Nucleon and $\Delta$ resonances in $\gamma p \to K^+ \Sigma^0(1385)$ photoproduction

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The photoproduction of $\gamma p \to K^+ \Sigma^0(1385)$ is investigated based on an effective Lagrangian approach at the tree-level Born approximation, with the purpose being to understand the reaction mechanisms and the resonance contents and their associated parameters in this reaction. In addition to the $t$-channel $K$ and $K^*$ exchanges, the $s$-channel nucleon ($N$) exchange, the $u$-channel $\Lambda$ exchange, and the generalized contact term, the exchanges of a minimum number of $N$ and $\Delta$ resonances in the $s$ channel are taken into account in constructing the reaction amplitudes to describe the experimental data. It is found that the most recent differential cross-section data from the CLAS Collaboration can be well reproduced by including one of the $N(1895)1/2^-$, $\Delta(1900)1/2^-$, and $\Delta(1930)5/2^-$ resonances. The reaction mechanisms of $\gamma p \to K^+ \Sigma^0(1385)$ are detailedly discussed, and the predictions of the beam and target asymmetries for this reaction are given. The cross sections of $\gamma p \to K^+ \Sigma^0(1385)$ are shown to be able to further constrain the theoretical models and pin down the resonance contents for $\gamma p \to K^+ \Sigma^0(1385)$.

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I. INTRODUCTION

The study of nucleon resonances ($N^*$'s) and $\Delta$ resonances ($\Delta^*$'s) has always been of great interest in hadron physics, since a deeper understanding of $N$ and $\Delta$ resonances is essential to get insight into the non-perturbative regime of Quantum Chromodynamics (QCD). It is known that most of our current knowledge about $N^*$'s and $\Delta^*$'s is mainly coming from $\pi N$ scattering or $\pi$ photoproduction reactions. Nevertheless, quark models $[2,3]$ predicted much more $N^*$'s and $\Delta^*$'s than experimentally observed. One possible explanation of this situation is that some of the $N^*$'s and $\Delta^*$'s couple weekly to $\pi N$ but strongly to other meson production reactions. Therefore, it is interesting and necessary to study the $N^*$'s and $\Delta^*$'s in production reactions of mesons other than $\pi$. In the present work, we concentrate on the photoproduction of $K^+ \Sigma^0(1385)$. Since the threshold of $K \Sigma(1385)$ is much higher than that of $\pi N$, the $K \Sigma(1385)$ photoproduction reaction is rather suitable to investigate the $N^*$'s and $\Delta^*$'s in the less-explored higher energy region.

Experimentally, in 1970's there were limited experimental data with large error bars on total cross sections for $\gamma p \to K^+ \Sigma^0(1385)$ $[4,5]$. In 2013, the differential cross-section data for $\gamma p \to K^+ \Sigma^0(1385)$ became available in the range of center-of-mass energy $W \approx 2.0 \sim 2.8$ GeV from the CLAS Collaboration at the Thomas Jefferson National Accelerator Facility $[6]$. These new differential cross-section data provide strengths in the aspects of constraining the theoretical amplitudes for $\gamma p \to K^+ \Sigma^0(1385)$, and, however, are scarce at very backward and very forward angles, which leads to much uncertainties in the theoretical investigations of this reaction.

Theoretically, based on an effective Lagrangian approach, a hadronic model for $\gamma p \to K^+ \Sigma^0(1385)$ has been proposed in 2008 in Ref. $[8]$, where eight $N$ and $\Delta$ resonances around 2 GeV among tens of resonances predicted by a quark model $[9]$ are considered. In this pioneering work, the resonance masses and the resonance hadronic and electromagnetic couplings are taken to be the corresponding values calculated in the quark model $[9]$, and the resonance widths are set to be a common value, 300 MeV. It was found that the resonance contributions are mainly coming from the $\Delta(2000)5/2^-$, $\Delta(1940)3/2^-$, $N(2120)3/2^-$ (previously called $N(2080)3/2^-$), and $N(2095)3/2^-$ resonances. One notices that in this work, although the calculated total cross sections are in good agreement with the corresponding preliminary data, there are still some discrepancies between their predicted differential cross sections with the CLAS data published in 2013 $[7]$, especially in the near-threshold energy region. In 2014, the reaction $\gamma p \to K^+ \Sigma^0(1385)$ has been investigated within a Regge-plus-resonance approach in Ref. $[10]$. The theoretical framework employed in this work is similar to that proposed in Ref. $[8]$, with the major difference being the following: (i) in Ref. $[10]$ the $t$-channel $K$ and $K^*$ exchanges are considered in a particular Regge type instead of a pure Feynman type, which introduces four additional parameters in the weighting function (form factors), (ii) nine instead of eight $N$ and $\Delta$ resonances around 2 GeV among tens of resonances predicted by the quark model of Ref. $[9]$ are considered, and (iii) a common width of 500 MeV instead of 300 MeV has been set for all the resonances. In Ref. $[10]$, the CLAS differential cross-section data $[7]$ have been well reproduced, and it was found that the cross sections of $\gamma p \to K^+ \Sigma^0(1385)$ are dominated by the contact term, while the contributions from all the considered resonances are much smaller than those in Ref. $[8]$ due to the much larger resonance width. In

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2017, the reaction $\gamma p \to K^+\Sigma^0(1385)$ has been studied in a Regge model in Ref. [11], where the Reggeized $t$-channel $K$, $K^*$, and $K_2^+(1430)$ exchanges are considered, and it was found that the reaction mechanism is featured by the dominance of the contact term plus the $K$ exchange with the role of the $K_2^+(1430)$ following rather than the $K^*$. One sees that in Ref. [11], the total cross-section data are well reproduced, but considerable discrepancies are still seen in the calculated differential cross sections compared with the corresponding data due to the lack of $N$ and $\Delta$ resonances.

In the present work, we investigate the $\gamma p \to K^+\Sigma^0(1385)$ reaction within an effective Lagrangian approach at the tree-level Born approximation. In addition to the $t$-channel $K$ and $K^*$ exchanges, the $s$-channel $N$ exchange, the $u$-channel $\Lambda$ exchange, and the generalized contact term, we consider as few as possible $\Delta$ resonances in the $s$ channel to describe the most recent differential cross-section data from the CLAS Collaboration [7]. The $t$-, $s$-, and $u$-channel amplitudes are obtained by evaluating the corresponding Feynman diagrams, and the generalized contact term is constructed to ensure the gauge invariance of the full photoproduction amplitudes. With regard to the $N$ and $\Delta$ resonances, the present work differs majorly from Refs. [8, 10] in the following three aspects: (i) in the present work we introduce $N$ and $\Delta$ resonances as few as possible to reproduce the data, while in Refs. [8, 10] eight or nine resonances among tens of resonances predicted by a quark model calculation [9] are considered, (ii) in the present work the masses and widths of the resonances are taken from a quark model calculation [9] and the widths for all the resonances are set to be a common value, 300 or 500 MeV, respectively, and (iii) in the present work the resonance couplings are treated as parameters to be determined by fits to the data, while in Refs. [8, 10] they are fixed by the decay amplitudes calculated in a quark model [9]. One believes that such an independent analysis of the available data for $\gamma p \to K^+\Sigma^0(1385)$ as performed in the present work is necessary and useful for a better understanding of the reaction mechanisms, the resonance contents, and the associated resonance parameters in this reaction.

The present paper is organized as follows. In Sec. II, we briefly introduce the framework of our theoretical model, including the generalized contact current, the effective interaction Lagrangians, the resonance propagators, and the phenomenological form factors employed in the present work. In Sec. III we present our theoretical results of differential and total cross sections for $\gamma p \to K^+\Sigma^0(1385)$, and a discussion of the contributions from individual terms is given as well. Furthermore, the beam and target asymmetries for $\gamma p \to K^+\Sigma^0(1385)$ and the total cross sections for $\gamma p \to K^0\Sigma^+$(1385) are shown and discussed in this section. Finally, a brief summary and conclusions are given in Sec. IV.
the unknown parts of the underlying microscopic model,
\[
M^\mu_{\text{int}} = \Gamma^\mu_{\Sigma^*NK}(q) C^\mu + M^\mu_{\text{KR}} f_t. \tag{2}
\]
Here \(\nu\) and \(\mu\) are Lorentz indices for \(\Sigma(1385)\) and \(\gamma\), respectively; \(\Gamma^\mu_{\Sigma^*NK}(q)\) is the vertex function of \(\Sigma(1385)NK\) coupling given by the Lagrangian of Eq. \(17\),
\[
\Gamma^\nu_{\Sigma^*NK}(q) = -\frac{g_{\Sigma^*NK}}{M_K} \nu^\nu,
\tag{3}
\]
with \(q\) being the 4-momentum of the outgoing \(K\) meson; \(M^\mu_{\text{KR}}\) is the Kroll-Ruderman term given by the Lagrangian of Eq. \(25\),
\[
M^\mu_{\text{KR}} = \frac{g_{\Sigma^*NK}}{M_K} g^{\nu\mu} T Q_K,
\tag{4}
\]
with \(T\) denoting the isospin factor of the \(\Sigma(1385)NK\) coupling and \(Q_K\) being the electric charge of outgoing \(K\) meson; \(f_t\) is the phenomenological form factor attached to the amplitude of \(t\)-channel \(K\)-exchange, which is given in Eq. \(32\); \(C^\mu\) is an auxiliary current, which is non-singular, introduced to ensure that the full photoproduction amplitudes of Eq. \(1\) are fully gauge invariant. Following Refs. \(14, 15\), we choose \(C^\mu\) for \(\gamma p \rightarrow K^+\Sigma^0(1385)\) as
\[
C^\mu = -Q_K \frac{f_s - \tilde{F}}{t - q^2} (2q - k) \mu - Q_N \frac{f_s - \tilde{F}}{s - p^2} (2p + k) \mu,
\tag{5}
\]
with
\[
\tilde{F} = 1 - \hat{h} (1 - f_s) (1 - f_t).
\tag{6}
\]
Here \(p, q, k\) are 4-momenta for incoming \(N, \) outgoing \(K,\) and incoming photon, respectively; \(Q_N(K)\) is the electric charge of \(N(K)\); \(f_s\) and \(f_t\) are the phenomenological form factors for \(s\)-channel \(N\) exchange and \(t\)-channel \(K\) exchange, respectively; \(\hat{h}\) is an arbitrary function going to unity in high-energy limit and is set to be \(\hat{h} = 1\) in the present work for simplicity.

In the rest of this section, we present the effective Lagrangians, the resonance propagators, and the phenomenological form factors employed in the present work.

### A. Effective Lagrangians

The effective interaction Lagrangians used in the present work for the production amplitudes are given below. For further convenience, we define the operators
\[
\Gamma^{(+)} = \gamma_5 \text{ and } \Gamma^{(-)} = 1,
\tag{7}
\]
the field
\[
\Sigma^{*} = \Sigma(1385),
\tag{8}
\]
and the field-strength tensors
\[
F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu,
\tag{9}
\]
with \(A^\mu\) denoting the electromagnetic field.

The electromagnetic interaction Lagrangians required to calculate the non-resonant Feynman diagrams are
\[
\mathcal{L}_{\gamma KK} = i e \left[ K^+ \left( \partial^\mu K^- \right) - K^- \left( \partial^\mu K^+ \right) \right] A_\mu, \tag{10}
\]
\[
\mathcal{L}_{\gamma KK^*} = \frac{g_{\gamma KK^*}}{M_K} e^{\alpha \mu \lambda \nu} (\partial_\alpha A_\mu) (\partial_\lambda K^*_\nu), \tag{11}
\]
\[
\mathcal{L}_{NN\gamma} = -e N \left[ \hat{e} \gamma^\mu - \hat{\kappa}_N \frac{N}{2M_N} g^{\mu\nu} \right] A_\nu \right] N, \tag{12}
\]
\[
\mathcal{L}_{\Sigma^*\Lambda\gamma} = -ie \frac{g_{\Sigma^*\Lambda\gamma}}{2M_N} \sigma_{\gamma^\nu} \gamma_5 F^{\mu\nu} \Lambda
\]
\[
+ e \frac{g_{\Sigma^*\Lambda\gamma}}{2M_N} \bar{\chi}_\gamma \gamma_5 F^{\mu\nu} \partial_\nu \Lambda + \text{H.c.}, \tag{13}
\]
where \(e\) is the elementary charge unit and \(\hat{e}\) stands for the charge operator; \(\hat{\kappa}_N = \kappa_p (1 + \tau_3) / 2 + \kappa_N (1 - \tau_3) / 2\), with the anomalous magnetic moments \(\kappa_p = 1.793\) and \(\kappa_N = -1.913; M_N\) and \(M_K\) stand for the masses of \(N\) and \(K\), respectively; \(e^{\alpha \mu \lambda \nu}\) is the totally antisymmetric Levi-Civita tensor with \(e^{0123} = 1\). The value of the electromagnetic coupling constant \(g_{\gamma KK^*}\) is determined by fitting the radiative decay width of \(K^+ \rightarrow K^\gamma\) given by PDG \(12\), which leads to \(g_{\gamma KK^*} = 0.413\) with the sign inferred from \(g_{\gamma\pi^\pm}\) \(17\) via the flavor SU(3) symmetry considerations in conjunction with the vector-meson dominance assumption. The coupling constants \(g_{\Sigma^*\Lambda\gamma}^{(1)}\) and \(g_{\Sigma^*\Lambda\gamma}^{(2)}\) are constrained by the radiative decay width of \(\Sigma^0(1385)\rightarrow\Lambda\gamma = 0.45\text{ MeV} \tag{12}\), thus only one of them is free. In the present work, we treat the ratio \(g_{\Sigma^*\Lambda\gamma}^{(1)}/g_{\Sigma^*\Lambda\gamma}^{(2)}\) as a fit parameter.

The resonance-nucleon-photon transition Lagrangians are
\[
\mathcal{L}_{RN\gamma}^{1/2\pm} = i e \frac{g_{RN\gamma}}{2M_N} R^{\Gamma(\pm)} \sigma_{\mu\nu} \left( \partial^\mu A^\nu \right) N + \text{H.c.}, \tag{14}
\]
\[
\mathcal{L}_{RN\gamma}^{3/2\pm} = -ie \frac{g_{RN\gamma}}{2M_N} R^{\Gamma(\pm)} F^{\mu\nu} N
\]
\[
+ e \frac{g_{RN\gamma}}{2M_N} R^{\Gamma(\pm)} F^{\mu\nu} \partial_\nu N + \text{H.c.}, \tag{15}
\]
\[
\mathcal{L}_{RN\gamma}^{5/2\pm} = e \frac{g_{RN\gamma}}{2M_N} R^{\Gamma(\pm)} \left( \partial^\mu A^\nu \right) N
\]
\[
+ ie \frac{g_{RN\gamma}}{2M_N} R^{\Gamma(\pm)} \partial_\mu \left( \partial^\nu A^\nu \right) N + \text{H.c.}, \tag{16}
\]
where \(R\) designates the \(N\) or \(\Delta\) resonance, and the superscript of \(\mathcal{L}_{RN\gamma}\) denotes the spin and parity of the resonance \(R\). The coupling constants \(g_{RN\gamma}^{(i)} \) \((i = 1, 2)\) can be, in principle, be determined by the resonance radiative decay amplitudes. Nevertheless, since the resonance hadronic coupling constants are unknown due to
the lack of experimental information on the resonance decay to $K\Sigma(1385)$, we treat the products of the electromagnetic and hadronic coupling constants—which are relevant to the production amplitudes—as fit parameters in the present work.

The effective Lagrangians for meson-baryon interactions are

$$\mathcal{L}_{\Sigma^*NK} = \frac{g_{\Sigma^*NK}}{M_K} \Sigma^* \mu (\partial \mu K) N + \text{H. c.}, \quad (17)$$

$$\mathcal{L}_{\Lambda NK} = -\frac{g_{\Lambda NK}}{2M_N} \bar{\Lambda} \gamma_5 \gamma^\mu (\partial \mu K) N + \text{H. c.}, \quad (18)$$

$$\mathcal{L}_{\Sigma^*NK^*} = -\frac{g_{\Sigma^*NK^*}}{2M_N} \bar{\Sigma} \gamma_5 \gamma^\mu \gamma_5 K^\mu \gamma^\nu N + \frac{g_{\Sigma^*NK^*}}{2M_N} \bar{\Sigma} \gamma_5 \gamma_\sigma (\partial_\sigma K^\mu \gamma_5 \gamma^\nu N) + \text{H. c.}. \quad (19)$$

The coupling constant $g_{\Lambda NK} \approx -14$ is determined by the flavor SU(3) symmetry, $g_{\Lambda NK} = (3\sqrt{3}/5) g_{\Sigma^*NK^*}$ with $g_{\Sigma^*NK^*} = 13.46$. The coupling constants $g_{\Sigma^*NK}$ and $g_{\Sigma^*NK^*}$ are also fixed by the flavor SU(3) symmetry [18-19].

$$\frac{g_{\Sigma^*NK}}{M_K} = -\frac{g_{\Delta N\pi}}{\sqrt{6} M_\pi}, \quad (20)$$

$$\frac{g_{\Sigma^*NK^*}}{M_K} = -\frac{1}{\sqrt{6} g_{\Delta N\rho}}. \quad (21)$$

By use of the value $g_{\Delta N\pi} = 2.23$ which is determined from the $\Delta$ resonance decay width, $\Gamma \rightarrow N\pi = 120$ MeV, and the empirical value $g_{\Delta N\rho} = -39.1$, one gets $g_{\Sigma^*NK} = -3.22$ and $g_{\Sigma^*NK^*} = -15.96$. As the $g$-(2) and $g$-(3) terms in the $\Delta N\rho$ interactions have never been seriously studied in literature, the corresponding coupling constants in $\Sigma^*NK^*$ vertices, i.e. $g_{\Sigma^*NK^*}$ and $g_{\Sigma^*NK}$, cannot be determined via flavor SU(3) symmetry, and we ignore these two terms in the present work, following Refs. [20-23].

The effective Lagrangians for resonance hadronic vertices can be written as

$$\mathcal{L}_{R^2\Sigma^*K}^{1/2} = \frac{g_{R^2\Sigma^*K}}{M_K} \bar{\Sigma} \gamma_5 \gamma^\mu (\partial \mu K) R + \text{H. c.}, \quad (22)$$

$$\mathcal{L}_{R^2\Sigma^*K}^{3/2} = \frac{g_{R^2\Sigma^*K}}{M_K} \bar{\Sigma} \gamma_5 \gamma^\mu (\partial_\mu K) R^\mu + \frac{g_{R^2\Sigma^*K}}{2M_K} \bar{\Sigma} \gamma_5 \gamma^\mu (\partial_\mu \partial_\nu K) R_\mu \rho + \text{H. c.}, \quad (23)$$

$$\mathcal{L}_{R^2\Sigma^*K}^{5/2} = \frac{g_{R^2\Sigma^*K}}{M_K} \bar{\Sigma} \gamma_5 \gamma^\mu \gamma^\nu (\partial_\mu K) R^{\alpha \beta} + \frac{g_{R^2\Sigma^*K}}{M_K} \bar{\Sigma} \gamma_5 \gamma^\mu (\partial^\mu \partial^\nu K) R_\alpha \beta + \text{H. c.}. \quad (24)$$

In the present work, the $g_{R^2\Sigma^*K}^{(2)}$ terms in $\mathcal{L}_{R^2\Sigma^*K}^{3/2\pm}$ and $\mathcal{L}_{R^2\Sigma^*K}^{5/2\pm}$ are ignored for the sake of simplicity. The coupling constants $g_{R^2\Sigma^*K}^{(1)}$ are treated as fit parameters. Actually, only the products of the electromagnetic couplings and the hadronic couplings of $N$ or $\Delta$ resonances are relevant to the reaction amplitudes, and these products are what we really fit in practice.

The effective Lagrangian for the Kroll-Ruderman term of $\gamma N \rightarrow K\Sigma(1385)$ reads

$$\mathcal{L}_{\gamma \Sigma \Lambda NK} = -iQ_K \frac{g_{\Sigma^*NK}}{M_K} \Sigma^* \mu A_\mu K N + \text{H. c.}, \quad (25)$$

which is obtained by the minimal gauge substitution $\partial_\mu \rightarrow D_\mu \equiv \partial_\mu - iQ_K A_\mu$ in the $\Sigma^*NK$ interaction Lagrangian of Eq. (17). The coupling constant $g_{\Sigma^*NK}$ has been given in Eq. (20).

### B. Resonance propagators

For spin-$1/2$ resonance propagator, we use the ansatz

$$S_{1/2}(p) = \frac{i}{p - M_R + i\Gamma_R/2}, \quad (26)$$

where $M_R$ and $\Gamma_R$ are, respectively, the mass and width of resonance $R$, and $p$ is the resonance four-momentum.

Following Refs. [24-26], the prescriptions of the propagators for resonances with spin-$3/2$ and -$5/2$ are

$$S_{3/2}(p) = \frac{i}{p - M_R + i\Gamma_R/2} \left( \begin{array}{c} \gamma_\mu + \frac{1}{3} \gamma_\mu \gamma_\nu \gamma_\nu \gamma_\alpha \\ -\frac{1}{\sqrt{2}} \gamma_\mu \gamma_\nu \gamma_\alpha + \frac{1}{\sqrt{2}} \gamma_\mu \gamma_\nu \gamma_\alpha \\ \gamma_\nu \gamma_\mu \gamma_\nu \gamma_\alpha + \frac{1}{\sqrt{2}} \gamma_\nu \gamma_\mu \gamma_\nu \gamma_\alpha \end{array} \right), \quad (27)$$

where

$$\gamma_\mu = \gamma_\mu + \frac{p_\mu p_\nu}{M_R^2}. \quad (29)$$

$$\gamma_\nu = \gamma_\nu + \frac{p_\mu p_\nu}{M_R^2}. \quad (30)$$

### C. Form factors

Each hadronic vertex obtained from the Lagrangians given in Sec. [14] is accompanied with a phenomenological form factor to parametrize the structure of the hadrons and to normalize the behavior of the production amplitude. Following Refs. [21, 22], for intermediate...
baryon exchange we take the form factor as

\[ f_B(p^2) = \left( \frac{\Lambda_B^2}{\Lambda_B^2 + (p^2 - M_B^2)^2} \right)^2, \]

where \( p \) and \( M_B \) denote the four-momentum and the mass of the exchanged baryon \( B \), respectively. The cutoff mass \( \Lambda_B \) is treated as a fit parameter for each exchanged baryon. For intermediate meson exchange, we take the form factor as

\[ f_M(q^2) = \left( \frac{\Lambda_M^2 - M_M^2}{\Lambda_M^2 - q^2} \right)^2, \]

where \( q \) represents the four-momentum of the intermediate meson, and \( M_M \) and \( \Lambda_M \) designate the mass and cutoff mass of exchanged meson \( M \), respectively. In the present work, we use the same cutoff parameter, \( \Lambda_{K,K^*} \), for both \( K \) and \( K^* \) exchanges in the \( t \) channel.

Note that the gauge-invariance feature of our photoproduction amplitude is independent of the specific form of the form factors.

### III. RESULTS AND DISCUSSION

As mentioned in Sec. [1] the reaction \( \gamma p \to K^+\Sigma^0(1385) \) has been investigated in Refs. [8, 10] within hadronic models based on effective Lagrangian approaches. In these two works, eight or nine \( N \) and \( \Delta \) resonances around 2 GeV among tens of resonances predicted by a quark model [9] have been considered. The resonance masses are taken from the quark model calculations. The resonance hadronic and electromagnetic coupling constants are determined by the resonance decay amplitudes calculated in the quark model [9]. The resonance widths are set to be a common value, 300 or 500 MeV. It was found that in Ref. [8] the contributions from the \( N \) and \( \Delta \) resonances to the cross sections are finite, and in Ref. [10] the contributions from the \( N \) and \( \Delta \) resonances are even smaller than those in Ref. [8] due to a much larger width being set for all the resonances.

In the present work, we analyze the available cross-section data for \( \gamma p \to K^+\Sigma^0(1385) \) within an effective Lagrangian approach at the tree-level Born approximation, with the purpose being to understand the reaction mechanisms and the resonance contents and their associated parameters in this reaction. In addition to the \( t \)-channel \( K \) and \( K^* \) exchanges, the \( s \)-channel \( N \) exchange, the \( u \)-channel \( \Lambda \) exchange, and the generalized contact term, we introduce a minimum number of \( N \) and \( \Delta \) resonances in the \( s \) channel in constructing the reaction amplitudes to describe the data. We take the PDG values for resonance masses and widths, and treat the products of resonance electromagnetic and hadronic coupling constants as fit parameters due to the lack of experimental information on resonance decays to \( K\Sigma(1385) \).

As mentioned above, we introduce \( N \) and \( \Delta \) resonances as few as possible to describe the data. If no resonance exchange is taken into account, we find that the experimental data in the high-energy region can be well described without any problem. However, the calculated theoretical cross sections in the low-energy region are much smaller than the corresponding experimental values, indicating the indispensability of the contributions from the \( N \) or \( \Delta \) resonances. We then introduce one resonance in the \( s \)-channel in constructing the reaction amplitudes. We test one by one of all the \( N \) and \( \Delta \) resonances with different spin-parity near the \( K\Sigma(1385) \) threshold in PDG [12]. Finally, we find that the most recent available differential cross-section data for \( \gamma p \to K^+\Sigma^0(1385) \) from the CLAS Collaboration [7] can be satisfactorily described with one of the \( N(1895)1/2^- \), \( \Delta(1900)1/2^- \), and \( \Delta(1930)5/2^- \) resonances, among which the first one is evaluated by PDG as a four-star resonance and the other two are evaluated as three-star resonances. We refer to the models including the \( N(1895)1/2^- \), \( \Delta(1900)1/2^- \), and \( \Delta(1930)5/2^- \) resonances as model I, model II, and model III, respectively. The parameters of these three models are listed in Table I and the corresponding theoretical results for differential cross sections are shown, respectively, in Figs. 2–4.

In Table I the uncertainties of the values of fit parameters are estimates arising from the uncertainties (error bars) associated with the fitted experimental differential cross-section data. One sees from Table I that the values of \( \Lambda_{K,K^*} \), the cutoff parameter for the \( t \)-channel \( K \) and \( K^* \) exchanges, are close to each other in all these three models, indicating similar contributions from \( t \)-channel \( K \) and \( K^* \) exchanges in these models. The values of \( \Lambda_N \), the cutoff parameter for the \( s \)-channel \( N \) exchange,
are very close to each other in models I and II, and both are much larger than that in model III, implying much smaller contributions from \(s\)-channel \(N\) exchange in model III than in models I and II. For the \(u\)-channel \(\Lambda\) exchange, the values of the cutoff parameter \(\Lambda_{\Lambda}\) in models I, II, and III are close to each other, but the values for the coupling constants are not, resulting in different \(u\)-channel contributions in these three models as can be seen in Figs. 2–4. For \(N\) and \(\Delta\) resonances, the asterisks below resonance names denote the overall status of these resonances evaluated by PDG \[12\]. The resonance mass \(M_R\) and width \(\Gamma_R\) in all these three models are not treated as fit parameters, but fixed to be the corresponding values estimated by PDG. The numbers in brackets below \(M_R\) and \(\Gamma_R\) represent the range of the corresponding quantities given by PDG \[12\]. The resonance cutoff parameter and the products of the resonance hadronic and electromagnetic coupling constants are determined by fits to the differential cross-section data.

The theoretical results of the differential cross sections for \(\gamma p \rightarrow K^+ \Sigma^0(1385)\) obtained in models I, II, and III

**FIG. 2.** (Color online) Differential cross sections for \(\gamma p \rightarrow K^+ \Sigma^0(1385)\) as a function of \(\cos \theta\) in model I. The black solid lines represent the results from the full calculation. The cyan dash-doted, blue dashed, green dash-double-dotted, red dot-double-dashed, and violet dotted lines represent the individual contributions from the \(s\)-channel \(N(1895)1/2^-\) exchange, the generalized contact term, the \(u\)-channel \(\Lambda\) exchange, the \(t\)-channel \(K\) exchange, and the \(s\)-channel \(N\) exchange, respectively. The scattered symbols denote the data from the CLAS Collaboration \[7\]. The numbers in parentheses denote the centroid value of the photon laboratory incident energy (left number) and the corresponding total center-of-mass energy of the system (right number), in MeV.

**FIG. 3.** (Color online) Differential cross sections for \(\gamma p \rightarrow K^+ \Sigma^0(1385)\) as a function of \(\cos \theta\) in model II. The notations are the same as in Fig. 2 except that the cyan dash-doted lines now represent the individual contributions from the \(s\)-channel \(\Delta(1900)1/2^-\) exchange.

**FIG. 4.** (Color online) Differential cross sections for \(\gamma p \rightarrow K^+ \Sigma^0(1385)\) as a function of \(\cos \theta\) in model III. The notations are the same as in Fig. 2 except that the cyan dash-doted lines now represent the individual contributions from the \(s\)-channel \(\Delta(1930)5/2^-\) exchange.
The differential cross sections at forward angles are dominated by the generalized contact term followed by the $t$-channel $K$ exchange, and the differential cross sections at backward angles are dominated by the $u$-channel $\Lambda$ exchange. In the whole energy region, the contributions from the $t$-channel $K$ exchange in all the models I, II, and III are very similar, which is easy to be understood since the values of the cutoff parameter $\Lambda_K$ are very close to each other in these three models as listed in Table I. The contributions from the generalized contact term in models I and II are very similar to each other, but both are smaller than those in model III in backward and intermediate angles. This is principally because the contributions of the generalized contact term are relevant to the cutoff parameters $\Lambda_K$ and $\Lambda_N$ via the form factors $f_t$ and $f_s$ (cf. Eq. (5)), while the values of $\Lambda_K$ in all the models I–III are very close to each other, and the values of $\Lambda_N$ in models I and II are almost the same but both are much larger than that in model III. The contributions from the $u$-channel $\Lambda$ exchange are noticeable at backward angles in the high-energy region, and are a little bit bigger in models I and II than in model III. The contributions from the $s$-channel $N$ exchange are visible but small at high energies in models I and II, while they are too small to be plotted in model III due to the much smaller values of $\Lambda_N$.

One sees from Figs. 2–4 that the overall agreement of our theoretical results with the CLAS differential cross-section data is rather satisfactory in all the models I, II, and III. In the low-energy region, the differential cross sections are dominated by the generalized contact term and the resonance exchange. In the high-energy region, the differential cross sections at forward angles are dominated by the generalized contact term followed by the $t$-channel $K$ exchange, and the differential cross sections at backward angles are dominated by the $u$-channel $\Lambda$ exchange. In the whole energy region, the contributions from the $t$-channel $K$ exchange in all the models I, II, and III are very similar, which is easy to be understood since the values of the cutoff parameter $\Lambda_K$ are very close to each other in these three models as listed in Table I. The contributions from the generalized contact term in models I and II are very similar to each other, but both are smaller than those in model III in backward and intermediate angles. This is principally because the contributions of the generalized contact term are relevant to the cutoff parameters $\Lambda_K$ and $\Lambda_N$ via the form factors $f_t$ and $f_s$ (cf. Eq. (5)), while the values of $\Lambda_K$ in all the models I–III are very close to each other, and the values of $\Lambda_N$ in models I and II are almost the same but both are much larger than that in model III. The contributions from the $u$-channel $\Lambda$ exchange are noticeable at backward angles in the high-energy region, and are a little bit bigger in models I and II than in model III. The contributions from the $s$-channel $N$ exchange are visible but small at high energies in models I and II, while they are too small to be plotted in model III due to the much smaller values of $\Lambda_N$. 

FIG. 5. Total cross sections with dominant individual contributions for $\gamma p \rightarrow K^+ \Sigma^0(1385)$. The panels from top to bottom correspond to the results of modes I–III, as indicated. The data are from CLAS [7] but not included in the fit.
smaller cutoff value of $\Lambda_N$ in model III than in models I and II. The resonance exchange contributes mainly in the low-energy region. One sees that the contributions from the resonance exchange in models I and II are similar to each other. This is mostly because in these two models, the resonances $N(1895)1/2^-$ and $\Delta(1900)1/2^-$ have the same quantum numbers of spin and parity, and the difference of the isospin factor can be absorbed into the fit parameter of the coupling constants. In model III, the resonance $\Delta(1930)5/2^-$ exchange contributes noticeably only below 3 GeV, and overall they are much smaller than the contributions of $N(1895)1/2^-$ and $\Delta(1900)1/2^-$ in models I and II. Of course, the shape of the resonance contribution in model III is quite different from those in models I and II due to the difference of the resonance quantum numbers.

Figure 5 shows our predicted total cross sections (black solid lines) together with individual contributions from the interaction current (blue dashed lines), the $s$-channel resonance exchange (cyan dash-dotted lines), the $u$-channel $\Lambda$ exchange (green dash-double-dotted lines), the $t$-channel $K$ exchange (dot-double-dashed lines), and the $s$-channel $N$ exchange (violet dotted lines) obtained by integrating the corresponding results for differential cross sections from models I–III. The contributions from the $t$-channel $K^*$ exchange are not plotted since they are too small to be clearly seen with the scale used. Note that the total cross-section data are not included in our fits. One sees from Fig. 5 that in all the models I–III, our predicted total cross sections are in good agreement with the data over the entire energy region considered. It is seen that in all these three models, the generalized contact term has dominant contributions. Actually, as has been discussed in connection with the differential cross section results, the generalized contact term is relevant to the parameters $\Lambda_K$ and $\Lambda_N$ via the $t$-channel and $s$-channel form factors (cf. Eq. 5). Therefore, in models I and II, the contributions from the generalized contact current are similar, and they both are a little bit smaller than those in model III, since the values of $\Lambda_K$ are similar in models I–III, while the values of $\Lambda_N$ are almost the same in models I and II but both are much larger than that in model III. The contributions from the $t$-channel $K$ exchange are considerable in models I–III, and they are almost the same in all these three models due to the similar values of the cutoff parameter $\Lambda_K$. Small but noticeable contributions of the $u$-channel $\Lambda$ exchange to the total cross sections are seen, and these contributions are bigger in models I and II than in model III. The contributions from the $s$-channel $N$ exchange are even smaller than the $u$-channel $\Lambda$ exchange, and in model III they are not plotted as they are too small due to the much smaller cutoff value of $\Lambda_N$ in model III than in models I and II. In all the models I–III, the contributions from the resonances are responsible for the bump structure exhibited by the total cross-section data. It is seen that the resonance exchange provides more important contributions in models I and II than in model III.

As can be seen in Figs. 2–5 and as has been discussed above, the models I–III describe the CLAS cross-section data for $\gamma p \rightarrow K^+\Sigma^0(1385)$ quite well with similar fit qualities in the whole energy region considered. Nevertheless, the resonance contents in these three models are quite different. It is expected that the spin observables are more sensitive to the dynamical contents of various models. In Figs. 6–7 we show the predictions of the photon beam asymmetry (\(\Sigma\)) and target nucleon asymmetry (T) from our present models. There, the black solid curve, blue double-dash-dotted curve, and green dashed curve represent the predictions from the models I–III, respectively. One sees that the $\Sigma$ in model I is similar to that in model II, both different from that in model III. So is the T. This means that model III can be distinguished from models I and II by such spin observables, but models I and II are still indistinguishable. This is not a big surprise if one notices that the major difference of models I and II is that the resonance has isospin 1/2 in model I and 3/2 in model II, while the resonance isospin factor can be absorbed into the fit parameters of the resonance coupling constants. Therefore, the contributions from all individual terms to differential and total cross sections in model I and model II are almost the same, as can be seen from Figs. 2–5. Given this, one understands that...
neither the $\Sigma$ and $T$ but nor the other spin observables for $\gamma p \to K^+\Sigma^0(1385)$ can be used to distinguish models I and II. Instead, the cross sections or spin observables for $\gamma p \to K^0\Sigma^+(1385)$ should be able to distinguish the models I–III due to the differences of isospin factors.

In Fig. 8, we show the predicted total cross sections together with dominant individual contributions for $\gamma p \to K^0\Sigma^+(1385)$ in models I–III. Note that there is no free parameters to calculate these results. All the differences of these contributions for $\gamma p \to K^0\Sigma^+(1385)$ compared with those for $\gamma p \to K^+\Sigma^0(1385)$ are due to the differences of the isospin factors for various interacting terms. In particular, the dominant contributions of the contact term and the considerable contributions of the $t$-channel $K$ exchange in $\gamma p \to K^+\Sigma^0(1385)$ now vanish in $\gamma p \to K^0\Sigma^+(1385)$. The contributions from the $N$ resonance exchange in $\gamma p \to K^0\Sigma^+(1385)$ are double of those in $\gamma p \to K^+\Sigma^0(1385)$, while the contributions from the $\Delta$ resonance exchange in $\gamma p \to K^0\Sigma^+(1385)$ are one half of those in $\gamma p \to K^+\Sigma^0(1385)$. Finally, one sees that the total cross sections for $\gamma p \to K^0\Sigma^+(1385)$ in models I–III are quite different, unlike the case of $\gamma p \to K^0\Sigma^+(1385)$ where the models I–III result in almost the same total cross sections. Therefore, the data on the total cross sections for $\gamma p \to K^0\Sigma^+(1385)$ could be used to distinguish the models I–III. We mention that for the same reason, the other observables of $\gamma p \to K^0\Sigma^+(1385)$ can also be used to further constrain the theoretical models of $\gamma p \to K^+\Sigma^0(1385)$.

IV. SUMMARY AND CONCLUSION

In the present work, we employ an effective Lagrangian approach at the tree-level Born approximation to analyze the most recent differential cross-section data from the CLAS Collaboration for the $\gamma p \to K^+\Sigma^0(1385)$ reaction. In addition to the $t$-channel $K$ and $K^*$ exchanges, the $s$-channel $N$ exchange, the $u$-channel $\Lambda$ exchange, and the generalized contact current, the exchanges of a minimum number of $N$ and $\Delta$ resonances in the $s$-channel are introduced in constructing the reaction amplitudes to describe the data. The $s$, $u$, and $t$-channel amplitudes are obtained by evaluating the corresponding Feynman diagrams, and the generalized contact current is constructed in such a way that the full photoproduction amplitudes are fully gauge invariant. It is found that the CLAS differential cross-section data for $\gamma p \to K^+\Sigma^0(1385)$ can be well described by including one of the $N(1895)1/2^-$, $\Delta(1900)1/2^-$, and $\Delta(1930)5/2^-$ resonances, with the resonance mass and width being fixed to their PDG values and the resonance coupling constants being determined by fits to the data. The total cross sections predicted in the theoretical models are in good agreement with the corresponding data.

It is shown that the generalized contact term provides dominant contributions to the differential cross sections of $\gamma p \to K^+\Sigma^0(1385)$ in the whole energy region considered. The $t$-channel $K$ exchange has important contributions to the differential cross sections at forward angles in the high-energy region, and the $u$-channel $\Lambda$ exchange has considerable contributions to the differential cross sections at backward angles in the high-energy region. The $s$-channel resonance exchange has significant contributions to the differential cross sections in the low-energy region. The total cross sections are dominated by the contributions from the generalized contact term and the $s$-channel resonance exchange, with the later being responsible for the bump structure exhibit by the CLAS total cross-section data. The $t$-channel $K$ exchange has noticeable but small contributions to the total cross sections. The $u$-channel $\Lambda$ exchange followed by the $s$-channel $N$ exchange has even smaller contributions to the total cross sections than the $t$-channel $K$ exchange.

The predictions of the photon beam asymmetry ($\Sigma$) and target nucleon asymmetry ($T$) from our theoretical models are also presented for the $\gamma p \to K^+\Sigma^0(1385)$ reaction. The shape of them in model I are similar to these in model II, and both are different from those in model III. The predications of the total cross sections for the $\gamma p \to K^0\Sigma^+(1385)$ reaction are also given, which are shown to be quite different in various theoretical models, and are expected to further constrain the theoretical models for $\gamma p \to K^+\Sigma^0(1385)$, leading to a better understanding of the reaction mechanisms and the resonance contents and associated parameters in this reaction.

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