

Quark model predictions for K^* photoproduction on the proton

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The photoproduction of K^* vector mesons is investigated in a quark model with an effective Lagrangian. Including both baryon resonance excitations and t -channel exchanges, observables for the reactions $\gamma p \rightarrow K^{*0}\Sigma^+$ and $\gamma p \rightarrow K^{*+}\Sigma^0$ are predicted, using the SU(3)-flavor-blind assumption of nonperturbative QCD.

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The availability of high-intensity photon and electron facilities at JLab, ELSA, ERSF, and SPring-8 has revived both experimental and theoretical interest in searching for “missing resonances” [1,2] in meson photoproduction and electroproduction processes. Baryon resonances excited by electromagnetic probes can be investigated through their various meson-nucleon and meson-hyperon decay channels. The exclusive study of meson photoproduction or electroproduction provides insights into the internal structures of the intermediate states. For K^* photoproduction JLab and ELSA have recently taken the first ever exclusive measurements in the resonance region.

The photoproduction of K^* vector mesons intersects, on the one hand, with other strangeness production reactions, such as $\gamma p \rightarrow K\Lambda$ and $\gamma p \rightarrow K\Sigma$, and, on the other hand, with the field of nonstrange vector meson production. Much work has been done in recent years on the former reactions [3–5]. At quark level, both (γ, K) and (γ, K^*) contain clear information about the production of an $s\bar{s}$ pair from the vacuum. At the hadronic level these reactions are related to each other since one reaction contains the meson produced in the other one as the t -channel exchanged particle, thus constraining the range of available couplings. With regard to the field of nonstrange vector meson photoproduction, only recently have there been theoretical efforts devoted to the processes $\gamma N \rightarrow \rho N$ and $\gamma N \rightarrow \omega N$ in the resonance region [6–9]. Sharing the same observables, the (γ, K^*) process can benefit from work on the structure of and the relationship between helicity amplitudes, vector meson multipoles, and polarization observables [10,11]. In contrast to the $\gamma p \rightarrow \rho^0 p$, $\gamma p \rightarrow \omega p$, and $\gamma p \rightarrow \phi p$ reactions, the t -channel Pomeron exchange is not possible for the $\gamma p \rightarrow K^* Y$ process, where Y denotes the hyperon. In this respect it shares similar features with charged ρ photoproduction, thus simplifying the study of intermediate resonance excitation.

The reason we choose a quark model approach is to avoid the uncertainties arising from a lack of knowledge about the $K^*\Sigma N^*$ couplings. A recent study of $N^* \rightarrow K^* Y$ by Capstick and Roberts [12], using a quark-pair-creation model, suggests that most $K^* Y$ decay branching ratios are small due to the high threshold for these channels. Only a few low-lying

negative-parity states were predicted to be strongly coupled to the $K^*\Sigma$ channels, including $N[\frac{1}{2}^-]_5(2070)$ (established in pion production), $\Delta[\frac{3}{2}^-]_3(2145)$, and $\Delta[\frac{1}{2}^-]_3(2140)$. Note that only those resonances above the decay threshold can be predicted by Ref. [12], the vector meson production could be the place where those below-threshold-resonance couplings to $K^* Y$ can be investigated. In our model, apart from the commonly-used quark model parameters, there are only two free parameters relating to the $K^*\Sigma N^{(*)}$ couplings that appear in the quark model symmetry limit. These are the vector and tensor couplings for the quark- K^* interaction. Meanwhile, the SU(3)-flavor-blind assumption is made in this model and suggests that these parameters should have values close to those used in the ω and ρ meson photoproductions. In this Rapid Communication, we shall adopt the most recently extracted information from the ω meson photoproduction as an input.

In this work, we present quark model predictions for the K^{*0} and K^{*+} photoproductions: $\gamma p \rightarrow K^{*0}\Sigma^+$ and $\gamma p \rightarrow K^{*+}\Sigma^0$. It is the first theoretical attempt to study nucleon resonance excitations in these two channels. Low-lying resonances within the $n \leq 2$ harmonic oscillator shells will be included explicitly in the formalism, while higher-mass resonances with $n > 2$, for which there is little information, are treated as being degenerate by summing over all states for the same n , which are taken to have the same mass and width [13]. As listed by the Particle Data Group [14], baryon resonances above 2 GeV generally have widths around 300–400 MeV, and large mass overlaps make this approximation a reasonable one. Taking such a scheme, we will concentrate in this paper on the following points: (i) the magnitude of the differential and total cross sections predicted by such a model; (ii) the differences between neutral and charged K^* photoproduction; and (iii) the effects of a t -channel kaon exchange in analogy with our study of the nonstrange ω and ρ meson photoproductions [6–8]. These results will be tested by forthcoming data from JLab and ELSA in the near future.

The K^* meson photoproduction involves the creation of s and \bar{s} quarks in the SU(3) quark model. With the effective Lagrangian of Refs. [6,7] adopted for the $K^*-q\bar{q}$ vertex, the s quark will couple to the meson in the same way as the u and d quarks, apart from its different mass ($m_s = 500$ MeV, $m_u = m_d = 330$ MeV). That is to say, the SU(3)-flavor-blind assumption of nonperturbative QCD is adopted in our model.

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Following the convention of Ref. [7], the transition amplitude can be expressed as the sum over the t -, s -, and u -channels,

$$M_{fi} = M_{fi}^t + M_{fi}^s + M_{fi}^u, \quad (1)$$

where the resonance excitations enter the s - and u -channels explicitly as follows:

$$\begin{aligned} M_{fi}^s + M_{fi}^u &= \sum_j \langle N_f | H_m | N_j \rangle \left\langle N_j \left| \frac{1}{E_i + \omega_\gamma - E_j} H_{em} \right| N_i \right\rangle, \\ &+ \sum_j \left\langle N_f \left| H_{em} \frac{1}{E_i - \omega_m - E_j} \right| N_j \right\rangle \langle N_j | H_m | N_i \rangle \\ &= i \langle N_f | [g_e, H_m] | N_i \rangle + i \omega_\gamma \sum_j \langle N_f | H_m | N_j \rangle \\ &\times \left\langle N_j \left| \frac{1}{E_i + \omega_\gamma - E_j} h_e \right| N_i \right\rangle \\ &+ i \omega_\gamma \sum_j \left\langle N_f \left| h_e \frac{1}{E_i - \omega_m - E_j} \right| N_j \right\rangle \langle N_j | H_m | N_i \rangle, \end{aligned} \quad (2)$$

with the quark-meson coupling

$$H_m = -\bar{\psi}_l \left(a \gamma_\mu + \frac{ib}{2m_q} \sigma_{\mu\nu} q^\nu \right) V^\mu \psi_l \quad (3)$$

and the quark-photon electromagnetic interaction

$$H_{em} = -\bar{\psi}_l \gamma_\mu e_l A^\mu \psi_l, \quad (4)$$

where ψ_l ($\bar{\psi}_l$) is the quark (antiquark) field, and V^μ is the vector meson field; e_l is the charge operator for the l th quark; ω_γ and ω_m denote the energy of the incoming photon and outgoing meson in the c.m. system, respectively, while E_i and E_j are the energy of the initial state proton and intermediate baryons (or hyperons). The summation should run over all the intermediate states $|N_j\rangle$, which can be explicitly described by the symmetric quark model wave functions.

In the second equivalence of Eq. (2), a standard transformation has been used [see Eqs. (14)–(19) in Ref. [13] for explicit deduction], where the electromagnetic interaction is transformed into $g_e \equiv \sum_l e_l \mathbf{r}_l \cdot \boldsymbol{\epsilon} e^{i\mathbf{k} \cdot \mathbf{r}_l}$, and $h_e \equiv \sum_l e_l \mathbf{r}_l \cdot \boldsymbol{\epsilon} (1 - \boldsymbol{\alpha} \cdot \mathbf{k} / \omega_\gamma) e^{i\mathbf{k} \cdot \mathbf{r}_l}$. Thus, we redefine the second and third term as the s - and u -channel transition, respectively, while the first term is identified as a “seagull” term. In Ref. [7], it was shown that the seagull term accompanied by the t -channel transition amplitude was essential for recovering gauge invariance for the theory.

An interesting feature arising from the effective Lagrangian is that the t -channel vector meson exchange M_{fi}^t and the seagull term are proportional to the charge of the outgoing K^* meson. Thus, they will vanish in the neutral vector meson production but play a role as background in the charged meson production. Meanwhile, the diffractive process is absent in the K^* photoproduction due to the strangeness production. These two features together make the neutral K^{*0}

production an opportunity to study the s - and u -channel contributions in the absence of those nonresonant processes.

The two parameters, a and b in Eq. (3), represent the vector and tensor couplings at the quark-meson interaction vertex, and are the basic parameters in this model. At present, no experimental data for K^* photoproduction can be used to constrain them. As mentioned above, the SU(3)-flavor-blind approach suggests that apart from the different quark mass, the parameters a and b should have the same magnitudes as those derived in the photoproduction of the nonstrange ω and ρ mesons. Therefore, we shall adopt the parameters used in the ω meson photoproduction [8] as a first test.

Our study of ω and ρ^0 meson photoproduction showed that the s - and u -channel contributions from the effective Lagrangian are not sufficient to describe the corresponding vector meson photoproduction reactions. Apart from diffractive Pomeron exchange in neutral vector meson production [7,8], scalar or pseudoscalar meson exchange terms are needed to reproduce the small angle forward-peaking behavior. For example, in $\gamma p \rightarrow \omega p$, the π^0 exchange dominates at small angles and accounts for large fractions of the cross section from threshold up to around 2.2 GeV. With the pion exchange as the main *unnatural* parity exchange process, it plays an important role in parity asymmetry observables. Similarly, in the reaction $\gamma p \rightarrow \rho^0 p$, a t -channel σ meson exchange must be introduced as well.

On the other hand, studies of kaon photoproduction with isobaric models [3,15] showed that K^* exchange terms were needed to reproduce forward peaking at higher energies. A chiral quark model study [16,17] arrived at similar conclusions. Recent data from SAPHIR [18,19] for $\gamma p \rightarrow K^+ \Sigma^0$ and $\gamma p \rightarrow K^0 \Sigma^+$ clearly showed a forward-peaking in both of these channels as well. This set of data provides interesting information to compare with the K^* photoproduction, where kaon exchange might play a similar role, since the $K^* K \gamma$ vertices are the same in both processes.

Taking into account the above features in K photoproduction, on the one hand, and ω and ρ photoproduction, on the other, it is reasonable to assume that a t -channel leading-order light meson exchange is needed for the K^* meson photoproduction as well. This kind of information, even if only based on phenomenological considerations, may help in shedding more light on the hadron duality hypothesis [20,21].

The kaon exchange is introduced with a pseudoscalar coupling for the $K \Sigma N$ vertex, which has the same form as a pseudovector coupling at tree level,

$$\mathcal{L}_{K\Sigma N} = -i g_{K\Sigma N} \bar{\psi}_\Sigma \gamma_5 \psi_p \phi_K, \quad (5)$$

where $g_{K\Sigma N}$ is the $K \Sigma N$ coupling constant, ψ_p and $\bar{\psi}_\Sigma$ are the initial state proton and final state Σ baryon, respectively, ϕ_K denotes the kaon. The $K^* K \gamma$ vertex is

$$\mathcal{L}_{K^* K \gamma} = e \frac{g_{K^* K \gamma}}{M_{K^*}} \varepsilon_{\alpha\beta\gamma\delta} \partial^\alpha A^\beta \partial^\gamma V^\delta \phi_K, \quad (6)$$

where A^β and V^δ are the photon and vector meson fields, $g_{K^*K\gamma}$ is the coupling constant, M_{K^*} denotes the K^* mass.

We determine the $K^*K\gamma$ coupling from K^* radiative decay, $K^* \rightarrow K + \gamma$. Adopting the partial decay width, $\Gamma_{(K^{*0} \rightarrow K^0 + \gamma)} = 116$ keV and $\Gamma_{(K^{*+} \rightarrow K^+ + \gamma)} = 50$ keV [14], we obtain $g_{K^{*0}K^0\gamma} = 1.134$ and $g_{K^{*+}K^+\gamma} = 0.744$, respectively, for the neutral and charged decay channels. A quark model constraint is adopted for the relative sign between these two couplings, i.e., a sign difference exists. For the $K\Sigma N$ coupling, there is more uncertainty over the value that should be used. The most recent studies [3] suggest that $g_{K^+\Sigma^0 p} / \sqrt{4\pi} = 1.2$ can be regarded as a reasonable value.¹ Isospin symmetry is taken into account and gives the following relation:

$$\frac{g_{K^0\Sigma^+ p}}{g_{K^+\Sigma^0 p}} = \frac{g_A(\gamma p \rightarrow K^0\Sigma^+)}{g_A(\gamma p \rightarrow K^+\Sigma^0)} = \sqrt{2}, \quad (7)$$

where the g_A is the axial vector coupling constant in pseudoscalar meson photoproduction. The ratio of the two values of g_A is derived in the SU(3) quark model.

From Eqs. (5) and (6), the t -channel kaon exchange amplitudes can be written as

$$M_T^t = \frac{e g_{K\Sigma N} g_{K^*K\gamma}}{2M_{K^*}(t - m_K^2)} e^{-(\mathbf{q}-\mathbf{k})^2/6\alpha_k^2} \{ \omega_\gamma \boldsymbol{\epsilon}_\gamma \cdot (\mathbf{q} \times \boldsymbol{\epsilon}_v) + \omega_m \mathbf{k} \cdot (\boldsymbol{\epsilon}_\gamma \times \boldsymbol{\epsilon}_v) \} \boldsymbol{\sigma} \cdot \mathbf{A}, \quad (8)$$

for the transverse transition, and

$$M_L^t = - \frac{e g_{K\Sigma N} g_{K^*K\gamma}}{2M_{K^*}(t - m_K^2)} \frac{M_{K^*}}{|\mathbf{q}|} e^{-(\mathbf{q}-\mathbf{k})^2/6\alpha_k^2} (\boldsymbol{\epsilon}_\gamma \times \mathbf{k}) \cdot \mathbf{q} \boldsymbol{\sigma} \cdot \mathbf{A}, \quad (9)$$

for the longitudinal transition, where $\mathbf{A} = \mathbf{q}/(E_f + M_\Sigma) - \mathbf{k}/(E_i + M_N)$ and $t = (q - k)^2$. The factor $e^{-(\mathbf{q}-\mathbf{k})^2/6\alpha_k^2}$ comes from the spatial integral over the initial state nucleon and final state Σ baryon, and plays the role of a form factor for the t -channel kaon exchange. The parameter, α_k , in the harmonic oscillator potential is treated as a free parameter such that it will partly take into account the form factor at the $K^*K\gamma$ vertex. Here we fix $\alpha_k = 290$ MeV, which is the same as used in ω meson photoproduction [8].

We adopt the following values for the two basic parameters in the quark-meson coupling vertex, $a = -2.8$ and $b = -5.9$, derived from ω meson photoproduction [8] using preliminary polarized beam asymmetry data from GRAAL [22].

Figure 1 shows the differential cross sections for $\gamma p \rightarrow K^{*0}\Sigma^+$ (left column) and $\gamma p \rightarrow K^{*+}\Sigma^0$ (right column) for

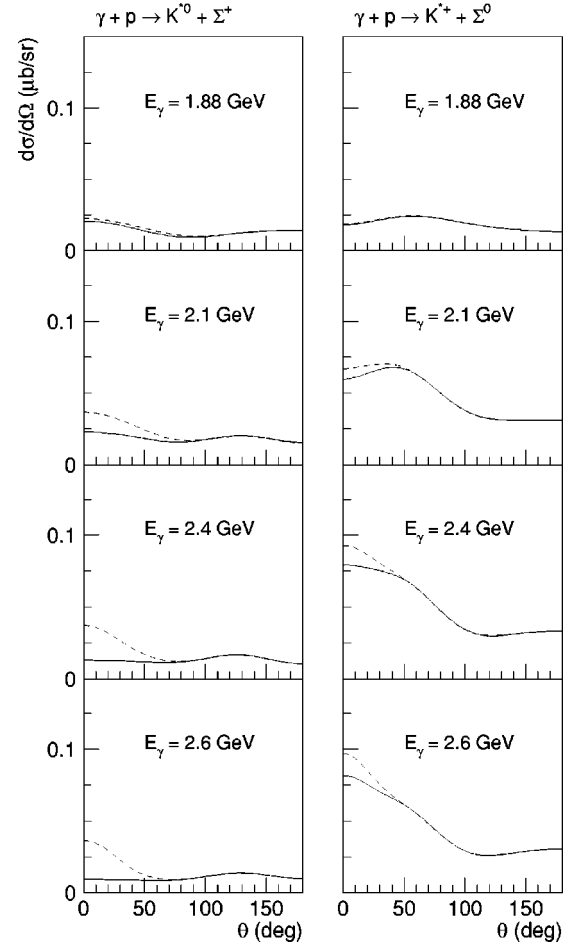


FIG. 1. Differential cross sections for $\gamma p \rightarrow K^{*0}\Sigma^+$ (left column) and $\gamma p \rightarrow K^{*+}\Sigma^0$ (right column) at four different energies. The dashed and solid curves are predictions with and without t -channel kaon exchange, respectively.

four energies, $E_\gamma = 1.88, 2.10, 2.40,$ and 2.60 GeV. The solid curves denote the results without the t -channel kaon exchange.

For the K^{*0} production, due to the absence of the seagull term and K^{*0} exchange, the solid curves represent contributions from s - and u -channel processes, and thus reflect the magnitudes of resonance excitations. For the K^{*+} production, although the near-threshold cross section is compatible with the K^{*0} production, strong forward peaking is found above threshold. The change of story is due to the dominant contribution from the seagull term as well as the t -channel K^{*+} exchange, which shifts the peaks even more forward. The flattened angular distributions in both reactions are produced by the large mass widths for higher mass resonances, which generally belong to $n > 2$ harmonic oscillator shells, and are treated as degenerate for each n since little is known about them. The off-shell low-lying resonances contribute only through their wave function tails, far from their mass positions. Near threshold, the cross section for the K^{*0} production slightly increases at large angles which is found to come from the u channel Λ and Σ transitions.

Compared to the seagull term and nucleon pole terms, the resonance contributions belong to higher orders, and gener-

¹It was also found in Ref. [3] that a free-parameter fitting of data gave $g_{K^+\Sigma^0 p} / \sqrt{4\pi} = -0.37$, which would produce negligible effects in this calculation.

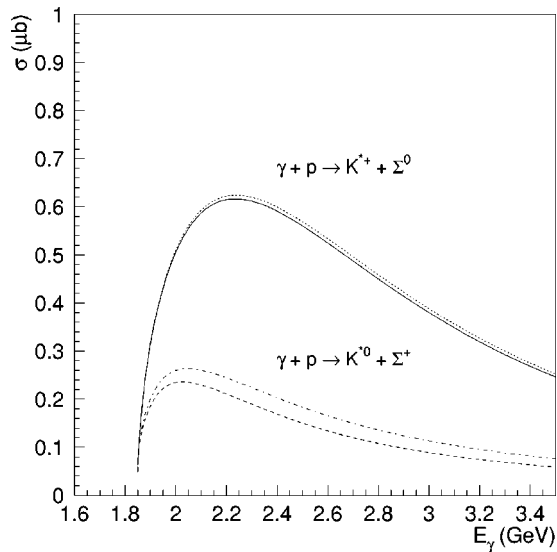


FIG. 2. Total cross sections for $\gamma p \rightarrow K^{*0}\Sigma^+$ with (dot-dashed curve) and without (dashed curve) the t -channel K^0 exchange, and for $\gamma p \rightarrow K^{*+}\Sigma^0$ with (dotted curve) and without (solid curve) the t -channel K^+ exchange.

ally have flattened distributions. Because of this, the dominance of the seagull term and t -channel K^{*+} exchange will put a strong constraint on the parameters when experimental data are available.

Calculations including the t -channel kaon exchanges are represented by the dashed curves in Fig. 1. Comparing these two reactions, it is clear that the near-threshold region is not sensitive to the possible kaon exchange. However, above threshold, strong forward-peaking is produced by K^0 exchange for the K^{*0} production, while only a small enhancement occurs at forward angles for the K^{*+} due to the K^+ exchange. An interesting feature of the kaon exchanges in these two reactions is that the K^+ exchange is relatively suppressed in comparison with the K^0 exchange, as can be seen by the couplings. Namely, $g_{K^{*0}K^0\gamma} = -1.525g_{K^{*+}K^+\gamma}$, due to the larger radiative decay width for K^{*0} ; and $g_{K^{*0}\Sigma^+p} = \sqrt{2}g_{K^{*+}\Sigma^0p}$ given by the SU(3) flavor symmetry. This feature is very similar to the charged ρ meson production, where the π^\pm exchanges were found to be negligible.

Total cross sections for these two reactions are shown in Fig. 2. The dotted and solid curves denote the predictions with and without the t -channel K^+ exchange for $\gamma p \rightarrow K^{*+}\Sigma^0$, while the dot-dashed and dashed curves denote with and without the t -channel K^0 exchange for $\gamma p \rightarrow K^{*0}\Sigma^+$. Again we find that cross sections for K^{*0} photoproduction are much lower than for K^{*+} production. The effects of t -channel kaon exchange are significant for K^{*0} photoproduction, but rather small for K^{*+} production.

Next we study the influence of t -channel kaon exchange on the beam polarization asymmetries. These *unnatural* parity exchanges and their interferences with the s - and u -channel transitions are expected to be particularly important at forward angles. Following the convention of Ref. [10], the beam polarization asymmetry can be expressed, in

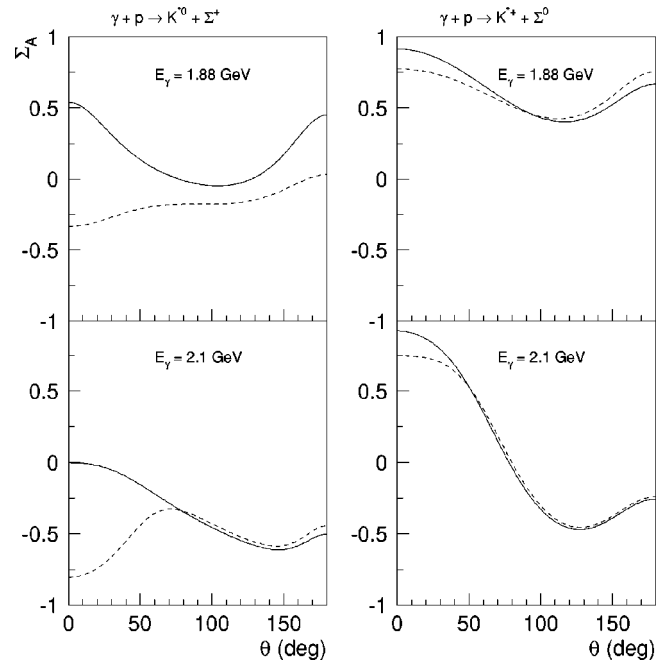


FIG. 3. Beam polarization asymmetry Σ_A^α at two energies, $E_\gamma = 1.88$ and 2.10 GeV. The dashed and solid curves denote calculations with and without the kaon exchange, respectively.

terms of the density matrix elements $\rho_{\lambda\lambda'}^\alpha$, of the vector meson decay, as

$$\Sigma_A^\alpha \equiv \frac{\rho_{11}^1 + \rho_{1-1}^1}{\rho_{11}^0 + \rho_{1-1}^0} = \frac{\sigma_{\parallel} - \sigma_{\perp}}{\sigma_{\parallel} + \sigma_{\perp}}, \quad (10)$$

where σ_{\parallel} represents the cross section of the vector meson decay with the decay particles in the photon polarization plane, while σ_{\perp} represents the cross section with the decay plane perpendicular to it. In Fig. 3, Σ_A^α is calculated at two energies, $E_\gamma = 1.88$ and 2.10 GeV. Comparing the solid and dashed curves, one can see that this observable is very sensitive to the kaon exchanges, whose exclusive contribution would result in $\Sigma_A^\alpha = -1$. For K^{*+} production, small contributions from the K^+ exchange produce significant effects at forward angles that shift the asymmetries to smaller values. For K^{*0} production, the effect is relatively strong and changes the sign of the asymmetry at $E_\gamma = 1.88$ GeV. Thus, with increasing energy, the large angle region will be dominated by the transitions from the effective Lagrangian, while the forward angle asymmetries are determined by the K^0 exchange.

In summary, this paper presents the first K^* meson photoproduction calculations for both isospin channels, $\gamma p \rightarrow K^{*0}\Sigma^+$ and $\gamma p \rightarrow K^{*+}\Sigma^0$, using a quark model with effective Lagrangian. Overall, the predicted cross sections are much smaller by at least an order of magnitude compared to either K or ρ and ω photoproduction. Adopting quark-meson vector and tensor couplings, $a = -2.8$ and $b = -5.9$, we find that K^{*+} production is significantly larger than K^{*0} production due to the presence of the seagull term and the t -channel K^{*+} exchange contribution. The effects of pseudoscalar

kaon exchange are studied in both reactions. We find that using a standard value for the $K\Sigma N$ coupling will produce clear forward-peaking behavior in $\gamma p \rightarrow K^{*0}\Sigma^+$, while only small enhancements are found in $\gamma p \rightarrow K^{*+}\Sigma^0$. This sensitivity of K^{*0} production to t -channel K^0 exchange might provide an additional constraint on the $K\Sigma N$ coupling, a valuable “by-product” from the measurement of K^* photo-production. We note that at present the sign between the kaon exchange terms and the s and u channel K^* production terms is unknown, due to our lack of knowledge of the $K^*\Sigma N$ couplings. Spin observables, rather than the differential cross section, would be more sensitive to this interference.

Also we note that this sensitivity is almost independent on the degenerate approximation for the $n > 2$ states since their contributions are generally small. Although the quark- K^* -meson couplings are compatible with the nonstrange quark meson couplings, suppressions of higher partial reso-

nances from the quark model form factors and large mass overlapping effects result in small cross sections for the $n > 2$ terms. Meanwhile, since the forward-peaking t -channel dominates at small angles, while the s - and u -channels (excluding the seagull term) generally have flattened behavior and dominate at large angles, the degenerate approximation turns out to be reasonable, at this stage. The calculations presented here should be regarded as a first step that provides a description of collective resonance excitations, rather than showing effects arising from individual resonances. With regard to our original motivation of searching for “missing resonances,” future work needs to include the high-lying states individually in order to assess their importance in these reactions. Also, a study of the $SU(6) \otimes O(3)$ symmetry violation would be necessary.

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