

Analysis of recent CLAS data on $\Sigma^*(1385)$ photoproduction off a neutron targetXiao-Yun Wang,^{1,2,3,*} Jun He,^{1,3,4,†} and Helmut Haberzettl^{5,‡}¹*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*²*University of Chinese Academy of Sciences, Beijing 100049, China*³*Research Center for Hadron and CSR Physics, Institute of Modern Physics of CAS and Lanzhou University, Lanzhou 730000, China*⁴*State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China*⁵*Institute for Nuclear Studies and Department of Physics, The George Washington University, Washington, DC 20052, USA*

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Based on recent experimental data obtained by the CLAS Collaboration, the $\Sigma(1385)$ photoproduction off a neutron target at laboratory photon energies E_γ up to 2.5 GeV is investigated in an effective Lagrangian approach including s -, u -, and t -channel Born-term contributions. The present calculation does not take into account any explicit s -channel baryon-resonance contributions; however, in the spirit of duality, we include t -channel exchanges of mesonic Regge trajectories. The onset of the Regge regime is controlled by smoothly interpolating between Feynman-type single-meson exchanges and full-fledged Regge-trajectory exchanges. Gauge invariance broken by the Regge treatment is fully restored by introducing contact-type interaction currents that result from the implementation of *local* gauge invariance in terms of generalized Ward-Takahashi identities. The cross sections for the $\gamma n \rightarrow K^+ \Sigma^*(1385)^-$ reaction are calculated and compared with experimental results from the CLAS and LEPS collaborations. Despite its simplicity, the present theoretical approach provides a good description of the main features of the data. However, the parameters fitted to the data show that the gauge-invariance-restoring contact term plays a large role, which may point to large contributions from final-state interactions.

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Over the last few decades, great strides have been made in baryon spectroscopy, in large part thanks to the high-quality photoproduction data obtained at electromagnetic facilities such as the Thomas Jefferson National Accelerator Facility (JLab), Mainz Microtron (MAMI), European Laboratory for Structural Assessment (ELSA), super photon ring 8 GeV (SPRING-8) facility, the Beijing Electron Positron Collider (BEPC), and others. Kaon photoproduction, in particular, with a strange (ground-state) Σ baryon, has been extensively studied. However, there exist only a limited number of studies of kaon photoproduction with a strange $\Sigma^*(1385)$ ($\equiv \Sigma^*$) baryon resonance [1–8]. In this respect, studies of the photoproduction of the $\Sigma^*(1385)$ off a neutron are particularly scarce both experimentally and theoretically. Recently, the JLab CLAS Collaboration released preliminary experimental data for the $\gamma n \rightarrow K^+ \Sigma^*(1385)^-$ process [9], where it was found that the differential cross sections of the CLAS experiment are in agreement with the published LEPS Collaboration results [10]. The present work provides an exploratory study of the dominant mechanisms that provide an understanding of the $\gamma n \rightarrow K^+ \Sigma^*(1385)^-$ reaction, based on these two data sets.

To this end we adopt here an effective Lagrangian approach in terms of standard s -, u -, and t -channel exchanges, similar to the studies of $\Lambda(1520)$ and $\Sigma(1385)$ photoproduction off the proton [6–8, 11–13]. At high energies, however, a more economical approach may be furnished by a phenomenological Regge treatment [14–16]. Hence, to be able to adapt

the standard effective-Lagrangian description and provide a transition into the Regge regime at higher energies, we adopt here a method that smoothly interpolates between Feynman-type low-energy single-meson t -channel exchanges and a full-fledged high-energy Regge treatment. Such a hybrid approach was seen to be quite successful in reproducing the experimental data in Refs. [8, 11–13]. The present treatment, however, is different from previous approaches in two important aspects.

First, in the present work, we will *not* include any baryon resonances in the s channel. We do not do so because the few CLAS and LEPS data points available do not exhibit any rapid variation with energy and angle [9, 10], which suggests that a calculation that concentrates on the major background mechanisms should be capable of capturing the main features of the data. Moreover, duality suggests that a full set of t -channel exchanges is equivalent to a full set of s -channel resonances [14–16]. Taking into account both, therefore, would correspond to double counting. While we do not suggest that the somewhat simplified Reggeized t -channel treatment described below corresponds to a true *full* set of t -channel exchanges in the sense of duality, we want to explore this avenue here to see whether one can describe the dominant features of the data without explicit s -channel resonances. Such an exploratory investigation may be thought of as a sort of “poor-man’s duality” treatment.

Second, to repair gauge invariance broken by the implementation of t -channel Regge exchanges, we will employ here the method we recently proposed [17] which is based on requiring the *off-shell* photoproduction current \mathcal{M}^μ to satisfy the generalized Ward-Takahashi identities that follow from consistently imposing *local* gauge invariance at the microscopic level [18, 19]. The procedure involves constructing a minimal *contact*-type interaction current utilizing

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Regge-trajectory exchanges, similar to what is proposed in Ref. [20] for ordinary Feynman-type single-hadron exchanges. The complete on-shell production current thus obtained satisfies the necessary (global) gauge-invariance condition $k_\mu \mathcal{M}^\mu = 0$ as a matter of course (with k being the photon four-momentum). As far as local gauge invariance is concerned, the procedure of Ref. [17] utilized here is dynamically complete. It is markedly different from the often-used prescription proposed in Ref. [21]; while the corresponding *ad hoc* recipe does indeed produce a globally gauge-invariant production current, it is without dynamical foundation, however.

The paper is organized as follows. In Sec. II, we present the formalism and main ingredients used for describing the reaction $\gamma n \rightarrow K^+ \Sigma^*(1385)^-$. The details of the interpolating Regge treatment and restoration of the local gauge invariance are also presented there. Numerical results are discussed in Sec. III, followed by a brief summary in Sec. IV.

II. FORMALISM

The basic tree-level Feynman diagrams for the $\gamma n \rightarrow K^+ \Sigma^*(1385)^-$ reaction are depicted in Fig. 1. These include the s -channel nucleon pole, the t -channel K and K^* exchanges, the Λ and Σ^* intermediate u channel, and the contact-type interaction current. In the present work, the contribution from t -channel K^* exchange is omitted since it is known to be negligibly small [6,8].

A. Lagrangians and amplitudes

For the s and t channels and the contact term, the relevant effective Lagrangian densities read as follows [6–8]:

$$\mathcal{L}_{\gamma KK} = ieA_\mu [K^-(\partial^\mu K^+) - (\partial^\mu K^-)K^+], \quad (1)$$

$$\mathcal{L}_{KN\Sigma^*} = \frac{f_{KN\Sigma^*}}{m_K} \bar{N} \Sigma^{*\mu} \cdot \tau (\partial_\mu K) + \text{H.c.}, \quad (2)$$

$$\mathcal{L}_{\gamma NN} = -e\bar{N} \left(Q_N \not{A} - \frac{\kappa_N}{4m_N} \sigma_{\mu\nu} F^{\mu\nu} \right) N, \quad (3)$$

$$\mathcal{L}_{\gamma KN\Sigma^*} = -ie \frac{f_{KN\Sigma^*}}{m_K} A^\mu (\bar{p} \Sigma_\mu^{*0} + \sqrt{2}\bar{n} \Sigma_\mu^{*-}) K^+ + \text{H.c.}, \quad (4)$$

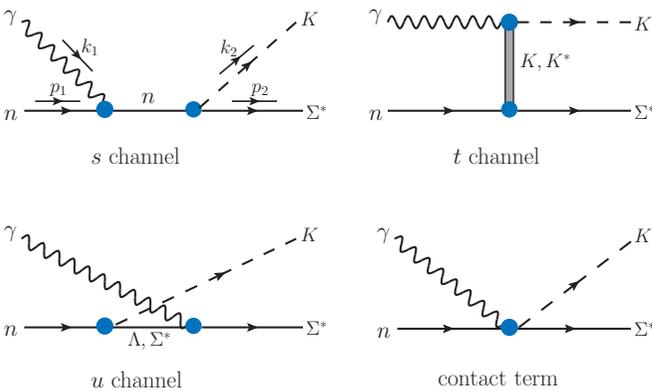


FIG. 1. Feynman diagrams for the $\gamma n \rightarrow K^+ \Sigma^*(1385)^-$ reaction. (The K^* t -channel exchange is not included since its contribution is negligibly small [6,8].)

with the isospin structure of $KN\Sigma^*$ coupling given by

$$\Sigma \cdot \tau = \begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix}, \quad K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix}, \quad N = \begin{pmatrix} p \\ n \end{pmatrix}, \quad (5)$$

and $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$, where A^μ , K , $\Sigma^{*\mu}$, and N are the photon, kaon, $\Sigma^*(1385)$, and nucleon fields. The kaon and nucleon masses, respectively, are m_K and m_N ; Q_N is the charge of the hadron in units of $e = \sqrt{4\pi\alpha}$, with α being the fine-structure constant, and $\kappa_N = -1.913$ is the anomalous magnetic moment for the neutron [22].

As alluded to in the Introduction, below we will introduce an interpolating Regge treatment for the t channel. In doing so, the coupling constant $f_{KN\Sigma^*}$ for this channel will be replaced by a free parameters $f_{KN\Sigma^*}^{\text{Regge}}$ that will be fitted to experimental data and thus need not be the same as $f_{KN\Sigma^*}$ for the $KN\Sigma^*$ vertex in the s channel.

For the u -channel $\Lambda(1116)$ exchange, the effective Lagrangians for $\gamma\Lambda\Sigma^*$ and $KN\Lambda$ couplings are [7]

$$\mathcal{L}_{\gamma\Lambda\Sigma^*} = -\frac{ief_1}{2m_\Lambda} \bar{\Lambda} \gamma_\nu \gamma_5 F^{\mu\nu} \Sigma_\mu^* - \frac{ef_2}{(2m_\Lambda)^2} (\partial_\nu \bar{\Lambda}) \gamma_5 F^{\mu\nu} \Sigma_\mu^* + \text{H.c.}, \quad (6)$$

$$\mathcal{L}_{KN\Lambda} = -ig_{KN\Lambda} \bar{N} \gamma_5 \Lambda K + \text{H.c.}, \quad (7)$$

where f_1 and f_2 are magnetic coupling constants determined from the partial decay width $\Gamma_{\Sigma^* \rightarrow \Lambda \gamma}$ [23] and model-predicted helicity amplitudes [24]. With the quark-model result for the helicity amplitudes $A_{1/2}$ and $A_{3/2}$, we get

$$f_1 = 4.52, \quad f_2 = 5.63. \quad (8)$$

Furthermore, the coupling-constant value $g_{KN\Lambda} = -13.24$ is an estimate based on flavor SU(3) symmetry relations [6,7,25].

For the u -channel Σ^* exchange, the effective Lagrangian for $\gamma\Sigma^*\Sigma^*$ is [7]

$$\mathcal{L}_{\gamma\Sigma^*\Sigma^*} = e\bar{\Sigma}_\mu^* A_\nu \Gamma_{\gamma\Sigma^*}^{\nu,\mu\alpha} \Sigma_\alpha^*, \quad (9)$$

with

$$A_\nu \Gamma_{\gamma\Sigma^*}^{\nu,\mu\alpha} = Q_{\Sigma^*} A_\nu \left[g^{\mu\alpha} \gamma^\nu - \frac{1}{2} (\gamma^\mu \gamma^\alpha \gamma^\nu + \gamma^\nu \gamma^\mu \gamma^\alpha) \right] - \frac{\kappa_{\Sigma^*}}{2m_N} \sigma^{\nu\beta} \partial_\beta A_\nu g^{\mu\alpha}, \quad (10)$$

where Q_{Σ^*} and κ_{Σ^*} denote the electric charge (in units of e) and the anomalous magnetic moment of $\Sigma^*(1385)$, respectively. Following the quark-model prediction, we take $\kappa_{\Sigma^{*-}} = -2.43$ [7,26].

To account for the internal structure of hadrons, we introduce phenomenological form factors. For the s and u channels, we adopt the functional form used in Refs. [7,8], i.e.,

$$F_{s/u}(q_{\text{ex}}^2) = \frac{\Lambda_{s/u}^4}{\Lambda_{s/u}^4 + (q_{\text{ex}}^2 - m_{\text{ex}}^2)^2}, \quad (11)$$

and for the t -channel K exchange, we take the monopole form

$$F_t(q_{\text{ex}}^2) = \frac{\Lambda_t^2 - m_{\text{ex}}^2}{\Lambda_t^2 - q_{\text{ex}}^2}, \quad (12)$$

where q_{ex} and m_{ex} are the respective four-momenta and masses of the exchanged hadrons. The values of the cutoff parameters Λ_s , Λ_u , and Λ_t will be determined here by fits to the data.

With the effective Lagrangian densities as listed above, the invariant channel scattering amplitudes for the $\gamma n \rightarrow K^+ \Sigma^*(1385)^-$ reaction are given as

$$-i\mathcal{M}_x = \bar{u}_\mu(p_2, \lambda_{\Sigma^*}) A_x^{\mu\nu} u(p_1, \lambda_n) \epsilon_\nu(k_1, \lambda_\gamma), \quad (13)$$

where the index $x = s, u, t$ corresponds to the appropriate Mandelstam variable, and $x = c$ denotes the contact-term contribution; the photon polarization vector is ϵ , and u_μ and u are dimensionless Rarita-Schwinger and Dirac spinors, respectively; λ_{Σ^*} , λ_n , and λ_γ are the helicities for the $\Sigma^*(1385)$, neutron, and photon, respectively. The four-momentum dependence here can be read off of Fig. 1.

The reduced $A_x^{\mu\nu}$ amplitudes for s -, t -, and u -channel contributions read

$$A_s^{\mu\nu} = -\sqrt{2} \frac{ef_{KN\Sigma^*}}{2m_K m_N} \frac{\kappa_N}{s - m_N^2} k_2^\mu (k_1 + p_1 + m_N) \gamma^\nu k_1 F_s, \quad (14)$$

$$A_t^{\mu\nu} = \sqrt{2} \frac{ef_{KN\Sigma^*}}{m_K} \frac{1}{t - m_K^2} (k_2^\nu - q_t^\nu) q_t^\mu F_t, \quad (15)$$

$$A_{u,\Lambda}^{\mu\nu} = g_{\kappa N\Lambda} \left\{ \frac{ef_1}{2m_\Lambda} \gamma_5 (k_1^\mu \gamma^\nu - g^{\mu\nu} k_1) + \frac{ef_2}{(2m_\Lambda)^2} \gamma_5 \right. \\ \left. \times (k_1^\mu q_u^\nu - g^{\mu\nu} k_1 \cdot q_u) \right\} \frac{q_u + m_\Lambda}{u - m_\Lambda^2} \gamma_5 F_u, \quad (16)$$

$$A_{u,\Sigma^*}^{\mu\nu} = \sqrt{2} \frac{Q_{\Sigma^*} ef_{KN\Sigma^*}}{m_K} \left\{ [g^{\mu\alpha} \gamma^\nu - \frac{1}{2} (\gamma^\mu \gamma^\alpha \gamma^\nu + \gamma^\nu \gamma^\mu \gamma^\alpha)] \right. \\ \left. - \frac{\kappa_{\Sigma^*}}{2m_N} \sigma^{\nu\rho} k_{1\rho} g^{\mu\alpha} \right\} \frac{q_u + m_{\Sigma^*}}{u - m_{\Sigma^*}^2} G_{\alpha\beta} k_2^\beta F_u, \quad (17)$$

with

$$G_{\alpha\beta} = g_{\alpha\beta} - \frac{1}{3} \gamma_\alpha \gamma_\beta - \frac{2(q_u)_\alpha (q_u)_\beta}{3m_{\Sigma^*}^2} - \frac{\gamma_\alpha (q_u)_\beta - \gamma_\beta (q_u)_\alpha}{3m_{\Sigma^*}}, \quad (18)$$

where $s = q_s^2 = (k_1 + p_1)^2$, $t = q_t^2 = (k_1 - k_2)^2$, and $u = q_u^2 = (p_2 - k_1)^2$ are the Mandelstam variables.

The contact-type interaction current amplitude $A_c^{\mu\nu}$ is given in Sec. II C below.

B. Interpolating Reggeized t -channel form factor

Standard Regge phenomenology for the t -channel meson exchange consists of replacing the product of the form factor and meson propagator in Eq. (15) according to [17,21]

$$\frac{F_t(t)}{t - m_K^2} \rightarrow \frac{\mathcal{F}_t(t)}{t - m_K^2}, \quad (19)$$

where the residual Regge function \mathcal{F}_t contains all higher mass poles along the Regge trajectory above the base state at $t = m_K^2$. The Reggeization of the t channel thus effectively corresponds to a prescription of how to choose the corresponding form factor.

Using the notation of Ref. [17], the residual function for the present application is written as

$$\mathcal{F}_t(t) = \left(\frac{s}{s_{\text{sc}}} \right)^{\alpha_K(t)} \frac{N_K(\alpha_K(t); \eta)}{\Gamma(1 + \alpha_K(t)) \sin(\pi \alpha_K(t))}, \quad (20)$$

where

$$\alpha_K(t) = \alpha'_K (t - M_K^2) \quad (21)$$

is the kaon trajectory with the usual slope parameter $\alpha'_K = 0.7 \text{ GeV}^{-2}$ [8,21,27]. The scale parameter of the exponential factor is taken as $s_{\text{sc}} = 1 \text{ GeV}^2$. The signature function is given as [17]

$$N[\alpha_K(t); \eta] = \eta + (1 - \eta) e^{-i\pi \alpha_K(t)}, \quad (22)$$

where η is a (phenomenological) real parameter whose three standard values are

$$\eta = \begin{cases} \frac{1}{2}, & \text{pure-signature trajectories,} \\ 0, & \text{add trajectories: rotating phase,} \\ 1, & \text{subtract trajectories: constant phase.} \end{cases} \quad (23)$$

Without going into detail here (for a discussion of this parametrization, see Ref. [17]), only the latter two choices ($\eta = 0, 1$) apply here in view of the degeneracy of the kaon trajectory starting at $m_K = 495 \text{ MeV}$ [21,27]. Numerical tests show that for the present case the best results are produced by the choice

$$\eta = 1 \quad \Rightarrow \quad N_K(\alpha_K(t); 1) = 1. \quad (24)$$

This corresponds to subtraction of the degenerate secondary trajectory [starting at $K_1(1270)$] from the primary one. Note that this subtraction is consistent with our choice of monopole form factor F_t for the standard Feynman-type single-meson exchange for the t -channel since

$$\frac{1}{t - m_K^2} \frac{\Lambda_t^2 - m_K^2}{\Lambda_t^2 - t} = \frac{1}{t - m_K^2} - \frac{1}{t - \Lambda_t^2}, \quad (25)$$

where the secondary pole contribution with ‘‘mass’’ Λ_t is also subtracted. (If the cutoff-mass in this Pauli-Villars-type regularization [28] were taken as $\Lambda_t = 1.29 \text{ GeV}$, this would correspond *exactly* to the second pole along the degenerate Regge trajectory. In the present application, however, Λ_t is fitted to the data.)

The onset of the ‘‘Regge regime’’ is oftentimes very much under debate in practical applications, in particular, if Regge exchanges are employed in medium-energy ranges relevant for baryon-resonance physics. It seems reasonable, therefore, to consider mechanisms for smooth transitions into that regime that can be fine tuned to the requirements of particular applications [8,11–13,29–32]. Fitting the parameters of such an interpolation scheme to experimental data lets the data ‘‘decide’’ whether Regge exchanges should be necessary for a particular process at a particular photon energy.

Since Regge phenomenology applies to high s and low $|t|$, we adopt here the interpolating mechanism proposed in Ref. [30] that provides separate switching functions for t and s , which we write as

$$R_s(s) = \frac{1}{1 + e^{-(s-s_R)/s_0}}, \quad R_t(t) = \frac{1}{1 + e^{-(t+t_R)/s_0}}, \quad (26)$$

where s_R and t_R describe the centroid values for the transition from non-Regge to Regge regimes, with s_0 and t_0 providing the respective widths of the transition regions. (The sign change for t_R is chosen merely for convenience to have positive values for both s_R and t_R in the physical region.) Combined as

$$R(t) = R_s(s) R_t(t), \quad (27)$$

this product provides an interpolating function in t for s fixed by experiment. The four parameters of this function will be fitted to the experimental data.

The interpolated Reggeized form factor can then be written as

$$F_t \rightarrow \mathcal{F}_{R,t}(t) = \mathcal{F}_t(t) R(t) + F_t(t) [1 - R(t)], \quad (28)$$

which replaces F_t on the left-hand side of Eq. (19) with $\mathcal{F}_{R,t}$, thus providing a smooth interpolation between the usual Feynman case ($R = 0$) and the full Regge case given by the right-hand side (for $R = 1$).

Since s is fixed, the switch R_s will only contribute a constant factor. Hence, the more relevant switch for reproducing detailed features of an experiment is R_t since it directly affects the description of angular behavior. While this may offer valuable flexibility for data that show rapid dependence on the scattering angle, this turns out to be not necessary for the present application. In fact we will find below that effectively the fitted values of t_R and t_0 correspond to $R_t = 1$ across the range of data considered here (see Fig. 2). For the present application, therefore, only the switch R_s will matter.

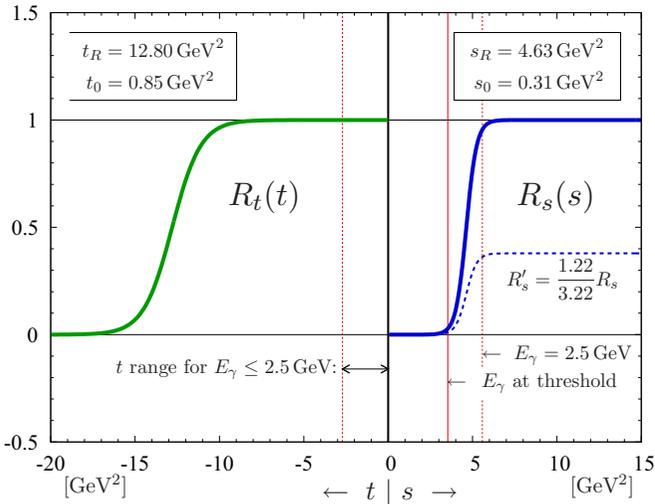


FIG. 2. Interpolating switching functions of Eq. (26), with parameter values resulting from the present fits (see Sec. III). The function $R_t(t)$ on the left is effectively unity for photon laboratory energies $E_\gamma \leq 2.5$ GeV. The function $R_s(s)$ on the right changes from essentially zero at threshold to almost unity across the energy range of the present data. For the correct interpretation of this finding and, in particular, the meaning of the dotted curve labeled R'_s on the right, see text.

Finally, it is obvious that the interpolation (28) does not change the normalization of the form factor, i.e.,

$$\mathcal{F}_{R,t}(m_K^2) = 1, \quad (29)$$

which is a necessary condition for the gauge-invariance-preserving procedure explained subsequently to work.

C. Preserving local gauge invariance

As is well known [17,21], Reggeization of the t -channel exchange destroys gauge invariance of the production current. However, following Ref. [17], this can easily be restored by generalizing the gauge-invariance-preserving procedure of Ref. [20] to the Regge case. Imposing *local* gauge invariance in the form of generalized Ward-Takahashi identities, this results in the contact-type interaction current [17]

$$A_c^{\mu\nu} = e\sqrt{2} \frac{f_{KN\Sigma^*}}{m_K} [g^{\mu\nu} \mathcal{F}_{R,t}(t) - k_2^\mu C^\nu], \quad (30)$$

with

$$C^\nu = -(2k_2 - k_1)^\nu \frac{\mathcal{F}_{R,t} - 1}{t - m_K^2} F_u + (2p_2 - k_1)^\nu \frac{F_u - 1}{u - m_{\Sigma^*}^2} \mathcal{F}_{R,t} + \hat{A}(1 - F_t)(1 - F_u) \left[\frac{(2k_2 - k_1)^\nu}{t - m_K^2} - \frac{(2p_2 - k_1)^\nu}{u - m_{\Sigma^*}^2} \right]. \quad (31)$$

In view of the normalization (29), the auxiliary current C^ν is manifestly nonsingular at the primary t -channel pole for $t = m_K^2$; however, it still retains the high-lying poles along the Regge trajectory via $\mathcal{F}_{R,t}$. The latter singularities are necessary to cancel the corresponding gauge-invariance-violating contributions of the production-current four-divergence resulting from Reggeization [17].

The last \hat{A} -dependent term in Eq. (31) is manifestly transverse and nonsingular. The function $\hat{A} = \hat{A}(t, u)$ here is a Lorentz-covariant, crossing-symmetric phenomenological function that must vanish at high energies, but otherwise can be freely chosen to improve fits to the data. Note here that the preceding Eq. (31) follows from Eq. (31) of Ref. [20] by choosing the function \hat{h} appearing there as $\hat{h} = 1 - \hat{A}$. The vanishing high-energy limit of \hat{A} is necessary to prevent the “violation of scaling behavior” noted in Ref. [33] if \hat{h} is different from unity at high energies. We simply choose here

$$\hat{A}(t, u) = A_0 \frac{\Lambda_c^4}{\Lambda_c^4 + (s - s_{\text{th}})^2}, \quad (32)$$

with

$$s_{\text{th}} = (m_\Sigma + m_K)^2, \quad (33)$$

which has the (dimensionless) value A_0 at the reaction threshold $s = s_{\text{th}}$. This choice has two parameters, the strength A_0 and cutoff Λ_c . For simplicity, we take $\Lambda_c = 3$ GeV and use only A_0 as a fit parameter. (There is no particular reason for choosing this cutoff value, other than not having \hat{A} fall off too rapidly for the present energy range.)

III. RESULTS AND DISCUSSION

The unpolarized differential cross section for the $\gamma n \rightarrow K^+ \Sigma^*(1385)^-$ reaction at the center of mass (c.m.) frame is

given by

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{32\pi s} \frac{|\vec{k}_2^{\text{c.m.}}|}{|\vec{k}_1^{\text{c.m.}}|} \left(\frac{1}{4} \sum_{\lambda} |\mathcal{M}|^2 \right), \quad (34)$$

where $s = (k_1 + p_1)^2 \equiv W^2$ with W being the total energy, and θ denotes the angle of the outgoing K^+ meson relative to beam direction in the c.m. frame, while $\vec{k}_1^{\text{c.m.}}$ and $\vec{k}_2^{\text{c.m.}}$ are the three-momenta of the initial photon beam and final kaon meson, respectively.

A. Fitting procedure

As discussed in the Introduction and Sec. II, we consider here only the “background” contributions, namely, the s channel with nucleon-pole exchange, the Reggeized t channel with K exchange, the u channel with $\Lambda(1116)$ and $\Sigma^*(1385)$ exchanges, and the contact term for the $\gamma n \rightarrow K^+ \Sigma^*(1385)^-$ process. The formalism was presented in the previous section, and the relevant input parameters are collected in Table I.

The preliminary CLAS data [9] and LEPS data [10] will be fitted with the help of the MINUIT code in the CERNLIB. In this work, we minimize χ^2 per degree of freedom (dof) for the differential cross sections $d\sigma/d\cos\theta$ for the CLAS and LEPS data by fitting the nine parameters $f_{KN\Sigma^*}^{\text{Regge}}$, s_R , s_0 , t_R , t_0 , Λ_s , Λ_u , Λ_t , and A_0 using a total of 75 data points as displayed in Fig. 3. The differential cross-section data are given for five intervals of the beam energy E_γ from 1.5 up to 2.5 GeV.

The parameter values determined in this manner are given in Table II, with a reduced value $\chi^2/\text{dof} = 1.75$, which suggests the CLAS [9] and LEPS [10] data sets can indeed be reproduced quite well by the presently considered mechanisms, without any need for explicit intermediate s -channel resonances.

This fit quality is achieved with reasonable cutoff values Λ_x ($x = s, u, t$) around the usual empirical 1-GeV value. The Regge interpolation parameters t_R and t_0 are largely irrelevant since, as shown in Fig. 2, the function $R_t(t) = 1$ across the range of data considered here.

The functional behavior of $R_s(s)$ for the parameters s_R and s_0 , on the other hand, exhibits a rapid variation from close to zero at threshold to almost unity at the upper energy end, $E_\gamma = 2.5$ GeV, of data employed here. While this seems to suggest that Regge behavior is fully switched on at $E_\gamma = 2.5$ GeV, this has to be taken with some caution because across the same energy range, the fitted value $f_{KN\Sigma^*}^{\text{Regge}}$ of the Reggeized t -channel $KN\Sigma^*$ coupling strength drops in magnitude by almost one third, from 3.22 to 1.22. Hence, since the strength of the Regge contribution is determined only

TABLE I. Input parameters for the formalism used in this work.

f_1	f_2	$g_{KN\Lambda}$	κ_n	κ_{Σ^*-}
4.52	5.63	-13.24	-1.91	-2.43
α'_K (GeV $^{-2}$)	s_{sc} (GeV 2)	η	Λ_c (GeV)	
0.7	1.0	1.0	3.0	

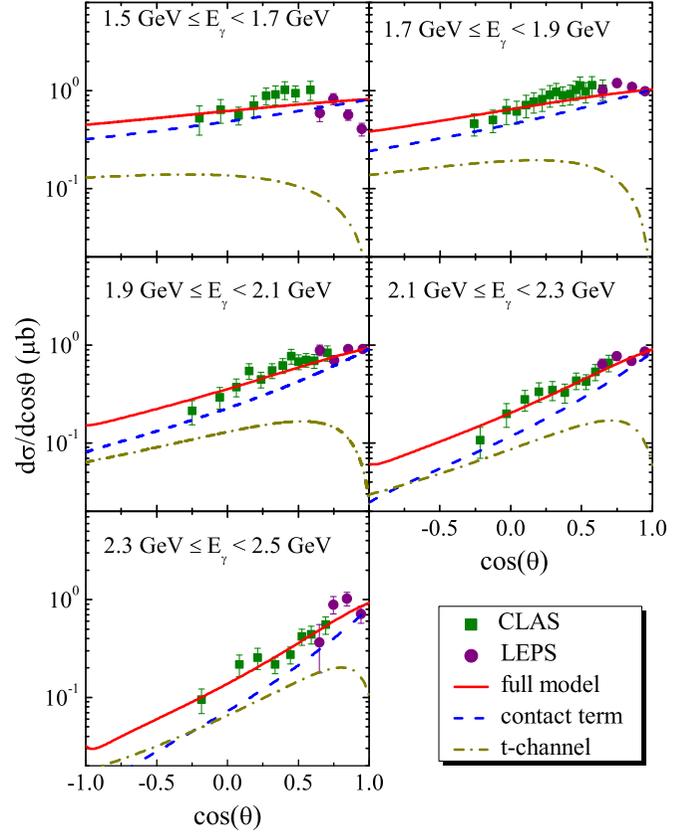


FIG. 3. Differential cross section $d\sigma/d\cos\theta$ for $\Sigma^*(1385)$ photoproduction off a neutron as function of $\cos\theta$. Data are from [9,10].

by the product $f_{KN\Sigma^*}^{\text{Regge}} R_s(s)$, one cannot really say at what energy Regge behavior will be switched on fully. Rescaling $R_s(s)$ with the ratio of the fitted coupling strength and its original SU(3) value, i.e., $R'_s(s) = (1.22/3.22)R_s(s)$ depicted as the dotted curve in Fig. 2, one can say, however, that the Regge vs non-Regge contribution must lie somewhere in the region between the solid R_s and the dotted R'_s curves in Fig. 2. This means, in particular, that Regge behavior already plays a significant role in this energy range, even if the detailed changeover behavior cannot be pinned down precisely by the present approach.

B. Cross section for $\gamma n \rightarrow K^+ \Sigma^*(1385)^-$

As can be seen from Fig. 3, the differential cross section $d\sigma/d\Omega$ for both CLAS and LEPS data sets [9,10] are well reproduced in our model, in particular, at the high-energy end of the data range. At lower energies, some structure at forward angles shown by the LEPS data is not so well described and, if it could be corroborated by other independent experiments, may require a more sophisticated approach, including perhaps some s -channel resonances. With the present simple “background” model, however, the s and u channels contribute so little to the cross section that we have omitted showing these very small contributions in the figure.

The bulk of the contributions are seen to come from the Reggeized t channel and, in particular, from the contact term

TABLE II. Fitted values of free parameters and corresponding reduced χ^2/dof value.

$f_{KN\Sigma^*}^{\text{Regge}}$	s_R (GeV ²)	s_0 (GeV ²)	t_R (GeV ²)	t_0 (GeV ²)
-1.22 ± 0.02	4.63 ± 0.06	0.31 ± 0.01	12.80 ± 0.35	0.85 ± 0.21
A_0	Λ_s (GeV)	Λ_u (GeV)	Λ_t (GeV)	χ^2/dof
0.03 ± 0.01	1.03 ± 0.12	0.81 ± 0.03	1.45 ± 0.05	1.75

of Eq. (30). Since the contact current can be understood as the minimal contribution from the hadronic final-state interaction (FSI) necessary to preserve gauge invariance [19,20], this may indicate that $K\Sigma$ FSI may play a role if one cannot resolve the discrepancies here by other means. However, since there are no data to constrain the parameters of such an FSI, an actual reliable calculation of such FSI processes would be impossible at present.

The primary objective of the present investigation was the description of the preliminary CLAS data [9]. However, since they still have large uncertainties, we also wanted to test our model for LEPS data [10]. Using the fit parameters of Table II, we see that we can reproduce reasonably well the differential cross sections (Fig. 4) and the total cross sections (Fig. 5) of that experiment. The LEPS data can be reproduced in our model except for some discrepancies at low energies, which is similar to the results in Ref. [34] obtained with the formalism in Ref. [6]. From Fig. 5, we again find a very large part of the final result is determined by the t channel and, again, by the gauge-invariance-preserving contact term. The s - and u -channel contributions are negligibly small.

IV. SUMMARY

We have presented here an effective Lagrangian approach to the photoproduction reaction $\gamma n \rightarrow K^+\Sigma^*(1385)^-$ with a Reggeized t -channel exchange that permits smooth interpolation between standard Feynman-type single-meson exchange

and a full-fledged Regge trajectory exchange. The present work is the first application of the method put forward recently by the present authors [17] that preserves full *local* gauge invariance in terms of generalized Ward-Takahashi identities [18,19].

Applying the model to recent CLAS data [9] and somewhat older LEPS data [10], we find good agreement with differential and total cross sections, with $\chi^2/\text{dof} = 1.75$. We cannot fit the data very well using the usual Feynman-type t -channel exchange alone. Inclusion of Regge trajectories is essential to achieve the fit quality exhibited in Figs. 3–5, in particular, with the added flexibility of the Reggeized interpolating t -channel form factor. Equally important are the contributions from the contact-type interaction current term that results from the gauge-invariance-preserving procedure of Ref. [17] since they account for a large part of the cross sections. The *microscopically* correct treatment of *local* gauge invariance thus turns out to be an essential ingredient of the present model.

As argued, the dominance of the contact term may point to $K\Sigma$ final-state contributions being important for this process; however, there are no data that would constrain any calculation along those lines, thus unfortunately making this an untestable proposition (at least at present).

In summary, since the present model does indeed reproduce quite well the main features of the process $\gamma n \rightarrow K^+\Sigma^*(1385)^-$, we are confident that the mechanisms incorporated in the model provide the dominant physics

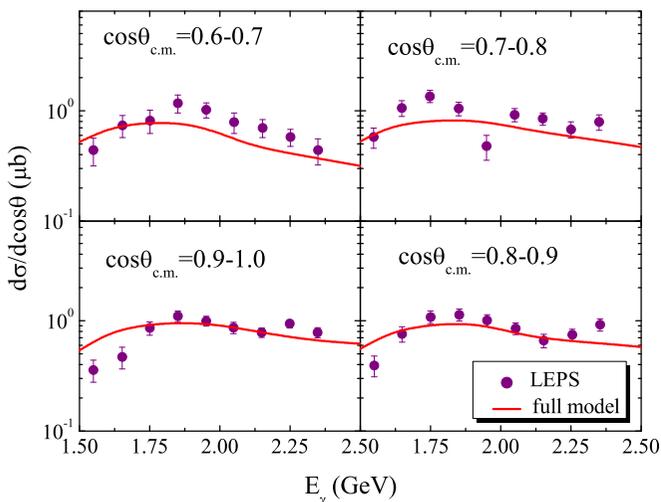


FIG. 4. Differential cross section $d\sigma/d\cos\theta$ for $\Sigma^*(1385)$ photoproduction off a neutron plotted against photon energy E_γ for LEPS data [10]. The line styles here are the same as in Fig. 3

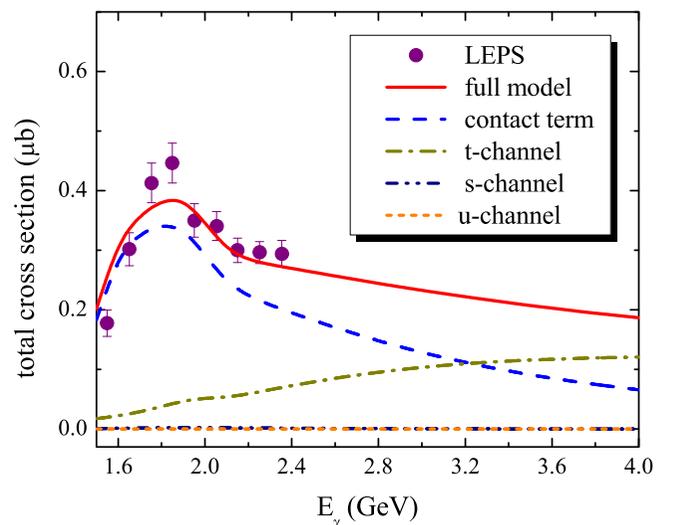


FIG. 5. Total cross section for $\Sigma^*(1385)$ photoproduction off a neutron, compared with LEPS data [10].

of the reaction, in particular, that the simplified duality treatment where s -channel baryon resonances are traded for t -channel meson Regge trajectories is indeed capable of describing magnitudes and average features of the observables.

To describe more detailed structures of the cross sections, inclusion of s -channel resonances may very well be necessary. However, to warrant expanding efforts in this direction, more precise data for $\Sigma^*(1385)$ production are necessary, covering wider energy and angle ranges. Such experiments could be carried out at the JLab CEBAF Large Acceptance Spectrometer

(CLAS) or the CERN Common Muon and Proton Apparatus for Structure and Spectroscopy (COMPASS).

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