Photoproduction Processes in the Quark Model

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Many sum rules for photoproduction processes are derived starting from the vector-dominance hypothesis and treating the mesons consistently as quark-antiquark composites.

INTRODUCTION

PHOTOPRODUCTION is one of the important processes that have been studied in the quark model[1] with success. Becchi and Morpurgo[2] calculated the M_1 transition matrix element between the proton and N^* resonance, each looked upon as a $3Q$ system belonging to the **56** representation. The electromagnetic operator in this model is the sum of the quark magnetic-moment operators, and the calculation is an evaluation of the transition magnetic moment between certain states of a three-particle system. Essentially here, the photon is a radiative field interacting with the quarks, and only the magnetic components are considered. The same ideas were further extended by treating the pion also as a radiative field.[3] This assumption is the same as in consideration of decays or of meson-baryon scattering. Gupta and Mitra[4] proceeded the same way but included the $SU(6)\times O(3)$ structure of the baryons. Here they were able to relate spin-flip and spin-nonflip amplitudes as well as positive-parity and negative-parity baryon amplitudes.

Another idea that has played an important role for photoproduction, without any reference to the quark model, is the vector-dominance hypothesis.[5] Here the photon is assumed to interact with the hadrons through vector mesons. Joos[6] used the quark model to calculate the ρ^0, ω, ϕ production amplitudes by relating them to the elastic vector-meson–baryon scattering amplitudes through the vector-dominance hypothesis. Using the same ideas, photoproduction was next correlated with inelastic meson-baryon scattering by Kajantie and Trefil.[7] However, it was essentially the rearrangement model of Lipkin[8] and the spin exchanges were ignored.

We rectify this here and consider quark-quark and quark-antiquark amplitudes separately as in the case of meson-baryon scattering.[9] Photoproduction is related to vector-meson–baryon scattering through the vector-dominance hypothesis. It is noticed that many of the relations obtained earlier are true for pseudoscalar-meson production, and some new relations are obtained for vector-meson production with the octet as well as the decuplet baryons.

The model presented here includes a specific type of $SU(3)$ violation in the quark space.[9] Since we consider both quark-quark and quark-antiquark forces, there are 16 independent amplitudes involved with spin-spin interactions only. However, when we consider photoproduction of mesons with either charge or hypercharge, only four constants occur, and this yields a large number of relations. We find that many of them are well satisfied.

SUM RULES

The calculations proceed exactly as in the case of meson-baryon scattering,[9] and the quark-quark and quark-antiquark interactions are given by

$$V|\mathcal{P}_+\mathcal{N}_-\rangle = V_{dd}|\mathcal{P}_+\mathcal{N}_-\rangle + V_{de}|\mathcal{N}_+\mathcal{P}_-\rangle + V_{ed}|\mathcal{P}_-\mathcal{N}_+\rangle + V_{ee}|\mathcal{N}_-\mathcal{P}_+\rangle ,$$

$$V|\mathcal{P}_+\lambda_-\rangle = V_{dd}{}^{(1)}|\mathcal{P}_+\lambda_-\rangle + V_{de}{}^{(1)}|\lambda_+\mathcal{P}_-\rangle + V_{ed}{}^{(1)}|\mathcal{P}_-\lambda_+\rangle + V_{ee}{}^{(1)}|\lambda_-\mathcal{P}_+\rangle , \quad (1)$$

and

$$V|\mathcal{P}_+\bar{\mathcal{N}}_-\rangle = \bar{V}_{dd}|\mathcal{P}_+\bar{\mathcal{N}}_-\rangle + \bar{V}_{ed}[|\mathcal{P}_+\bar{\mathcal{N}}_-\rangle - |\mathcal{P}_-\bar{\mathcal{N}}_+\rangle],$$

$$\begin{aligned} V|\mathcal{P}_+\bar{\mathcal{P}}_-\rangle = {} & \bar{V}_{dd}|\mathcal{P}_+\bar{\mathcal{P}}_-\rangle + \bar{V}_{de}[|\mathcal{P}_+\bar{\mathcal{P}}_-\rangle - |\mathcal{N}_+\bar{\mathcal{N}}_-\rangle] \\ & + \bar{V}_{de}{}^{(1)}|\lambda_+\bar{\lambda}_-\rangle + \bar{V}_{ed}[|\mathcal{P}_+\bar{\mathcal{P}}_-\rangle - |\mathcal{P}_-\bar{\mathcal{P}}_+\rangle] \\ & + \bar{V}_{ee}[|\mathcal{P}_+\bar{\mathcal{P}}_-\rangle - |\mathcal{P}_-\bar{\mathcal{P}}_+\rangle - |\mathcal{N}_+\bar{\mathcal{N}}_-\rangle + |\mathcal{N}_-\bar{\mathcal{N}}_+\rangle] \\ & + \bar{V}_{ee}{}^{(1)}[|\lambda_+\bar{\lambda}_-\rangle - |\lambda_-\bar{\lambda}_+\rangle], \end{aligned} \quad (2)$$

and similarly for any other quark-quark and quark-antiquark pair. Also, the photon is assumed to transform as

$$\gamma_Q \propto [2\mathcal{P}\bar{\mathcal{P}} + \mathcal{N}\bar{\mathcal{N}} - \lambda\bar{\lambda}], \quad (3)$$

where the spin components are suppressed for the present. Now any photoproduction amplitude $\langle \gamma_Q p | MB \rangle$, where M and B stand for mesons and baryons, can be expressed in terms of the quark-quark and quark-antiquark amplitudes but for a constant of proportionality. As is usual in the quark model, we do not really know at what energies we can expect such spin-spin interaction to give useful information, and the justification is mostly *a posteriori* on comparison with the experimental results.

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We have, e.g.,

$$\langle\gamma_{-1}p_{1/2}|\pi p_{-1/2}\rangle \propto \left(\frac{3}{2\sqrt{6}}V_{\text{ed}}+\frac{7}{6\sqrt{6}}V_{ee}\right) +\left(\frac{3}{2\sqrt{6}}\bar{V}_{\text{ed}}+\frac{7}{6\sqrt{6}}\bar{V}_{ee}\right),$$

and any other amplitude can be obtained in a similar way. Averaging over the initial spin states and summing over the final spin states, the following relations for the cross sections for the pseudoscalar-meson production in the forward direction are obtained with $SU(2)_I$ invariance in the quark space:

$$\bar{\sigma}(\gamma p\to\pi^+n)=(25/8)\bar{\sigma}(\gamma p\to\pi^+N^{*0}) =(25/24)\bar{\sigma}(\gamma n\to\pi^+N^{*-}),\quad(4)$$

$$\bar{\sigma}(\gamma n\to\pi^-p)=(25/8)\bar{\sigma}(\gamma n\to\pi^-N^{*+}) =(25/24)\bar{\sigma}(\gamma p\to\pi^-N^{*++}),\quad(5)$$

$$\bar{\sigma}(\gamma p\to K^+\Sigma^0)=\tfrac{1}{2}\bar{\sigma}(\gamma n\to K^+\Sigma^-) =(1/27)\bar{\sigma}(\gamma p\to K^+\Lambda) =\tfrac{1}{8}\bar{\sigma}(\gamma p\to K^+Y_1^{*0}) =\tfrac{1}{16}\bar{\sigma}(\gamma n\to K^{*+}Y_1^{*-}),\quad(6)$$

$$\bar{\sigma}(\gamma p\to K^0\Sigma^+)=2\bar{\sigma}(\gamma n\to K^0\Sigma^0)=(2/27)\bar{\sigma}(\gamma n\to K^0\Lambda) =\tfrac{1}{8}\bar{\sigma}(\gamma p\to K^0Y_1^{*+}) =\tfrac{1}{4}\bar{\sigma}(\gamma n\to K^0Y_1^{*0}),\quad(7)$$

$$\bar{\sigma}(\gamma p\to\pi^0N^{*+})=\bar{\sigma}(\gamma n\to\pi^0N^{*0}),\quad(8)$$

$$\bar{\sigma}(\gamma p\to\eta N^{*+})=\sin^2\theta[\bar{\sigma}(\gamma p\to\pi^0N^{*+})].\quad(9)$$

Note that the relations are to be subjected to experimental test only after correcting for the phase space.[10] Kupsch[3] obtained the above results with the meson as a radiative field, which we find is not necessary. The recent experimental data[11,12] indicate that Eqs. (4) and (5) with N^* production are well satisfied. At very high energy, where we can assume the quark-quark and quark-antiquark forces to be equal, we obtain

$$\bar{\sigma}(\gamma p\to\pi^+n)=\bar{\sigma}(\gamma n\to\pi^-p) =(25/24)(\gamma p\to\pi^-N^{*++}),\quad(10)$$

which is in very good agreement with experiments at 16 GeV.[11] However, the ratio 1/27 of Σ^0 production to Λ production by photons on proton targets is a bad result which still remains. Note that this defect has occurred in almost every quark-model calculation except that of Meshkov and Ponzini.[13] Their consideration of the **405** representation with a crossed t channel as $\mathbf{35}\times\mathbf{35}\to\overline{\mathbf{56}}\times\mathbf{56}$ avoids this difficulty. However, the nonrelativistic quark model does not permit the channel $\mathbf{35}\times\mathbf{35}$ of quark-antiquark systems to baryon-antibaryon systems, which needs pair creation in the quark space. Hence we suspect that exclusion of pair creation and annihilation contributions may be the cause of this anomaly. It is also otherwise obvious that we should include such contributions even to explain strong decays in this composite model for the mesons. For the Σ-particle production with K^+ in Eq. (6), the ratio 2 is not bad when compared to the experimental value.

If we assume complete $SU(3)$ symmetry in the quark space, we obtain

$$\bar{\sigma}(\gamma n\to K^+Y_1^{*-})=\tfrac{1}{3}\bar{\sigma}(\gamma n\to\pi^+N^{*-}),\quad(11)$$

$$\bar{\sigma}(\gamma p\to K^+Y_1^{*0})=\tfrac{1}{2}\bar{\sigma}(\gamma p\to\pi^+N^{*0}),\quad(12)$$

$$\bar{\sigma}(\gamma p\to\pi^+n)=50\bar{\sigma}(\gamma p\to K^+\Sigma^0).\quad(13)$$

Equations (11)–(13) are in disagreement with experiment.[11] The discrepancy occurs over a wide range of momentum transfers, and it is not easy to put the blame on the $K\pi$ mass difference. But this disagreement is not unexpected since the violation of $SU(3)$ symmetry in the quark-antiquark space is large, as indicated by the $\eta-X$ mixing angle[14] or baryon-antibaryon scattering.[15]

For the vector-meson photoproduction, we obtain

$$\frac{\bar{\sigma}(\gamma p\to\rho^0N^{*+})}{\bar{\sigma}(\gamma p\to\omega N^{*+})}=\frac{\bar{\sigma}(\gamma n\to\rho^0N^{*0})}{\bar{\sigma}(\gamma n\to\omega N^{*0})}=\tfrac{1}{9}.\quad(14)$$

This relation was also obtained earlier by Kajantie and Trefil. No experimental result seems to be available regarding this because of the scarcity of data on double-resonance production. However, Kajantie and Trefil also obtain

$$\frac{\bar{\sigma}(\gamma p\to\rho^0p)}{\bar{\sigma}(\gamma p\to\omega p)}=\frac{\bar{\sigma}(\gamma n\to\rho^0n)}{\bar{\sigma}(\gamma n\to\omega n)}=9,\quad(15)$$

which is not true here, and is also not very much favored by experiment, which gives this value as[11] 5.1 at 5 GeV.

We also further derive the following relations for vector-meson production, with $SU(2)_I$ invariance in the quark-quark and quark-antiquark space:

$$\bar{\sigma}(\gamma p\to K^{*+}\Sigma^0)=\tfrac{1}{2}\bar{\sigma}(\gamma n\to K^{*0}\Sigma^0) =\tfrac{1}{2}\bar{\sigma}(\gamma n\to K^{*+}\Sigma^-),\quad(16)$$

$$\bar{\sigma}(\gamma p\to\rho^0N^{*+})=\bar{\sigma}(\gamma n\to\rho^0N^{*0}),\quad(17)$$

$$\bar{\sigma}(\gamma p\to\rho^-N^{*++})=\tfrac{3}{2}\bar{\sigma}(\gamma n\to\rho^-N^{*+}),\quad(18)$$

$$\bar{\sigma}(\gamma p\to\rho^+N^{*0})=\tfrac{1}{3}\bar{\sigma}(\gamma n\to\rho^+N^{*-}),\quad(19)$$

$$\bar{\sigma}(\gamma p\to K^{*+}Y_1^{*0})=\tfrac{1}{2}\bar{\sigma}(\gamma n\to K^{*+}Y_1^{*-}),\quad(20)$$

$$\bar{\sigma}(\gamma p\to K^{*+}Y_1^{*0})=2\bar{\sigma}(\gamma n\to K^{*0}\Sigma^0).\quad(21)$$

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Experimental data are not available to check the above relations. If we assume $SU(3)$ symmetry in the quark-quark and quark-antiquark space, we obtain

$$\bar{\sigma}(\gamma p \to \rho^+ N^{*0}) = \tfrac{1}{2}\bar{\sigma}(\gamma p \to K^{*+} Y_1^{*0}), \quad (22)$$

$$\bar{\sigma}(\gamma p \to \rho^0 N^{*+}) = \tfrac{1}{2}\bar{\sigma}(\gamma p \to K^{*0} Y_1^{*+}). \quad (23)$$

In the high-energy limit (where the Pomeranchuk theorem can be assumed to hold), we also get

$$\bar{\sigma}(\gamma p \to \rho^+ N^{*0})/\bar{\sigma}(\gamma p \to \rho^- N^{*+}) = \tfrac{1}{3}, \quad (24)$$

$$\bar{\sigma}(\gamma p \to \pi^+ N^{*0})/\bar{\sigma}(\gamma p \to \pi^- N^{*++}) = \tfrac{1}{3}, \quad (25)$$

$$\bar{\sigma}(\gamma p \to \pi^+ n)/\bar{\sigma}(\gamma n \to \pi^- p) = 1, \quad (26)$$

and

$$\bar{\sigma}(\gamma p \to \rho^0 N^{*+}) = \bar{\sigma}(\gamma p \to \omega N^{*+}) = \bar{\sigma}(\gamma p \to K^{*0} Y_1^{*+}) = \bar{\sigma}(\gamma n \to \rho^0 N^{*0}) = \bar{\sigma}(\gamma n \to \omega N^{*0}) = 0. \quad (27)$$

Equations (24)–(26) were also obtained earlier in the quark model in the high-energy limit.[7] Equation (25) has also been obtained when $I=2$ exchange in the t channel is neglected,[11] and there is about a 15% error. Equation (26) was also obtained from Regge-pole analysis.[15]

DISCUSSIONS

We have considered here mainly photoproduction results with $SU(3)$ breaking in the quark space. They are essentially linked with meson-baryon scattering through the vector-dominance hypothesis. The mesons are treated as quark-antiquark composites, and it is noticed that with all this, many of the results of the elementary meson model are still true for composite mesons also. However, many of the new results are for double-resonance production processes for which we have no experimental data, and the experimental data are also scarce elsewhere.

The same problem has been considered recently by Choudhury[16] in a $QQ\bar{Q}$ model proposed by Mitra,[17] with the assumption of negligible quark-quark forces and with $SU(3)$ symmetry. Here explicit use is made of the representations of mesons and baryons with $SU(6)\times O(3)$ symmetry. We have not included this detailed representation[14] in our model and have considered rather a continuation of meson-baryon scattering[9] applied to photoproduction with mesons as quark-antiquark composites and with $SU(3)$-symmetry breaking in the quark space.

Note that in this model one of Eqs. (7), the one regarding Σ^0 and Λ production, is wrong on confrontation with experiments. Although this equation is a long-standing bad result of the quark model,[7] we consider this to be very undesirable. We feel that this is due to our failure to include quark-antiquark creation and annihilation terms. Without these terms, we have largely succeeded in explaining most results of the meson-baryon scattering and photoproduction with composite mesons. But these terms are necessary to explain even strong decays, which implies that they are quite important. These terms are difficult to incorporate into the quark model and go against the present philosophy of having nonrelativistic quarks only. We have here, however, shown how far it is possible to treat mesons consistently as composite particles without these effects, and the results seem to be encouraging.

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