"Recoil Effects" in a Model of Higher Baryon Couplings. I. Photoproduction

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(Received 12 April 1971)

A recently proposed model (MM) of higher baryon couplings for P and V mesons is reformulated by reviewing the fuller possibilities of the "recoil term" in the primitive quark-meson interaction. While this introduces no basic change in the P-meson coupling structures, it yields an entirely new $(L-1)$-wave coupling of V mesons to $J=L+\frac{1}{2}$ baryons, which is capable of generating helicity-flip amplitudes. The advantage of this new coupling structure over the earlier one is demonstrated through the excellent reproduction of (i) the $E1$ angular distribution in $Y^* \to \Lambda\gamma$ decay and (ii) the appreciable magnitudes as well as energy variations of the asymmetry parameter $\Sigma(\theta)$ in pion photoproduction. In addition to a comparison of the two coupling structures (old and new), the present paper is also designed to study the role of still another parametric structure for the form factor – one which exhibits better convergence properties at higher energies than those discussed in MM. The additional processes studied in this connection are (i) η and X_0 photoproduction at intermediate energies (>2 GeV), (ii) polarization of the recoil proton in η and π photoproduction, and (iii) π^0 photoproduction at high energies (~ 6 GeV), in accordance with our earlier scheme of s-channel resonances. In connection with η photoproduction the roles of some pertinent $I=\frac{1}{2}$ resonances such as S_{11}, P_{11}, and G_{17} are discussed, especially in relation to supermultiplet assignments.

I. INTRODUCTION

Recently, a general relativistic coupling scheme[1,2] was suggested by one of us (A.N.M.) for baryon resonances (B_L), which in turn are classified according to the $(56, 2L^+)$ and $(\underline{70}, (2L+1)^-)$ representation of $SU(6)\times O(3)$.[3] In this model, the coupling structures are of the multiple-derivative type connecting Dirac fields with generalized Rarita-Schwinger fields, and the geometrical factors multiplying the various coupling terms correspond to certain form factors for each supermultiplet transition and are given suitable parametrizations so as to conform to a set of general requirements.[4] So far, three different types of form factors[5] have been suggested within this framework, so as to satisfy the above "requirements" in varying degrees, keeping in mind the fits to observed decay patterns. We shall refer to these form factors as I,[1] II,[4] and III,[5] in the chronological order of their introduction. One seeks to connect the structures of the $\bar{B}B_L P$ and $\bar{B}B_L V$ couplings in all these cases via the requirement of partial symmetry or[6] a chiral $SU(3)\times SU(3)$ at the level of $\bar{Q}MQ$ ($M=P, V$) interactions. Two recent applications of this formalism to several aspects of the processes $\gamma N \to \pi N$[7] and $\pi N \to \rho N$,[8] which have been made with I and II, show that they can indeed fit the data quite well, II giving a somewhat better fit than I. Since the general formalism has been worked out in sufficient detail in these two papers, we shall refer to them as MM[7] and SG,[8] respectively, and make free use of their results.

The above coupling scheme, which is fairly unambiguous for the $(L+1)$ wave, has had to be supplemented by additional assumptions for the $(L-1)$ wave, which corresponds in this formalism to the lower-rank terms in the Clebsch-Gordan expansion of the product of orbital and spin components and nearly always involves the multiplying factor $\vec{k}^2$ ($\vec{k}$ being the 3-momentum of the radiation quantum in the c.m. frame of the resonance). In order to simulate the correct threshold behavior for the $(L-1)$ wave, the ansatz used so far has been the replacement $\vec{k}^2 \to k_\mu k_\mu$, where the right-hand side in turn has been replaced by a quantity equal to the square of the meson mass (as in form factor I), or is proportional to the square of the mass of the axial-vector counterpart (as in form factor II). One disadvantage of this prescription appears to be that the $(L-1)$-wave coupling does not generate a helicity-flip amplitude which is important for reproducing certain observed angular distributions such as in the process $K^- p \to Y^* \to \Lambda\gamma$,[9] which indicates an almost pure $E1$ transition for the electromagnetic decay of Y^*.

In this paper we extend the earlier model by reformulating the $(L-1)$-wave part of the coupling. For this purpose we review the role of the recoil term[10] in the primitive $\bar{Q}MQ$ interaction from the following point of view. The $(L+1)$-wave couplings of both pseudoscalar and vector mesons will be assumed to be generated entirely via the "direct term" within the partial-symmetry framework, but the terms of lower rank in J, generated with this formalism by the $(L-1)$-wave coupling will now be dropped in favor of a direct parametrization generated entirely by the recoil term in the primitive interaction. Effectively, this will mean an independent parametrization for the $(L-1)$-wave $\bar{B}B_L P$ coupling, unlike the earlier formulation which sought to achieve this more economically through the replacement $\vec{k}^2 \to k_\mu k_\mu$. However, we now hope to incorporate certain additional features, especially helicity-flip structures in the coupling, for the price of an extra parametrization in the $(L-1)$ wave. Indeed, such a parametrization can be made comprehensive enough to incorporate both the $\bar{B}B_L P$ and $\bar{B}B_L V$ sets via the partial-symmetry[6] requirement in the recoil term, as was done in the earlier corresponding formulation with the direct term. However, to avoid duplication, we shall follow the original recipe of Mitra and Ross,[10] viz., to parametrize the entire $(L+1)$-coupling structure via the direct term alone and the entire $(L-1)$-wave structure through only the recoil term. More specifically, we shall (i) ignore the various $\bar{B}B_L M$ couplings in the $(L+1)$ wave via the recoil term and (ii) drop the $(L-1)$-wave terms in the corresponding couplings generated by the direct term. Thus, we will have two sets of supermultiplet form factors for the $\bar{B}B_L M$ couplings, the $(L+1)$-wave terms being kept as before and the $(L-1)$-wave terms replaced by the new structure. Guidelines for the form factors in the new coupling scheme of course will be provided from the earlier results. The new $\bar{B}B_L V$ couplings for $J=L+\frac{1}{2}$ states in the $(L-1)$ wave will now be found to generate helicity-flip structures, which were missing in the earlie. calculation.

In this paper we will consider the following applications of this extended formalism: (1) angular distribution of the process $K^- p \to Y^* \to \Lambda\gamma$, (2) photoproduction of η and X_0 mesons, (3) polarization and asymmetry in pion photoproduction.

For the second and third processes we shall continue to keep to the duality spirit of MM on pion photoproduction, by including only s-channel resonances such as was done by Dikmen,[11] rather than use an interference model[12] or the one including the partial effect of the t or u channel suggested by comparison with the Veneziano model.[13] Our basic motivation still remains the same as in MM, viz. to study the role of the coupling structures and a comparison of the off-shell effects of the form factors, through a consideration of s-channel resonances up to ~2 GeV. However, in the pion-photoproduction case, the comparison with data will be extended to ~6 GeV as a probe for possible duality effects[14] whose meaning still retains its earlier flexibility. As to the problems of gauge invariance, our point of view has already been stated in MM.

In Sec. II we give the formalism for the recoil term, summarize the structure of the new set of $(L-1)$ wave couplings, and give necessary formulas of the photoproduction amplitudes for calculations. Section III gives the photon angular distribution in the process $K^- p \to Y^* \to \Lambda\gamma$. Section IV is concerned with the input data on $I=\frac{1}{2}$ resonances and their supermultiplet assignments, in terms of which the results on η and X_0 photoproduction are described in Sec. V. Section VI contains the results of polarization and asymmetry in pion photoproduction as well as differential cross sections at higher energies up to ~6 GeV. Section VII gives a summary of our main conclusions, and a comparison with related approaches.

II. FORMULATION OF "RECOIL" COUPLINGS

As described in Ref. 15, the complete structure of the $\bar{Q}QP$ vertex for emission of a P meson is of the form

$$f_q \sum_{\alpha=0}^{8} \sum_{i=1}^{3} \mu_\alpha{}^{-1} \vec{\sigma}^{(i)} \cdot \left(\vec{k} - \frac{\omega}{M_Q}\vec{p}_i\right) \lambda_\alpha^{(i)} \pi_\alpha, \tag{2.1}$$

where the recoil contribution represented by the second term (associated with the momentum p_i of the quark) is obtained from the direct term merely by the replacement

$$\vec{k} \to \vec{k} - \frac{\omega}{M_Q}\vec{p}_i, \tag{2.2}$$

which preserves Galilean invariance. It is clear that the same recipe is applicable to the more general $\bar{Q}MQ$ ($M=P$ or V) coupling, whose complete expression generated by the direct coupling alone is given according to partial symmetry by the M matrix[1]

$$M_{\text{dir}} = -i(\vec{\pi}\cdot\vec{\tau})\sigma_i q_i - i\epsilon_{ijk}\sigma_i q_j(\vec{\rho}_k\cdot\vec{\tau} + \omega_k \hat{1}) - m_\rho \vec{\rho}_0\cdot\vec{\tau} - m_\omega \omega_0 \hat{1}, \tag{2.3}$$

where the first term represents the pion coupling and the second and third group of terms represent the V-meson couplings of "magnetic" and "minimal" type, respectively. Now making the replacement (2.2) in the derivative terms (proportional to $\vec{k}$) of Eq. (2.3), the partial-symmetry structure of the M matrix arising from pure recoil effects may be expressed as

$$M_{\text{rec}} = \frac{\omega_k}{M_Q}[i(\vec{\pi}\cdot\vec{\tau})\sigma_i p_i + i\epsilon_{ijk}\sigma_i p_j(\vec{\rho}_k\cdot\vec{\tau} + \omega_k\hat{1})], \tag{2.4}$$

which incorporates the necessary geometrical connections among the P and V terms at the primitive (quark) interaction level. Note that the mass terms in Eq. (2.3), which are not proportional to momenta, do not have recoil counterparts. The rest of the procedure for a fresh deduction of the coupling structures arising from the recoil term is exactly the same as before,[1,2] except that we have now two independent sets of overlap integrals for the $(L+1)$ and $(L-1)$ wave, respectively. However, as mentioned in Sec. I we shall ignore the $(L+1)$-wave terms arising from the recoil effect in order to avoid duplication with the direct terms. For the $(L-1)$ wave the overlap integral between two supermultiplet wave functions ψ_0 and ψ_L is of the form[2]

$$-\int \psi^{\dagger}_{LM}(p',p'')(\tfrac{2}{3})^{1/2}\vec{p}''\psi_0(\vec{p}',\vec{p}''+(\tfrac{2}{3})^{1/2}\vec{k})dp'dp'', \tag{2.5}$$

which can be expressed as

$$f_L(k^2)B^{LM}_{\alpha_1,\alpha_2,\ldots,\alpha_L}(k_{\alpha_2}\cdots k_{\alpha_L}), \tag{2.6}$$

where f_L is a scalar function of $\vec{k}^2$ involving no threshold factors and $B^{LM}_{\alpha_1,\alpha_2,\ldots,\alpha_L}$ is an irreducible spherical tensor of rank L. The free index α_1 in Eq. (2.6) gets contracted with the correct index arising from the spin structures which have one of the following forms:

$$i\chi^{\dagger}\sigma_{\alpha_1}\chi, \quad i\chi^{\dagger}\chi_{\alpha_1} \tag{2.7}$$

and

$$-\chi^{\dagger}i(\sigma\times\rho)_{\alpha_1}\chi, \quad \chi^{\dagger}i\epsilon_{\alpha\alpha_1\gamma}\rho_{\gamma}\chi_{\alpha} \tag{2.8}$$

for the P and V mesons, respectively, and χ (χ_i) is the Pauli (Rarita-Schwinger) spinor (nonrelativistic).

The remaining manipulation for obtaining couplings between definite J states can be made exactly as in Ref. 2 to finally obtain the following types of couplings (after effecting the necessary relativistic boost) which are all related geometrically.

(a) $\bar{B}B_LP$ couplings:

$$(q)^{L-1}i\chi^{\dagger}\sigma_{\alpha_1}\chi\otimes B^{LM}_{\alpha_1,\ldots,\alpha_L}\Rightarrow\left(\frac{2L+1}{L}\right)^{1/2}\bar{\psi}iq_{\mu_2}\cdots q_{\mu_L}\psi^{L-1/2}_{\mu_2,\ldots,\mu_L} \tag{2.9}$$

and

$$(q)^{L-1}i\chi^{\dagger}\chi_{\alpha_1}\otimes B^{LM}_{\alpha_1,\ldots,\alpha_L}\Rightarrow\left(\frac{2(2L+1)}{L(L+1)}\right)^{1/2}\bar{\psi}iq_{\mu_2}\cdots q_{\mu_L}\psi^{L-1/2}_{\mu_2,\ldots,\mu_L}+\left(\frac{2(L-1)(2L+1)}{L(L+1)(2L-1)}\right)^{1/2}q_{\mu_3}\cdots q_{\mu_L}\bar{\psi}\gamma_5\gamma q\psi^{L-3/2}_{\mu_3,\ldots,\mu_L} \tag{2.10}$$

(b) $\bar{B}B_LV$ couplings:

$$-ik_{\alpha_2}\cdots k_{\alpha_L}\chi^{\dagger}(\sigma\times\epsilon)_{\alpha_1}\chi\otimes B^{LM}_{\alpha_1,\ldots,\alpha_L}$$

$$\Rightarrow k_{\mu_2}\cdots k_{\mu_L}\bar{\psi}\epsilon_{\mu_1}\psi^{L+1/2}_{\mu_1,\ldots,\mu_L}+\frac{L+1}{[L(2L+1)]^{1/2}}\bar{\psi}i\gamma_5\gamma\cdot\epsilon(k_{\mu_2}\cdots k_{\mu_L})\psi^{L-1/2}_{\mu_2,\ldots,\mu_L}-i\frac{L-1}{[L(2L+1)]^{1/2}}\bar{\psi}\epsilon_{\mu_2\beta\gamma\rho}k_{\beta}\epsilon_{\gamma}\gamma_{\rho}k_{\mu_3}\cdots k_{\mu_L}\psi^{L-1/2}_{\mu_2,\ldots,\mu_L} \tag{2.11}$$

and

$$\chi^{\dagger}\epsilon_{\alpha\beta\gamma}\epsilon_{\gamma}k_{\alpha_2}\cdots k_{\alpha_L}\chi_{\alpha}\otimes B^{LM}_{\beta\alpha_2,\ldots,\alpha_L}\Rightarrow 0 \tag{2.12}$$

for $S=\frac{1}{2}\to\frac{1}{2}$ and $\frac{3}{2}$, respectively, for both the cases.

In all these expressions on the right-hand side we shall henceforth divide by the factor $[(2L+1)/L]^{1/2}$ in order to normalize the spin part of the $P\bar{B}B_L$ couplings for the $J=L-\frac{1}{2}$ to $J=\frac{1}{2}$ transitions to unity. It should be noted that for the $\bar{B}B_LP$ couplings the present coupling scheme does not introduce any new structure, except for a change in the coupling constant for the $(L-1)$ wave. For the $\bar{B}B_LV$ couplings, however, the first term of Eq. (2.11) represents a new structure not contained in the (earlier) list [(A)–(D)] given in MM, generated via the direct term. We designate this interaction, henceforth, as type (E):

$$\text{(E)}\qquad \bar{\psi}\epsilon_{\mu_1}\psi^{L+1/2}_{\mu_1,\ldots,\mu_L}(k_{\mu_2}\cdots k_{\mu_L}), \tag{2.13}$$

which now connects a $J=L+\frac{1}{2}$ state to a BV system mainly in a helicity-flip manner.

To summarize, the complete set of $\bar{B}B_LM$ $(M=P,\ V)$ couplings to be used in the new coupling scheme are

(1) only the $(L+1)$-wave parts of the $\bar{B}B_LM$ interactions listed in MM;

(2) the $(L-1)$-wave parts [Eqs. (2.9)–(2.12)] of the same interaction as derived in this section.

As to the question of gauge invariance, type (E) coupling can be made formally gauge invariant through the modification

$$\epsilon_{\mu_1} \to \epsilon_{\mu_1} - k_{\mu_1}(P+p)\cdot\epsilon/(P+p)\cdot k, \tag{2.14}$$

where P_μ is the 4-momentum of the resonance. However, the second term gives no contribution to processes in which a real photon is involved. On the other hand, its effect is nontrivial when the photon is involved in a virtual state, e.g., in a calculation of electromagnetic masses.[16]

Form Factors

Since our primary aim is to study the role of the form factors multiplying the various coupling structures, it is also of interest to compare the new $(L-1)$-wave coupling scheme with the earlier version. Keeping these points in mind, we henceforth designate the earlier and present coupling schemes for the $(L-1)$ wave by the subscripts α and β, respectively. Further, the words "old" and "new" form factors used in MM, will now be replaced by the symbols I and II, respectively. In this notation the form factors used in MM will be renamed as I_α and II_α standing for the old coupling scheme. Further, we introduce the symbol II_β, where the subscript (β) stands for the present coupling scheme and the form factor is still given by II for the $(L-1)$ wave, except for a trivial adjustment for the differences in normalization. Indeed, the II_β version differs from II_α merely to the extent of absorbing a factor $[L/(2L+1)]^{1/2}$ in the definition of g_L for the $(L-1)$ wave. However, the $V\bar{B}B_L$ couplings in the II_β version are controlled by the geometrical ratios implied in Eqs. (2.9)–(2.12) and are now different from the corresponding ratios in the earlier version of the $(L-1)$ wave. In addition we shall use still another form factor which we shall call III_β (or III), implying that only the (β) version of the $(L-1)$-wave scheme is being used for it. This form factor whose motivations and results are reported separately[5] has the following structure:

$$\left(\frac{\mu}{m\pi}\right)^{1/2}\left(\frac{2S_F(Mm)^{1/2}(J)^{1/4}}{-p^2-q^2-P^2}\right)^{L+1,L}\left\{C_L^+;\frac{m_A{}^2}{m_{A_1}}C_L^-\right\} \tag{2.15}$$

for the $(L\pm1)$ waves, respectively, where s_F is a scale factor adjusted from absolute decay rates to a value 1.26; P_μ, p_μ, and q_μ stand for the 4-momenta of the parent, daughter hadrons, and the P (or V) meson, respectively; μ is the mass of the appropriate meson P (or V); m_A and m_{A_1} the masses of the axial-vector counterparts of the P (or V) meson and A_1 meson, respectively; and M and m are the masses of the resonance and the baryon, respectively.

We add a word about the off-shell extension of the various momenta involved in the form factors. While we take the off-shell value $-P^2$ for the resonance and of course the on-shell value $+m^2$ for the nucleon, there is a slight ambiguity about the value to choose for the momentum of the vector meson, whose values should strictly be taken as $m_V{}^2$ and zero (appropriate to the mass of the photon) on and off the V-meson mass shell, respectively. Fortunately, in this calculation (also in MM) the numerical difference in these two recipes is negligible. However, one can expect much higher differences in processes where the photon is virtual, e.g., electromagnetic mass differences.[16]

Finally, the vector dominance[17] as described in MM provides the mechanism for the photon couplings to $\bar{B}B_L$ currents. Also, the kinematical structure of the photoproduction amplitude as given in MM continues to be valid for this investigation on η, X_0, and π photoproduction as well as for the formulas for differential cross section, total cross section, and polarization of recoil proton. However, we record here the formula for the asymmetry parameter $\Sigma(\theta)$ of linearly-polarized incident photons, which was not discussed in MM.

In a coordinate system with $\vec{k}$ (photon momentum) along the z axis, $\vec{q}$ (meson momentum) in the xz plane, and $\phi=0$, $\vec{k}\times\vec{q}$ in the direction of the y axis, linearly-polarized photons with electric vectors perpendicular and parallel to the production plane have polarization vectors $\epsilon_\perp$ and $\epsilon_\parallel$ given by

$$\epsilon_\perp=\hat{e}_y,\quad \epsilon_\parallel=\hat{e}_x \tag{2.16}$$

so that the polarized-photon asymmetry parameter $\Sigma(\theta)$, defined by

$$\Sigma(\theta)=\frac{\sigma_\perp-\sigma_\parallel}{\sigma_\perp+\sigma_\parallel}, \tag{2.17}$$

works out as

$$\frac{d\sigma}{d\Omega}\Sigma(\theta)=-\frac{|\vec{q}^3|\sin^2\theta}{64\pi^2W^2|\vec{k}|}\,[-|A_4|^2(m^2+p_1\cdot p_2)+2|A_3|^2p_1\cdot kp_2\cdot k+2\mathrm{Re}A_3^\dagger A_4m(p_2-p_1)k$$
$$-2m\,\mathrm{Re}A_1^\dagger A_4-2p_1\cdot k(\mathrm{Re}A_2^\dagger A_4+\mathrm{Re}A_1^\dagger A_3)]\,. \tag{2.18}$$

Here $d\sigma/d\Omega$ is the unpolarized differential cross section, $p_{1\mu}$ and $p_{2\mu}$ are the 4-momenta of the initial and final nucleons, and the coefficients A_1–A_4 are defined by the general structure of the photoproduction amplitude, viz.,

$$M_{\pi\gamma}=\bar{u}(p_2)\gamma_5(A_1 i\gamma\cdot\epsilon+A_2\gamma\cdot k\gamma\cdot\epsilon+iA_3 q\cdot\epsilon\gamma\cdot k+A_4 q\cdot\epsilon)u(p_1)\,. \tag{2.19}$$

We conclude this section with a few remarks on the structure of our coupling scheme. Now it was found in MM that for the vector couplings of the (A), (B), and (C) types only the coefficients A_1 and A_2 survive, while the other two coefficients A_3 and A_4, which generate helicity-flip structures, receive contribution from only the (D)-type coupling, and hence in general are very small in magnitude. In the present coupling scheme β, however, we have an additional $(L-1)$-wave coupling [(E) type] for the $J=L+\frac{1}{2}$ state, and this makes significant contributions not only to A_1 and A_2, but to A_3 and A_4 as well. This feature of the (E)-type coupling will figure extensively in the subsequent sections.

III. ANGULAR DISTRIBUTION FOR $Y^*\to\Lambda\gamma$

As the simplest example of the new formalism for $(L-1)$-wave couplings, we consider the angular distribution of the process $K^-p\to Y^*\to\Lambda\gamma$, which is experimentally[9] known to be almost a $(5-3\cos^2\theta)$ distribution characteristic of an $E1$ transition. Assuming the process to be dominated by the $Y(1520)$ resonance, the $(L\pm1)$ $\bar{B}B_L V$ couplings of this particle are

$$f_V^+\frac{1}{\sqrt{2}}\,\bar{\psi}(i\sigma_{\mu\nu}k_\mu\epsilon_\nu+im_V\epsilon_\mu\gamma_\mu)k_{\mu_1}\psi_{\mu_1}{}^{3/2} \tag{3.1}$$

and

$$-f_V^-\frac{1}{\sqrt{6}}\,\bar{\psi}\epsilon_{\mu_1}\psi_{\mu_1}\,, \tag{3.2}$$

while the corresponding KNY^* coupling is

$$-(\tfrac{3}{2})^{1/2}f_\mu^+\bar{\psi}_{\mu_1}\gamma_5\gamma\cdot q q_{\mu_1}\psi\,. \tag{3.3}$$

The $\gamma Y^*\Lambda$ couplings can be worked in terms of the vector-dominance hypothesis[17]; the ρ contribution for this case being, of course, zero. The term (3.2) representing the $(L-1)$ wave comes from the present formalism and was absent in the treatment of MM.

Let the 4-momenta of the initial and final baryons be $p_{2\mu}(-\vec{p}_2, iE_2)$ and $p_{1\mu}(-\vec{p}_1, iE_1)$, respectively, and those of the photon (polarization ϵ_μ) and meson be $k_\mu(\vec{k}, ik_0)$ and $q_\mu(\vec{q}, iw_q)$, respectively. Let the initial and final baryon masses (unlike the case of pseudoscalar-meson photoproduction) be m and m', respectively. Further, since the resonance is sufficiently "long-lived," we shall take it on the mass shell, viz., $P^2=-M^2$.

The complete amplitude for this transition after some routine simplifications in the center-of-mass frame is proportional to

$$\bar{\psi}[f_V^+(i\sigma_{\mu\lambda}k_\mu\epsilon_\lambda+im_V\epsilon_\mu\gamma_\mu)(\vec{k}\cdot\vec{q}-\tfrac{1}{2}i\vec{\sigma}\cdot\vec{k}\times\vec{q})$$
$$-(i/\sqrt{3})f_V^-(\vec{q}\cdot\vec{\epsilon}-\tfrac{1}{2}i\sigma_{\lambda\nu}\epsilon_\lambda q_\nu)]\,\tfrac{1}{2}(1+\gamma_4)\gamma_5\psi\,, \tag{3.4}$$

a form which brings out the structure of $(L\pm1)$-wave terms explicitly and leads to the angular distribution

$$a(5-3\cos^2\theta)+b(1+3\cos^2\theta)+c(3+\cos^2\theta)\,, \tag{3.5}$$

where the constants a, b, and c depend on the Λ and photon energies as well as the form factors $f_V^\pm$. The a term arising from the (E)-type $(L-1)$-wave coupling gives a pure $E1$ transition and accounts for the major effect, while the small phase space is responsible for suppressing the $(L+1)$ wave as well as the interference contributions, represented by b (which gives a decay into a pure helicity-$\frac{1}{2}$ state distribution) and c, respectively. Indeed, the numerical estimates of the parameters a, b, and c for the form of factors II_β and III_β are as follows:

	a	b	c
II_β	3.16	0.0635	0.3357
III_β	1.123	0.012	0.0826

They yield the distributions $(5-2.51\cos^2\theta)$ and $(5-2.7\cos^2\theta)$, respectively. Both of these are in excellent accord with an observed,[9] almost pure $(5-3\cos^2\theta)$ distribution and a distinct improvement over the almost pure $\sin^2\theta$ or $(5-5\cos^2\theta)$ distribution from a quark-model calculation[18] using harmonic-oscillator wave functions. Unfortunately, this distribution could not be obtained in MM because of the absence of the (E)-type $(L-1)$-wave coupling which can be recognized to produce a pure $E1$ transition.

Further, the absolute decay width for the process $Y^*(1520)\to\Lambda\gamma$ turns out to be 0.189 MeV and 0.205 MeV with form factors II_β and III_β, respectively, as compared to the quoted experimental value 0.15 ± 0.03 MeV.[9] The above values are a fair improvement over that obtained by form factor II_α (0.0825 MeV)[7] as well as calculated by Copley *et al.*[18] (0.10 MeV). We would like to add that the interference between ω and ϕ mesons for the $\bar{B}B_L\gamma$ vertex according to vector dominance, makes a significant contribution in the determination of the above decay rate. The inclusion of the ϕ meson greatly improves the results.

IV. RESONANT STATES USED FOR η PHOTOPRODUCTION

In this section we consider the salient features of, and the input data for, η and X_0 photoproduction. The isoscalar structure of the η meson keeps out the Δ-type intermediate states from an s-channel calculation and therefore provides a comparatively cleaner mechanism for the study of mixing effects in certain N^* resonances, especially the S_{11} states. Some of the salient experimental features of η photoproduction are

(1) The total cross-section (σ_T) curve[19,20] shows a sharp peak just above threshold, presumably representing the effect of the $S_{11}(1525)$ resonance which has a large $N\eta$ coupling. This identification is confirmed by the near isotropy of the differential cross section $d\sigma/d\Omega$ around this energy.[21]

(2) This peak is followed by a fairly sharp dip in both σ_T and $d\sigma/d\Omega$ (Refs. 19, 22, 23), which is presumably the result of interference between S_{11} and P_{11} resonances.

(3) The next structure shows up as a fairly broad maximum in the $d\sigma/d\Omega$ around 1.15 GeV,[24] which is believed to be the effect of $P_{11}(1750)$ with possible interference from $S_{11}(1710)$.

(4) Again, around 2 GeV, the differential cross-section curve shows a marked increase in the forward direction, possible candidates for which effect can be $G_{17}(2190)$ or $D_{13}(2030)$.[24]

(5) Unlike pion photoproduction, the η differential cross section shows little structure as a function of angle.[25,26]

(6) A recent experiment[27] indicates considerable recoil-proton polarization effects at 90° from threshold to $W \approx 1700$ MeV, thus pointing to a sizable interference between two opposite-parity states, presumably S_{11} and P_{11}.

In order to study the above and related features systematically within our framework, we choose the input set of nucleon resonances which are listed in Table I together with their J values and $(L-1)$-wave $\bar{B}B_LP$ and $\bar{B}B_LV$ couplings (in the notation of MM) generated by the recoil term in couplings scheme β. [The direct-coupling scheme α as well as $(L+1)$-wave couplings for β can be read from Table I of MM.] The mixing angle δ between the actual η_1 and η_8 states for calculational purposes is taken as

$$\eta = \eta_8 \cos\delta + \eta_1 \sin\delta, \tag{4.1}$$

$$X_0 = -\eta_8 \sin\delta + \eta_1 \cos\delta, \tag{4.2}$$

with $\delta = 10.5° \pm 0.5°$, in conformity with the accepted value[28] of the parameter.

Of the N^* states listed in Table I we have also considered mixing between $S_{11}(1525)$ and $S_{11}(1710)$ states which are respectively taken as the orthogonalized states

$$S_{11}(1525) = \cos\theta_S\,(\underline{8}^q) + \sin\theta_S\,(\underline{8}^d), \tag{4.3}$$

$$S_{11}(1710) = -\sin\theta_S\,(\underline{8}^q) + \cos\theta_S\,(\underline{8}^d), \tag{4.4}$$

where the superscripts q and d refer to the quark spins $\frac{3}{2}$ and $\frac{1}{2}$, respectively. The angle θ_S is determined through a fit to the experimental decay ratios $N\eta/N\pi$ (Ref. 29) with the three form factors, the main problem being to reconcile the large $N\pi/N\eta$ ratio of ~23.3 for $N^*(1710)$ decay to the relatively small ratio of ~0.5 for $N(1550)$. The value obtained for θ_S works out nearly the same for all the form factors, at $\theta_S \approx 63° \pm 2°$. A second solution corresponding to $\theta_S \approx 4° \pm 2°$, which would essentially amount to putting $N(1550)$ in an almost pure

TABLE I. List of baryon resonances ($I=\frac{1}{2}$) used in calculation of η photoproduction, together with their $(L-1)$-wave $\bar{B}B_LP$ and $\bar{B}B_LV$ couplings generated via the recoil term, in coupling scheme β. δ is the mixing angle between the actual η_1 and η_8 states. Column 3 is still to be multiplied by P-meson coupling structures as defined in MM.

Resonance	J	$(L-1)$-wave $\bar{B}B_LP$ coupling	$(L-1)$-wave $\bar{B}B_LV$ coupling
1. $N(938)$	$L+\frac{1}{2}$	0	0
2. $P_{11}(1470)$	$L+\frac{1}{2}$	0	0
3. $P_{11}(1750)$	$L+\frac{1}{2}$	0	0
4. $S_{11}^d(1525)$	$L-\frac{1}{2}$	$(\frac{2}{3})^{1/2}\cos\delta + \frac{2}{\sqrt{3}}\sin\delta$	$\frac{2}{3}\sqrt{2}\,C(\frac{2}{3}C_\rho\tau_3 + C_\omega)$
5. $S_{11}^d(1715)$	$L-\frac{1}{2}$		
6. $D_{13}(1515)$	$L+\frac{1}{2}$	0	$(\frac{2}{3})^{1/2}E(\frac{2}{3}C_\rho\tau_3 + C_\omega)$
7. $D_{13}(1675)$	$L+\frac{1}{2}$	0	0
8. $D_{15}(1675)$	$L+\frac{3}{2}$	0	0
9. $P_{13}(1855)$	$L-\frac{1}{2}$	$\frac{1}{\sqrt{3}}\cos\delta + (\frac{2}{3})^{1/2}\sin\delta$	$\frac{1}{5}(3C-D)(\frac{5}{3}\tau_3 C_\rho + C_\omega)$
10. $F_{15}(1690)$	$L+\frac{1}{2}$	0	$(\frac{2}{5})^{1/2}E(\frac{5}{3}C_\rho\tau_3 + C_\omega)$
11. $G_{17}(2190)$	$L+\frac{1}{2}$	0	$(\frac{8}{21})^{1/2}E(C_\rho\tau_3 + \frac{3}{2}C_\omega)$

quartet state and $N(1710)$ in a pure d state,[15] is also compatible with the above experimental ratios. The value $\theta_S \approx 63° \pm 2°$ is in fair agreement with the harmonic-oscillator model[30] of $\theta = 35°$, remembering the correspondence $\theta_S = \frac{1}{2}\pi - \theta$. The solution $\theta_S \approx 4°$ was used in MM, but since the pion photoproduction amplitude receives a very small contribution from this state, the distinctions between the two solutions would hardly show up in that process. For the present $\gamma p \to \eta p$ process, however, the dominant contributors are the low partial-wave states like S_{11} and in this paper we choose the solution $\theta_S \approx 63° \pm 2°$, in keeping with the experimental result of a copious photoproduction of this state in relation to the Moorhouse selection rule.[31]

As for the $P_{11}(1750)$ resonance, we believe that its fairest assignment under our framework of $(\underline{56}, 2L^+)$ and $(\underline{70}, (2L+1)^-)$ structures is a radial excitation of $(\underline{56}, 0^+)$ [possibly this is a second excitation, the first being the Roper resonance, $P_{11}(1470)$]. Recently,[32] some doubt has been cast on this assignment in favor of $(\underline{70}, 0^+)$ through a comparison of the data with quark-model calculations using harmonic-oscillator wave functions; so we have included for this state both possibilities of $(\underline{70}, 0^+)$ and $(\underline{56}, 0^+)$ for an evaluation of its coupling to $N\eta$. The supermultiplet coupling constant (g_R) for this state just as for the Roper resonance, may be determined from its observed $N\pi$ width (~90–150 MeV)[29] for each of the three structures I, II, and III assumed for the form factors.

Another point of interest concerns the quark-spin

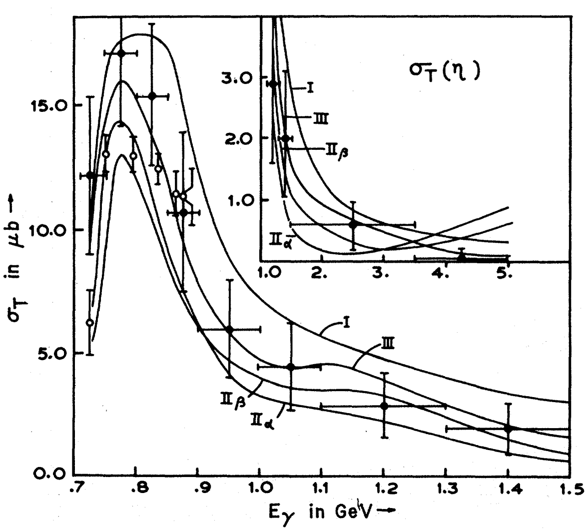

FIG. 1. Total cross section (σ_T) with form factors I_α, II_α, II_β, and III_β for the process $\gamma p \to \eta p$ as a function of lab photon energy (E_γ in GeV) compared with the data of (●) Ref. 19 and (O) Ref. 20. In the right-hand upper corner σ_T is compared with data of Ref. 19 from $E_\gamma = 1$ to 5 GeV.

assignments q or d of the state $G_{17}(2190)$, which has been claimed as a quartet[33] [possibly a Regge recurrence of $D_{13}(1675)$]. More recently, Feynman *et al.*,[34] using a new mass formula, arrived at the same conclusion. On the other hand, if this state is photoproduced (and the experimental information on this question is not yet unambiguous) then it should at least contain a substantial mixture of d[31] under quark-model assignments. In this paper we have kept both the d and q possibilities in mind in order to be able to make a more positive inference from the experimental data within the framework of our coupling scheme. This resonance presumably belongs to the $L = 3$ supermultiplet, so its coupling constant is automatically determined from Regge universality, viz., $g_1{}^2 = g_3{}^2$, for all the form factors considered.[35]

Finally, we have not considered the resonances $D_{13}(2030)$, $F_{17}(1983)$, and $D_{13}(1730)$ in our calculation, because experimentally their predictions are still very doubtful. As would be seen from the results in Sec. V, there seems to be no compelling reason to include these resonances.

V. RESULTS ON η PHOTOPRODUCTION

We give here the numerical results on η photoproduction in respect of (i) total cross section, (ii) energy and angular dependence of differential cross section, and (iii) polarization of the recoil proton. (For X_0 production only the total-cross-section data[19] are available for comparison.) Our main interest in this comparison is to check on two independent aspects of our model: (i) the role of the new coupling structure β described in this paper in relation to the earlier version α and (ii) a comparison of the quality of fits to the data obtained with the three different form factors with a view to discriminating between their parametric structures. Further, in order to explore numerically the quantitative aspects of duality,[14] we have extended the comparison on total cross sections to about 6 GeV, which is well beyond the "strict jurisdiction" of the resonance region (1–2 GeV) and bordering on the Regge domain (≳5 GeV). (This is not to claim that our model is automatically valid at high energy.)

The region of the first peak [mainly due to the resonance $S_{11}(1525)$ with some contribution from $P_{11}(1470)$ in the total-cross-section data[19,20]] seems to be well reproduced by the three form factors, as seen from Fig. 1. In the region of the second group of resonances ($E_\gamma = 1.0$–1.2 GeV) there seems to be little evidence for any structure in the total cross section, which is again well reproduced by all the form factors except I. The X_0 total cross section, which also agrees reasonably with experiment (Fig. 2),[19] shows some rise above the thresh-

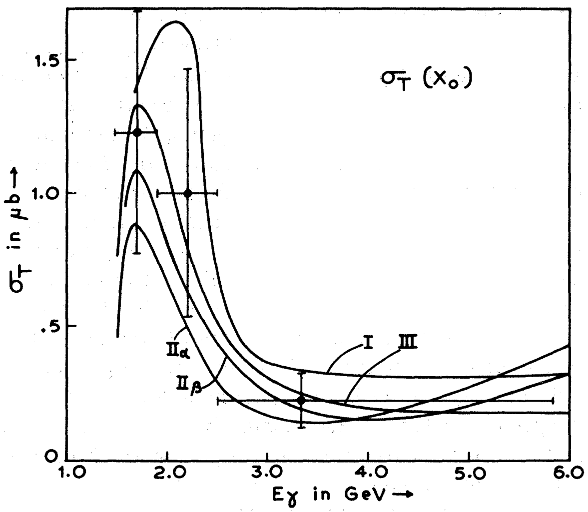

FIG. 2. Total cross section for the process $\gamma p \to X_0 p$ as a function of E_γ compared with the data of (●) Ref. 19.

old, followed by a rapid fall and later a gradual decrease at high energies. Thus the total-cross-section data do not seem to provide much discrimination on the details of our model.

A more discriminating test can be provided by the differential cross section (Fig. 3). Here, the form factor I seems to be already ruled out even on the basis of the first peak and the competition is really between II and III, with a slight edge to the latter. In the second resonance region (E_γ = 1–1.2 GeV), the coupling structure β predicts a slightly sharper peak than α, though the data are somewhat ambiguous on this point. The main contributors to this region are the resonances $P_{11}(1750)$ and the "doublet component" of $S_{11}(1710)$, while the small ηN couplings of the states $P_{13}(1855)$ and $F_{15}(1688)$ prevent them from playing a significant role in this region[32] and the Moorhouse selection rule[31] is responsible for the suppression of the $D_{13}(1675)$ and $D_{15}(1675)$ resonances, which are mainly quartet states. Finally, the 2-GeV region does not show much structure. As mentioned in Sec. IV, one point of interest is the quantum-number assignment of the G_{17} resonance. Our curves with form factors II and III, which have been calculated with the d assignment for this state, seem to be in good agreement with the data points[24] (Fig. 3), leading us to believe in the correctness of this assignment, considering the over-all performance of these two form factors. On the other hand, a similar calculation with the spin-quartet assignment for this state (which forbids its photoproduction off protons[31]) brings the theoretical curves (with both

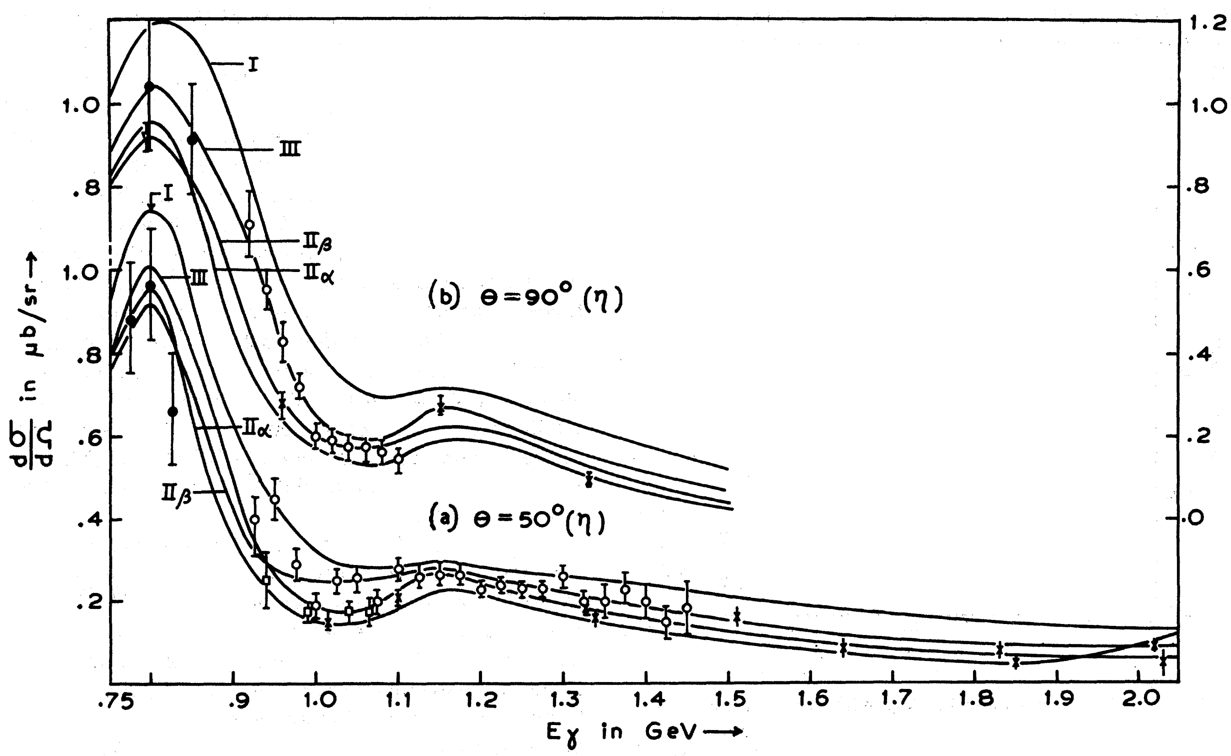

FIG. 3. Differential cross section for η photoproduction as a function of lab photon energy E_γ compared with the following experimental data: (●) Ref. 21, (○) Ref. 22, (□) Ref. 23, (×) Ref. 24, and (▽) Ref. 20, at $\theta = (50 \pm 10)°$ and $\theta = (90 \pm 10)°$ in (a) and (b), respectively. The vertical scale on the right-hand side is for the curves 3(b).

II and III) appreciably below the data points. This result seems to be in disagreement with the q assignment to this state by Feynman *et al.*[34] on the basis of Feynman's new mass formula.

The angular distribution (Fig. 4) shows little structure, in conformity with experiment[20-25] and in keeping with the dominance of the low partial-wave resonances. On the whole, the reasonably good agreement with the data for η photoproduction, demonstrates conclusively the importance of the "Weisskopf factor" $(m_\eta/m_\pi)^{1/2}$ in the form factors as well as the (E)-type $(L-1)$-wave coupling. Both of the above quantities contribute significantly to the numerical values for the process.

In passing, we would like to draw attention to the effect of the supermultiplet assignment of the $P_{11}(1750)$ resonance on the structure of the cross section in the second resonance region. The two assignments $(\underline{70}, 0^+)$ and a second radial excitation of $(\underline{56}, 0^+)$ seem to produce an almost imperceptible difference in the results for differential cross sections in this region, so that it is not possible to distinguish between the two possibilities. This result is in discord with the finding of Ref. 32 on the basis of the harmonic-oscillator model, and encourages us to persist in our interpretation of a second radial excitation of $(\underline{56}, 0^+)$ for this state,[3,36] independently of the details of a model as specific as the harmonic oscillator.[32] More discriminating evidence could come from an accurate diffraction experiment in this region,[32] which, however, does not seem to be in sight as yet.

Finally, in Fig. 5 we have compared the recoil-proton polarization at $\theta = 90°$ with experimental data.[27] Though the coupling schemes α and β give slightly different distributions, the data are too ambiguous for any conclusion to be drawn from them. A point to note is that the value of the polarization vector just above the threshold is comparatively small. This indicates once again that the $S_{11}(1525)$ state is the sole important contributor in this region, since any significant contribution from $P_{11}(1470)$, would have produced a larger value though interference of opposite-parity states. On the contrary, near $E_\gamma \sim 1.1$ GeV the value of the polarization vector is comparatively large, indicating a considerable S-P wave interference. Despite the inconclusive nature of the data, these general features do seem to be there.

VI. RESULTS ON PION PHOTOPRODUCTION

Since a detailed account of pion photoproduction within this model has been already given in MM, we shall confine this section to a few salient features on the process, viz., those which were not covered in the earlier analysis. Thus, we shall not discuss again the results on total cross section which are already in excellent agreement with the data for both form factors I and II and shall deal only with the high-energy features (2–6 GeV) of the

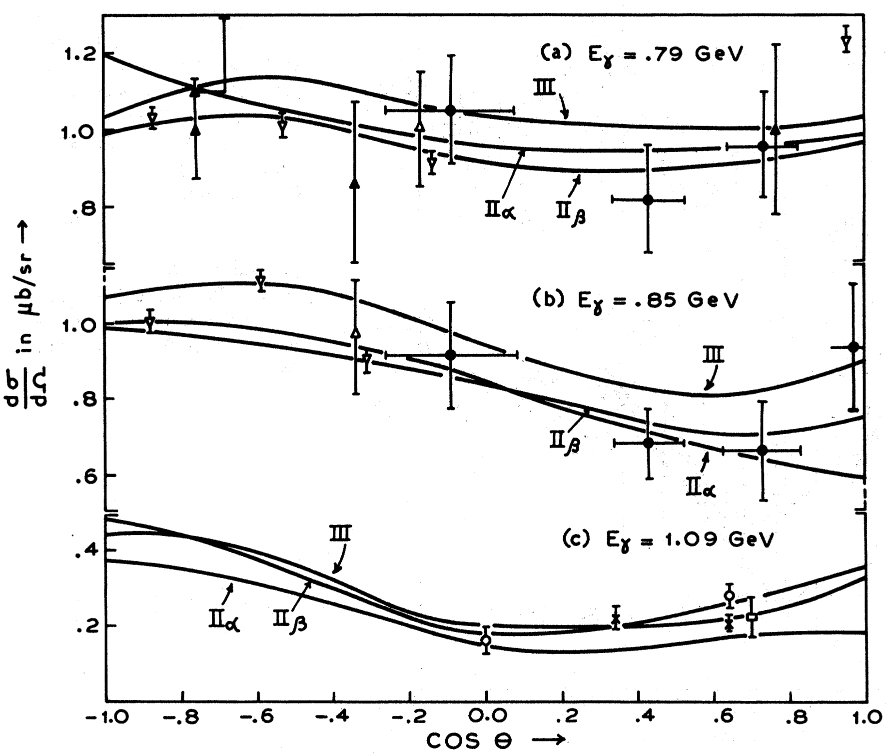

FIG. 4. Differential cross section for η photoproduction as a function of the c.m. angle θ at the indicated values of lab photon energy E_γ compared with the following experimental data: (▽) Ref. 20, (●) Ref. 21, (○) Ref. 22, (□) Ref. 23, (×) Ref. 24, (▲) Ref. 25, and (△) Ref. 26. The data are taken at $E_\gamma = 0.79 \pm 0.01$ GeV, $E_\gamma = 0.85 \pm 0.015$ GeV, and $E_\gamma = 1.09 \pm 0.05$ GeV in parts (a), (b), and (c), respectively.

differential cross section. The role of the form factor I will also not figure any more in this discussion. The main emphasis in this section will be on making a comparison between (i) the recoil-proton polarization $P(\theta)$ and (ii) the asymmetry parameter $\Sigma(\theta)$ due to linearly polarized photons, where much more accurate data are available than in the case of η photoproduction discussed in Sec. V. These comparisons should hopefully provide a more discriminating test of the relative roles of the coupling structures α and β and possibly also of the form factors II and III in the context of pion photoproduction.

Though a comparison with experimental data[37–43] of the recoil-proton polarization was already given in MM for the case of π^0 photoproduction with form factor II_α, we reproduce in Fig. 5 the results of similar calculations with the form factors II_β and III_β as well, in order to gain a further assessment of our coupling scheme. It is clear from a comparison between the curves II_α on one hand, and II_β, III_β on the other, that the coupling structure β gives much sharper dips and peaks than does α. This feature of our new coupling structure β is a direct result of the role of the (E)-type coupling which has the effects of providing appreciable helicity-flip amplitudes (a factor mainly responsible for producing the sharp peaks and dips) via the lower $(L-1)$ wave. This contrasts with the roles of (A)- and (B)-type couplings which operate in the higher $(L+1)$ wave and produce very small helicity-flip effects. While the data are not completely un-

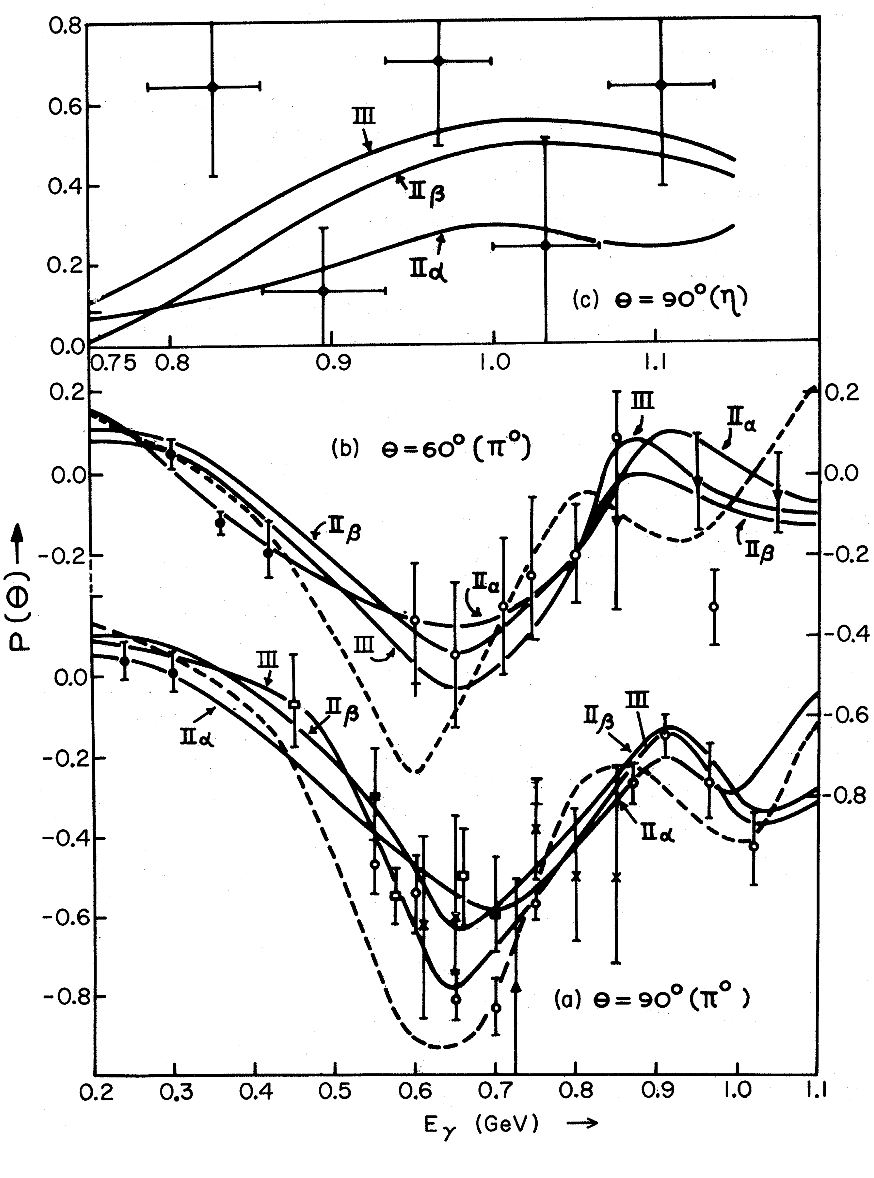

FIG. 5. Polarization of the recoil proton with form factors II_α, II_β, and III_β for the reactions $\gamma p \rightarrow \pi^0 p$ [(a) and (b)] and $\gamma p \rightarrow \eta p$ (c) as a function of E_γ at the indicated values of θ. The pion-photoproduction data are from (○) Ref. 37, (●) Ref. 38, (×) Ref. 39, (▲) Ref. 40, (□) Ref. 41, (■) Ref. 42, and (▼) Ref. 43, while the η photoproduction is from Ref. 27. The dashed curves in (a) and (b) are Walker's (Ref. 44). The right-hand side vertical scale is for the curves (b).

ambiguous (though much better than in the case of η photoproduction), it looks, especially near $E_\gamma \sim 0.7$ GeV region (Fig. 5), as though the "sharp feature" predictions of the coupling structure β (unlike those of α) are in rather good agreement with Walker's curve[44] (based on an analysis of experimental data) which is also reproduced for ease of comparison.

The asymmetry parameter $\Sigma(\theta)$, which is given by Eq. (2.18) is shown in Fig. 6 for the reactions $\gamma p \to \pi^0 p$ and $\gamma p \to \pi^+ n$ at $\theta = 90°$ using the form factors II_α, II_β, and III_β. This comparison brings out more directly the distinct superiority of the coupling structure β over α, as had also been seen (Sec. III) in connection with the angular distribution for the process $K^- p \to Y^* \to \Lambda\gamma$. The main experimental feature,[45-50] which seems to be well reproduced by the coupling structure β (not α), is an appreciable magnitude (~0.2–0.6) of the asymmetry parameter and its considerable fluctuations (~0.3) with energy. This feature is in turn brought about by the dominant contributions to $\Sigma(\theta)$ from helicity-flip amplitudes A_3 and A_4 [Eq. (2.19)] which, as mentioned in Sec. II, are significant for (E)-type coupling only. This result thus brings out rather directly the important role of the (E)-type coupling in relation to experiment. On the other hand, the data on $\Sigma(\theta)$ do not seem to discriminate much on the parametric structure of the form factors, in particular between II_β and III_β.

To attempt a more quantitative comparison between the form factors II_β and III_β, we have chosen to compare the energy distribution of the differential cross section for a convenient angle over a wider energy range (1–6 GeV) than was attempted in MM. A comparatively clean experimental curve for this process is provided by the data of Buschhorn *et al.*[51,52] for $\gamma p \to \pi^0 p$ at $\theta = 180°$. This is shown in Fig. 7 together with the form factors II_β and III_β, where we have included the two main resonances in the 2–2.5 GeV region, viz., $N^*\frac{7}{2}^-$ and $\Delta\frac{11}{2}^+$, over and above the list considered in MM, so as (hopefully) to extend the physical domain of the validity of this model. The curve III_β seems to reproduce reasonably well all the experimental features including the resonance peak at $E_\gamma \sim 2.5$ GeV and a reasonably rapid fall of the cross section at higher energies. On the other hand, the form factor II_β, though yielding a reasonable fit in the lower-energy region ($E_\gamma \approx 2.4$), shows a tendency to increase with energy beyond $E_\gamma > 4$ GeV, a feature distinctly ruled out by experiment.[53] The small disagreement between the theory and experiment for the form factor III in the region $E_\gamma \sim 4.0$ GeV is most likely due to our neglect of a few still-higher spin resonances, e.g., $N\frac{13}{2}^-$, $\Delta\frac{15}{2}^+$, $N\frac{17}{2}^-$, and $\Delta\frac{19}{2}^+$.

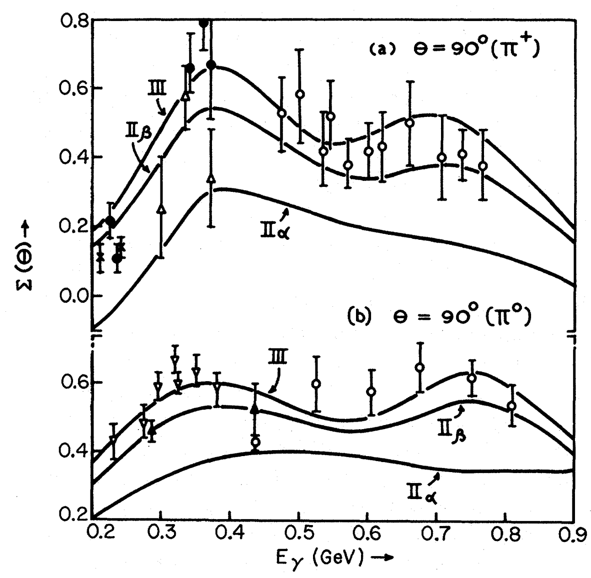

FIG. 6. Asymmetry for linearly polarized photons for $\gamma p \to \pi^0 p$ and $\gamma p \to \pi^+ n$ reactions at $\theta = 90°$ compared with the data of (○) Ref. 45, (●) Ref. 46, (×) Ref. 47, (△) Ref. 48, (▲) Ref. 49, and (▽) Ref. 50. The π^0 data of R. Zdarko and R. F. Mozley (○) are taken from Ref. 44.

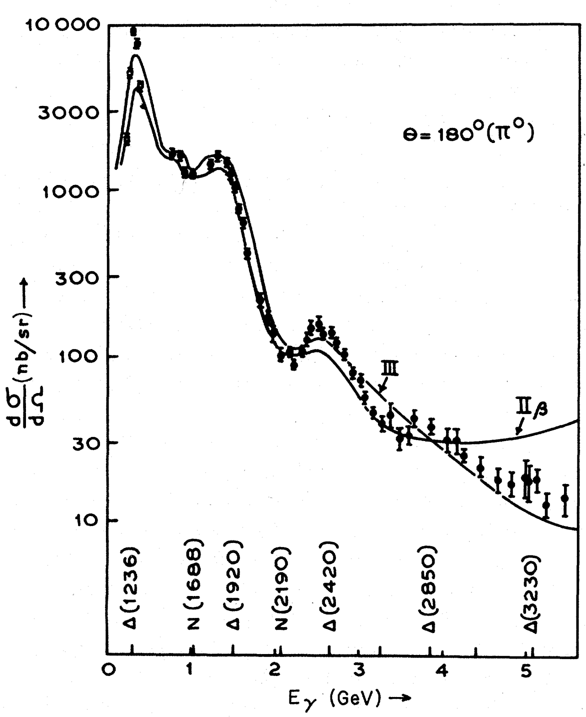

FIG. 7. The differential cross section for $\gamma p \to \pi^0 p$ as a function of lab photon energy E_γ in GeV with form factors II_β and III, compared with the data of (□) Ref. 52 and (●) Ref. 51.

VII. SUMMARY AND CONCLUSIONS

In this paper we have made a reassessment of our coupling scheme and also introduced still another parametric structure (denoted by III) for the form factor[5] which combines in it certain desirable features of the two form factors I[1] and II[4] described in MM. The motivation for a reassessment of the coupling scheme has been twofold: (i) to avoid certain problems of ambiguity involved in the relativistic extension ansatz $\vec{k}\cdot\vec{k} \to k_\mu k_\mu$, which were necessitated for the $(L-1)$-wave terms in our earlier framework and (ii) to explore more fully the possibilities of generating additional coupling structures with the help of the "quark-recoil term"[10] in the primitive quark-meson interaction. This new coupling scheme β does not introduce any additional structure in the $\bar{B}B_L P$ coupling, except for a new "coupling constant" for the $(L-1)$ wave, a feature which is effectively present even in form factor II of the earlier coupling scheme α. However, the scheme β produces considerable changes in the structure of the $\bar{B}B_L V$ couplings, an important one being the generation of (E)-type coupling, viz., $\bar{\psi}\epsilon_{\mu_1}k_{\mu_2}\cdots k_{\mu_L}\psi^{L+1/2}_{\mu_1,\ldots,\mu_L}$ which connects a $J=L+\frac{1}{2}$ state via the $(L-1)$ wave and gives significant contributions to helicity-flip amplitudes. Finally, within the partial-symmetry hypothesis,[6] there are now two sets of coupling constants $C^{\pm}$ for the $(L\pm1)$ waves respectively, covering both P- and V-meson interactions within a common framework of parametrization.

In this paper the scheme β has been applied to (i) the angular distributions in $Y(1520)\to\Lambda\gamma$, (ii) photoproduction of η and X_0 mesons, and (iii) polarization and asymmetry comparisons in pion photoproduction, in order to provide suitable experimental criteria for distinguishing between α and β, on the one hand, and the three form factors I, II, and III, on the other. Thus the importance of (E)-type coupling is convincingly demonstrated through (i) the excellent reproduction of the $(5-3\cos^2\theta)$ angular distribution for $K^-p\to Y^*\to\Lambda\gamma$ process, an almost pure $E1$ transition effect,[9] and (ii) the fairly sharp energy variations as well as comparatively large magnitudes (~0.5) in the asymmetry parameter for pion photoproduction.[45-50] The performance of the form factor III is found on the whole to be superior to that of the earlier form factor II, which in turn is superior to I, thus marking a hierarchy of successive improvements in the description of hadronic processes through the construction of form factors endowed with an increasing number of desirable features.

The η-photoproduction calculations were designed mainly to bring out the roles of certain crucial N^* resonances in this process on the basis of confidence in the coupling structures acquired through the $Y^*\to\Lambda\gamma$ and pion-photoproduction processes. The good numerical agreement with the data brings out rather neatly the importance of the Weisskopf factor $(m_\eta/m_\pi)^{1/2}$ as well as (E)-type $(L-1)$ wave, both of which make substantial contributions to the numerical values. We have also reexamined the supermultiplet assignment for the resonance $P_{11}(1750)$, in the context of a recent controversy,[32] but the results do not seem to warrant any revision in the assignment of a second radial excitation of nucleon to this state,[3,36] which fits in naturally with the description of resonances in terms of $[\underline{56}, (\text{even})^+]$ and $[\underline{70}, (\text{odd})^-]$ states. As to the $S_{11}(1550)$ resonance, a second solution for the mixing angle that we have now found within our model, makes our conclusions considerably closer to the results based on the harmonic-oscillator model.[30] Further, the magnitude of the contribution to the η-photoproduction cross sections, of the $G_{17}(2190)$ resonance, which is the most prominent one in the 2-GeV region, seems to suggest a doublet quark-spin assignment to this particle in apparent discord with the result of Feynman *et al.*[34]

We conclude with a few remarks on (i) the role of duality[14] within our present approach and (ii) the difference between our treatment and some contemporary analyses on photoproduction, based on interference models[54] or purely phenomenological descriptions[44,55-57] in terms of specified lists of resonances. As we had seen in the s-channel analysis in MM, the results of several processes already seem to be in good qualitative accord with the duality spirit inasmuch as no t- or u-channel exchanges were considered. This feature not only appears in the present investigation but its validity seems to warrant extension even to higher energies (~6 GeV) – a conclusion based on the good agreement with data on the differential cross section with the inclusion of additional resonances. Since our approach is basically committed to duality, it is not possible to make a direct comparison of these results with those of Refs. 44, 54, or 55 based on entirely different principles, viz., the interference of s, t, and u channels in varying degrees. Our main object has been not so much to obtain agreement with the experimental curves with a sufficiently flexible number of parameters represented by a good set of resonances and their partial widths as to test the following broad hypotheses for hadron couplings in the over-all spirit of duality: (i) existence of only $(\underline{56}(\text{even})^+)$ and $(\underline{70}(\text{odd})^-)$ states and their radial excitations, (ii) partial symmetry in the $\bar{B}B_L V$ and $\bar{B}B_L P$ coupling structure, (iii) Regge universality in the reduced supermultiplet coupling constants, and (iv) crossing symmetry in the form factors. In this respect, our approach can be regarded as a sort of bridge between a full-fledged theory and a purely phenomenological analysis of experimental data. Very similar conclusions on the validity of the above four hypotheses seem to be indicated from calculations on vector-meson production[8] and pion-nucleon scattering[58] as well.

ACKNOWLEDGMENTS

One of us (A. N. M.) is grateful to Dr. S. R. Choudhury for useful discussions which led to the consideration of the recoil term. We also gratefully acknowledge the active help of Professor S. H. Patil and Dr. D. K. Choudhury.

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