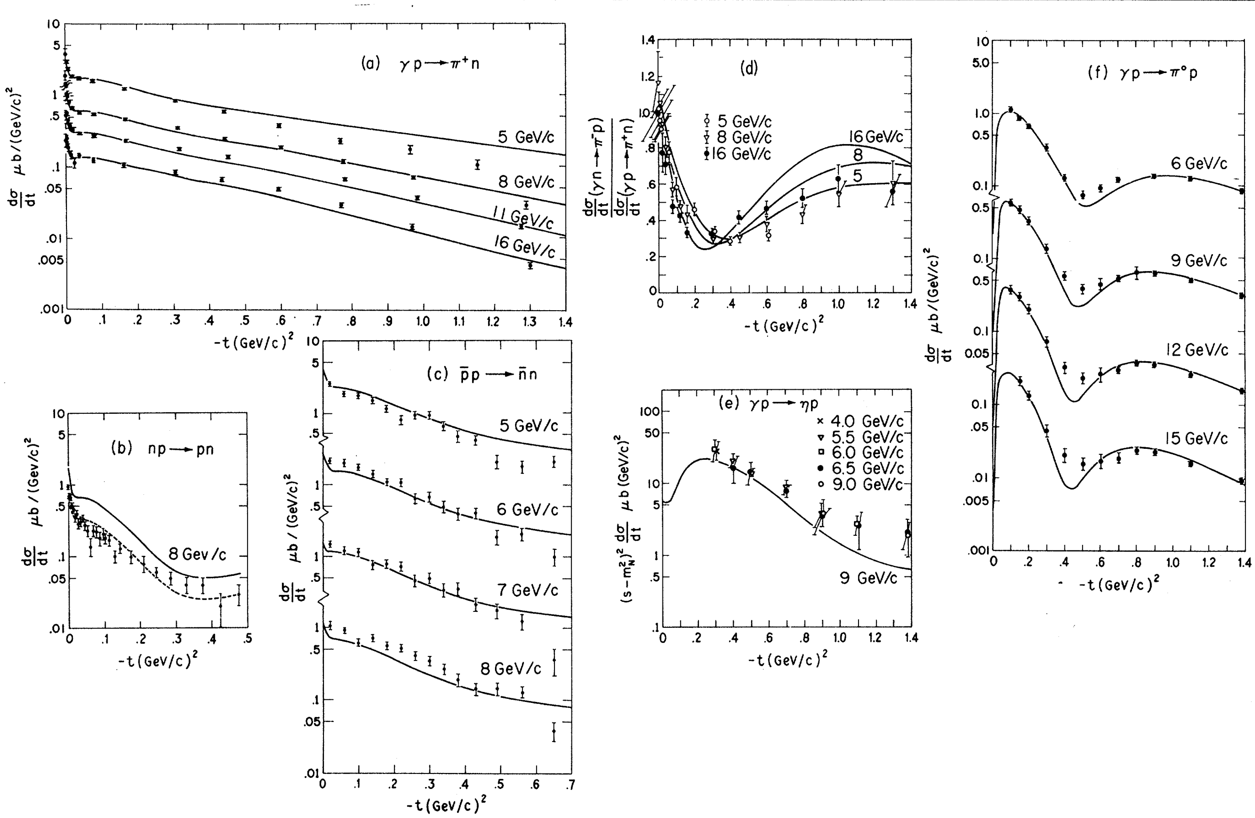

FIG. 1. Fits to data obtained from the following sources: (a), (d) Boyarski *et al.*, Ref. 8; Heide *et al.*, Ref. 9. (b) Manning *et al.*, Ref. 16, solid curve agrees with the normalization of Miller *et al.*, Ref. 17. Dotted curve is drawn a factor of 2 smaller to coincide with the normalization of Manning *et al.* (c) Astbury *et al.*, Ref. 18. (e), (f), Anderson *et al.*, Ref. 13.

fits which call for discussion. The sharp forward spike in charged photoproduction and baryon-baryon charge exchange is explained by interference between the $(n, x) = (0, 2)$ π-exchange pole and cut. The cut is approximately flat and the pole drops to zero at $t=0$ over a range in t of roughly m_π^2. This mechanism has been widely discussed.[4,25,26] It is also well known that polarized-photon asymmetry is correctly described by such a mechanism.[1]

Fitting the magnitude of the forward cross section for charged photoproduction requires $\lambda^\pi = 3.55$. This gives rise to gross overabsorption of the amplitude in the lowest partial wave: $M = (1-\lambda/1.6)M^P \simeq -1.3M^P$. In the parametrization used here it has been assumed that the inelastic contribution to the cut has the same t dependence as the elastic. We are in the process of considering the alternative assumption that the important inelastic states are peripheral.[7] Preliminary results indicate that the predictions of the model are not greatly altered, while a satisfactorily small amplitude is obtained in the lowest partial wave.

Note also that no feature of the data is clearly characteristic of A_2 exchange. We suspect that A_2 parameters, like λ_π, were adjusted to compensate for inadequacies of the model. Certainly the large value for $G_A{}^T/G_A{}^V$, if taken seriously, implies a dip near $t = -0.6$ in $\pi^- p \to \eta n$, which is not observed.

The difference in differential cross sections $d\sigma(\gamma p \to \pi^+ n)/dt - d\sigma(\gamma n \to \pi^- p)/dt$ is proportional to the ρ-exchange amplitude. This amplitude is predominantly nucleon helicity flip. Since there is one unit of helicity flip at the $\gamma \to \pi$ vertex, the $n=0$ and 2 amplitudes dominate the difference, and there is no structure near $-t = 0.6$ GeV/c^2. This is in contrast to conventional Regge-pole models in which there is a single or double "nonsense" zero near $-t = 0.6$ in the ρ-exchange amplitude, depending on the model. The addition of absorptive cuts to such models, unless they are very strong, does not change this prediction. The data (Fig. 2) at the satisfyingly high energy of 16 GeV/c shows smooth behavior near $-t = 0.6$, in strong disagreement with the existence of "nonsense wrong-signature zeros." Similar re-

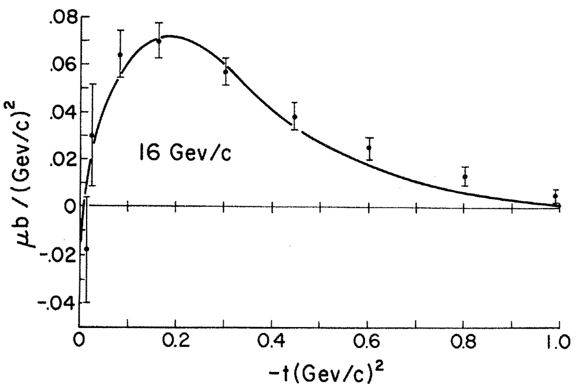

FIG. 2. Difference between π^+ and π^- photoproduction cross sections, which is proportional to the ρ-exchange amplitude.

marks apply to the difference $d\sigma(np\to pn)/dt - d\sigma(\bar{p}p\to\bar{n}n)/dt$, but the data available are not yet adequate to test the predictions.

The dip in the π^0 photoproduction cross section near $t=-0.5$ results from dominance of the $n=1$ amplitude. The strikingly different shape of the η-photoproduction cross section follows from the relative sizes of the ω and ρ exchange couplings for that process. Since there is one unit of helicity flip at the $\gamma\to\pi^0$ and $\gamma\to\eta$ vertices, the nucleon helicity-nonflip amplitudes for π^0 and η photoproduction have $n=1$. We expect that π^0 photoproduction is dominated by ρ exchange. The ωNN coupling is primarily helicity nonflip so π^0 photoproduction is dominated by the $n=1$ amplitude which has a zero near $t=-0.6$. The ρNN coupling is primarily helicity flip so η photoproduction is dominated by the $n=0$, 2 amplitudes which do not lead to dips near $t=-0.6$. Conventional Regge-pole models would yield a dip near $t=-0.6$ in η photoproduction.

A general discussion of π exchange processes is contained in Ref. 7.

We would like to thank the Michigan State University Cyclotron Laboratory for providing computer time for the initial phase of this work.

---

*Research supported in part by the U. S. Atomic Energy Commission.

†Research supported in part by the National Science Foundation and a University of California at Los Angeles computer grant.

[1]F. Henyey, G. L. Kane, J. Pumplin, and M. H. Ross, Phys. Rev. 182, 1579 (1969). Some of these data have been described with a similar model by A. Kaidalov and S. Karnakov, Phys. Lett. 29B, 372, 376 (1969); and by G. Benfatto, F. Nicolo, and G. Rossi, Lett. Nuovo Cimento 1, 537 (1969).

[2]D. R. Richards and G. L. Kane, "Meson-Baryon Scattering by Vector and Tensor Meson Exchange" (to be published).

[3]R. L. Kelly, G. L. Kane, and F. Henyey, Phys. Rev. Lett. 24, 1511 (1970).

[4]R. C. Arnold, Phys. Rev. 153, 1523 (1967).

[5]G. Cohen-Tannoudji, A. Morel, and H. Navlet, Nuove Cimento 48A, 1075 (1967).

[6]V. N. Gribov, Zh. Eksp. Teor. Fiz. 53, 654 (1967) [Sov. Phys. JETP 26, 414 (1968)].

[7]M. Ross, F. S. Henyey, and G. L. Kane, "On the Structure of High Energy Two Body Non-Diffractive Reactions" (to be published).

[8]A. M. Boyarski *et al.*, Phys. Rev. Lett. 20, 300 (1968), and 21, 1767 (1968).

[9]P. Heide *et al.*, Phys. Rev. Lett. 21, 248 (1968).

[10]C. Geweniger *et al.*, Phys. Lett. 28B, 155 (1968), and 29B, 41 (1969).

[11]H. Burfeindt *et al.*, as reported by K. Lübelsmeyer in *Proceedings of the Fourth International Symposium on Electron and Photon Interactions at High Energies, Liverpool, England, 1969*, edited by D. W. Braben (Daresbury Nuclear Physics Laboratory, Daresbury, Lancashire, England, 1970).

[12]Z. Bar-Yam *et al.*, reported by Lübelsmeyer, Ref. 11.

[13]R. Anderson *et al.*, Phys. Rev. Lett. 21, 479 (1968), and Phys. Rev. D 1, 27 (1970). Data shown in Fig. 1 [as contributed to the International Conference on High Energy Physics, Kiev, U. S. S. R., 1970 (to be published)] include both some new data and previously published data which have been reanalyzed using the measured Compton-scattering cross section. Note that the dips in these new data no longer disappear at high energy. We wish to thank J. Johnson for communicating these new results to us.

[14]D. Bellinger *et al.*, Phys. Rev. Lett. 23, 540 (1969).

[15]G. C. Bolon *et al.*, reported by Lübelsmeyer, Ref. 11.

[16]G. Manning *et al.*, Nuovo Cimento 41, 167 (1966).

[17]E. L. Miller, M. Elfield, N. W. Reay, N. R. Stanton, M. A. Abolins, M. T. Lin, and K. W. Edwards, Bull. Amer. Phys. Soc. 15, 660 (1970); N. R. Stanton, private communication.

[18]P. Astbury *et al.*, Phys. Lett. 22, 537 (1966), and 23, 160 (1966).

[19]J. Frøyland and D. Gordon, Phys. Rev. 177, 2500 (1969).

[20]J. D. Jackson and C. Quigg, Phys. Lett. 29B, 236 (1969).