$\Sigma(1385)$ photoproduction from the proton within a Regge-plus-resonance approach

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The interaction mechanism of the $\Sigma(1385)$ photoproduction from proton $\gamma p \to K^+\Sigma^0(1385)$ is investigated within a Regge-plus-resonance approach based on the experimental data released by the CLAS Collaboration recently. The t channel and the u channel are responsible for the behaviors of differential cross sections at forward and backward angles, respectively. The contributions from nucleon resonances including N^* and Δ^*, which are determined by the predicted decay amplitudes in the constituent quark model, are found to be small, but the F_{35} state $\Delta(2000)$ is essential to reproduce the differential cross section.

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I. INTRODUCTION

The study of nucleon resonances is an important topic of hadron physics. The information about nucleon resonance is mainly extracted from the pion-nucleon scattering especially in the early stage of the study of nucleon resonance [1]. Based on a large number of nucleon resonances found in the experiment, the constituent quark model (CQM) was developed and achieved great success in the explanation about the property of nucleon resonance [2,3]. However, the predicted nucleon resonances in the CQM are much more than the ones found in the experiment, which is the so-called "missing resonance" problem. One explanation about this problem is that the decay ratio of the "missing resonance" is very small in the usual experimental detected channels, such as the pion-nucleon channel. Hence, the channels more than the pion-nucleon channel, such as the ηN and strange channels, attract much attention.

A large amount of experimental data of the kaon photoproduction companied by a ground strange baryon Λ or Σ have been accumulated in recent years [4]. However, the study of the kaon photoproduction with a strange baryon resonance is scarce. Very recently, the CLAS Collaboration released their experimental data about the kaon photoproduction with $\Sigma(1385)$, $\Lambda(1520)$, and $\Lambda(1405)$ with high precision [5], which provide an opportunity to study nucleon resonances in these channels.

The strong decays of nucleon resonances to $\Sigma(1385)$, $\Lambda(1520)$, or $\Lambda(1405)$ witha kaon meson have been studied in the CQM [6]. Combined with the theoretical prediction about the radiative decay [7], one can make a rough estimation about which nucleon resonances play important roles in a certain photoproduction process. For example, the large decay widths to $N\gamma$ and $K\Lambda(1520)$ suggest that $N(2120)$ should be easy to be found in the kaon photoproduction with $\Lambda(1520)$, which has been confirmed by many theoretical analyses of the $\Lambda(1520)$ photoproduction data [8,9]. The CQM prediction suggests a large decay ratio of the D_{13} state $N(2095)$ and the F_{35} state $\Delta(2000)$ in the $\Sigma(1385)K$ decay channel [6]. Hence it is interesting to study the roles played by such states in the $\Sigma(1385)$ photoproduction.

There exist only some old experimental data about the $\Sigma(1385)$ photoproduction with low precision, which were obtained before the 1970s [10,11]. The LEPS Collaboration also released some results in this channel but only at extreme forward angles [12]. Correspondingly, theoretical studies are also scarce. In Ref. [13] the $\Sigma(1385)$ photoproduction has been studied in an effective Lagrangian approach based on the preliminary data from CLAS Collaboration. However, due to the absence of the constraint of the precise data large discrepancies at low energies between the experimental data and the theoretical predictions can be found in the differential cross section released by the CLAS Collaboration [5]. In this work, I will analyze the new CLAS data within a Regge-plus-resonance approach and investigate the roles played by nucleon resonances.

This paper is organized as follows. After the Introduction, I will present the effective Lagrangian used in this work and Reggeized treatment for the t channel. The gauge invariance will also be discussed in this section. The numerical results for the cross section will be given and compared with the experimental data in Sec. III. Finally, the paper ends with a brief summary.

II. FORMALISM

The four types of interaction mechanism, the s channel, the u channel, the t channel, and the contact term for the $\Lambda(1520)$ photoproduction from a nucleon with K are presented in Fig. 1. The Born terms contain the N, Y, K intermediate states and the contact term.

For the Born s channel, t channel, and contact term, the Lagrangians involved are given as below:

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

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

$$\mathcal{L}_{\gamma NN} = -e\bar{N}\left(e_N\gamma^\mu - \frac{\kappa_N}{2M_N}\sigma^{\mu\nu}\partial_\nu\right)A_\mu N, \quad (3)$$

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

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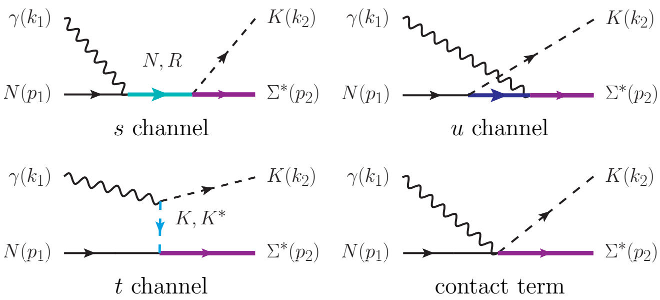

FIG. 1. (Color online) The diagrams for the s, u, and t channels and contact term for $\gamma p \to K^+\Sigma^0(1385)$.

where A^μ, N, K, $\Sigma^{*\mu}$ are the photon, nucleon, kaon, and $\Sigma^*(1385)$ fields and the charge of the nucleon $e_N = 1,0$ for proton and neutron in the unit of $e = \sqrt{4\pi\alpha}$ with α being the fine-structure constant. The anomalous magnetic moment $\kappa_N = 1.79$ for the proton. m_K and M_N are the masses of the kaon and nucleon. The coupling constant for the $KN\Sigma^*$ vertex can be related to the $\pi N\Delta$ coupling by the SU(3) flavor symmetry relation, and the value $f_{KN\Sigma^*} = -3.22$ can be obtained [13,14].

The t channel for the $\Sigma(1385)$ photoproduction occurs through both K and K^* exchanges. As shown in Ref. [13], the contribution from the K^* exchange is negligible at energies $E_\gamma = 3 \sim 4$ GeV with the reasonable coupling constant. Hence only the K exchange will be considered in this work.

The u channel diagram shown in Fig. 1 contains intermediate hyperons. The effective Lagrangians for these diagrams are

$$\begin{aligned}\mathcal{L}_{\Sigma^*Y\gamma} &= -\frac{ief_1}{2M_Y}\overline{Y}\gamma_\nu\gamma_5 F^{\mu\nu}\Sigma^*_\mu \\ &\quad - \frac{ef_2}{(2M_Y)^2}\partial_\nu\overline{Y}\gamma_5 F^{\mu\nu}\Sigma^*_\mu + \text{H.c.},\\ \mathcal{L}_{KNY} &= \frac{g_{KNY}}{M_N+M_Y}\overline{N}\gamma^\mu\gamma_5 Y\partial_\mu K + \text{H.c.},\end{aligned} \quad (5)$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ and Y stands for a hyperon with spin-1/2 carrying a mass M_Y. For the intermediate $\Lambda(1116)$ state, $f_1 = 4.52$ and $f_2 = 5.63$ [13]. The coupling constant $g_{KN\Lambda}$ can be determined by the flavor SU(3) symmetry relation, which gives a value $g_{KN\Lambda} = -13.24$ [13]. The Σ exchange is negligible due to to the small coupling constant determined from SU(3) symmetries [13]. Besides, the effect of higher resonances can be included through Reggeized treatment. Due to the large uncertainty at backward angles of the CLAS experimental data and much larger masses of Λ and Σ baryons compared with the mass of K in the t channel we do not consider the Reggeized treatment in the u channel in this work as Ref. [15].

The amplitude for the u channel is gauge invariant itself while the amplitudes for the Born s channel, t channel, and contact term are not gauge invariant. After summing up the amplitudes from the s channel, the t channel, and the contact term of the $\Sigma(1385)$ photoproduction, the gauge invariance can be guaranteed as the π and $\Lambda(1520)$ photoproductions [16,17]. The effect of the hadron internal structure can be reflected by the form factor added at each vertex. Unfortunately, it will violate the gauge invariance. To restore the gauge invariance, a generalized contact term is introduced as [18]

$$\begin{aligned}\mathcal{M}_c^{\mu\nu} &= \frac{ief_{KN\Sigma^*}}{m_K}\bigg[g^{\mu\nu}F_t + k_2^\mu(2k_2-k_1)^\nu \\ &\quad\times\frac{(F_t-1)[1-h(1-F_s)]}{t-m_K^2}\\ &\quad + k_2^\mu(2p_1-k_1)^\nu\frac{(F_s-1)[1-h(1-F_t)]}{s-M_N^2}\bigg],\end{aligned} \quad (6)$$

where the h is a free parameter and will be fitted and F_i with $i = s,t$ is the form factor.

In this work, for the Born s channel and the u channel we choose the form factor in the form

$$F_i(q^2) = \left(\frac{n\Lambda_i^4}{n\Lambda_i^4 + (q^2-M^2)^2}\right)^n, \quad (7)$$

which goes to Gaussian form as $n \to \infty$ and for t channel K exchange,

$$F_i(q^2) = \frac{\Lambda_i^2 - M^2}{\Lambda_i^2 - q^2}, \quad (8)$$

where M and q are the mass and momentum of the off-shell intermediate particle. The cutoff Λ_i for the s, u, or t channel should be about 1 GeV and will be set as a free parameter in this work.

I introduce a K Reggeized treatment as follows to describe the behavior of the differential cross section of the $\Sigma(1385)$ photoproduction at high photon energies [15,19,20]:

$$\frac{1}{t-m_K^2} \to \mathcal{D}_K = \left(\frac{s}{s_{\text{scale}}}\right)^{\alpha_K}\frac{\pi\alpha'_K}{\Gamma(1+\alpha_K)\sin(\pi\alpha_K)}, \quad (9)$$

where α'_K is the slope of the trajectory and the scale factor s_{scale} is fixed at 1 GeV^2. α_K is the linear trajectory of the K meson, which is a function of t assigned as follows: $\alpha_K = 0.70\,\text{GeV}^{-2}(t-m_K^2)$. The K^* Reggeized treatment is analogous. There is no reason *a priori* that the coupling constants for Reggeized treatment $f^{\text{Reg}}_{KN\Sigma^*}$ and $f^{\text{Reg}}_{K^*N\Sigma^*}$ are the same as those for the real K and K^* exchange [21]. The same observation applies to the Reggeized K^* coupling. In this work we set them as free parameters. I expect the difference should not be very large, so the K^* exchange is still very small and omitted in this work as Ref. [13].

The Reggeized treatment should work completely at high photon energies and interpolate smoothly to low energies. It is implemented by Toki *et al.* [21] and Nam and Kao [17] by introducing a weighting function $\mathcal{R}$. Here we adopt the treatment as

$$\frac{F_t}{t-m_K^2} \to \frac{F_t}{t-m_K^2}\mathcal{R} = \mathcal{D}_K R + \frac{F_t}{t-m_K^2}(1-R), \quad (10)$$

where $R = R_s R_t$ with

$$R_s = \frac{1}{2}\left[1 + \tanh\left(\frac{s - s_{\rm Reg}}{s_0}\right)\right],$$
$$R_t = 1 - \frac{1}{2}\left[1 + \tanh\left(\frac{|t| - t_{\rm Reg}}{t_0}\right)\right]. \quad (11)$$

The free parameters $s_{\rm Reg}$, s_0, $t_{\rm Reg}$, and t_0 will be fitted with the differential cross section.

As an inclusion of the from factor F_i, the Reggeized treatment will violate the gauge invariance and current conservation also. To restore the current conservation, I redefine the relevant amplitudes,

$$\begin{aligned} i\mathcal{M}^{\mu\nu} &= i\mathcal{M}_t^{\mu\nu} + i\mathcal{M}_s^{\mu\nu} + i\mathcal{M}_c^{\mu\nu} \\ &\to \left(i\mathcal{M}_t^{\mu\nu} + i\mathcal{M}_s^{\mu\nu} + i\mathcal{M}_c^{\mu\nu}\right)\mathcal{R} \\ &\equiv i\mathcal{M}_t^{\mathrm{Reg}\ \mu\nu} + \left(i\mathcal{M}_s^{\mu\nu} + i\mathcal{M}_c^{\mu\nu}\right)\mathcal{R}. \end{aligned} \quad (12)$$

With such definition, the relation $k_1^\mu \mathcal{M}^{\mu\nu} = 0$ is satisfied. For the nucleon resonance contributions, I adopt the Lagrangians for the radiative decay,

$$\begin{aligned} \mathcal{L}_{\gamma NR(\frac{1}{2}^\pm)} &= \frac{ef_2}{2M_N}\bar{N}\Gamma^{(\mp)}\sigma_{\mu\nu}F^{\mu\nu}R + \text{H.c.}, \\ \mathcal{L}_{\gamma NR(J^\pm)} &= \frac{-i^n f_1}{(2M_N)^n}\bar{N}\gamma_\nu\partial_{\mu_2}\cdots\partial_{\mu_n}F_{\mu_1\nu}\Gamma^{\pm(-1)^{n+1}}R^{\mu_1\mu_2\cdots\mu_n} \\ &\quad + \frac{-i^{n+1} f_2}{(2M_N)^{n+1}}\partial_\nu\bar{N}\partial_{\mu_2}\cdots\partial_{\mu_n}F_{\mu_1\nu}\Gamma^{\pm(-1)^{n+1}}R^{\mu_1\mu_2\cdots\mu_n} \\ &\quad + \text{H.c.}, \end{aligned} \quad (13)$$

where $F^{\mu\nu} = \partial^\mu A\nu - \partial^\nu A_\mu$ with $R_{\mu_1\cdots\mu_n}$ is the field for the nucleon resonance with spin $J = n + 1/2$, and $\Gamma^{(\pm)} = (i\gamma_5, 1)$ for the different resonance parity. The Lagrangians here are also adopted from the previous works on nucleon resonances with spins 3/2 or 5/2 [8,13,17].

The Lagrangians for the strong decay can be written as

$$\begin{aligned} \mathcal{L}_{R(\frac{1}{2}^\pm)K\Sigma^*} &= \frac{h_2}{2m_K}\partial_\mu K\bar{\Sigma}_\mu^*\Gamma^{(\pm)}R, + \text{H.c.}, \\ \mathcal{L}_{R(J^\pm)K\Sigma^*} &= \frac{-i^{n+1}h_1}{m_K^n}\bar{\Sigma}_{\mu_1}^*\gamma_\nu\partial_\nu\partial_{\mu_2}\cdots\partial_{\mu_n}K\Gamma^{\pm(-1)^n}R^{\mu_1\mu_2\cdots\mu_n} \\ &\quad + \frac{-i^n h_2}{m_K^{n+1}}\bar{\Sigma}_\alpha^*\partial_\alpha\partial_{\mu_1}\partial_{\mu_2}\cdots\partial_{\mu_n}K\Gamma^{\pm(-1)^n}R^{\beta\mu_1\mu_2\cdots\mu_n} \\ &\quad + \text{H.c.} \end{aligned} \quad (14)$$

In this work the coupling constants f_1, f_2, h_1, and h_2 will be determined by the helicity amplitudes $A_{1/2}$ and $A_{3/2}$ and the decay amplitudes $G(\ell_1)$ and $G(\ell_2)$, which are obtained in the CQM. The interested reader is referred to Refs. [9,13] for further information.

In this work the nucleon resonances R including N^* and Δ^* will be considered. The resonance field R carries either isospin-1/2 or isospin-3/2. By omitting the space-time indices, the isospin structure of $RK\Sigma^*$ vertex reads as

$$\overline{R}\boldsymbol{\Sigma}^*\cdot\boldsymbol{\tau}K = p\Sigma^0K^+ - n\Sigma^0K^0 + \sqrt{2}n\Sigma^-K^+ + \sqrt{2}p\Sigma^+K^0, \quad (15)$$

for resonance R with isospin-1/2. If the resonance R carries isospin-3/2, the effective Lagrangian has the isospin structure as

$$\begin{aligned} \overline{R}\boldsymbol{\Sigma}^*\cdot\boldsymbol{T}K &= \sqrt{3}\Delta^{++}\Sigma^+K^+ - \sqrt{2}\Delta^+\Sigma^0K^+ - \Delta^0\Sigma^-K^+ \\ &\quad - \sqrt{2}\Delta^0\Sigma^0K^0 + \Delta^+\Sigma^+K^0 - \sqrt{3}\Delta^-\Sigma^-K^0. \end{aligned} \quad (16)$$

III. RESULTS

As shown in the previous section, I consider the s channel with intermediate nucleon, the Reggeized t channel with K exchange, the u channel with intermediate Λ, the contact term, and the nucleon resonance intermediate s channel in the $\Sigma(1385)$ photoproduction. By using the MINUIT code the differential cross section recently released by the CLAS Collaboration will be fitted with the help of the Lagrangians presented in the previous section. The free parameters involved and their fitted values are listed in Table I. Here I exclude total cross section in the fitting procedure because it can be obtained by integrating the differential cross section.

As expected, the fitted values of cutoffs Λ_i for the s channel, the t channel, the u channel, and the nucleon resonance contributions are close to 1 GeV. The $s_{\rm Reg}$ is about 2.1 GeV, which indicate the Reggeized treatment plays an important role even at energies not as high as the K photoproduction with Λ baryon in Ref. [15]. The coupling constant $f_{KN\Sigma^*}^{\rm Reg}$ for the Reggeized t channel is about one and a half as large as the values obtained by SU(3) symmetry, which is consistent with my expectation. As will be presented, the experimental CLAS data are well reproduced with $\chi^2 = 0.8$ per degree of freedom. If the systematic uncertainties are excluded, the best fitted χ^2 per degree of freedom is 2.5. The results of the cross section are similar to those with systematic uncertainty.

A. Contributions from nucleon resonances

First, I will present the contributions from nucleon resonances. As predicted in the CQM, for the $\Sigma(1385)K$ channel the decay widths of nucleon resonances, such as $N(2095)$ and $\Delta(2000)$, are large and expected to play more important roles than other nucleon resonances [6,7]. In this work I use the following criterion to select the resonances which will be considered in the fitting:

$$\lambda = \left(A_{1/2}^2 + A_{3/2}^2\right)\left(G(\ell_1)^2 + G(\ell_2)^2\right)I^2 \cdot 10^5 > \lambda_0, \quad (17)$$

where helicity amplitudes $A_{1/2,3/2}$ and partial wave decay amplitudes $G(\ell)$ are in units of $10^{-3}/\sqrt{\rm GeV}$ and $\sqrt{\rm MeV}$. A

TABLE I. The free parameters used in fitting. The cutoffs Λ_i are in the units of GeV, the parameters $s_{\rm Reg}$, s_0, $t_{\rm Reg}$, and t_0 for Reggeized treatment are in units of GeV^2.

Λ_s	0.77 ± 0.03	Λ_t	1.48 ± 0.04	Λ_u	0.98 ± 0.01
Λ_R	1.19 ± 0.03	h	1.66 ± 0.07		
$\sqrt{s_{\rm Reg}}$	2.10 ± 0.01	s_0	0.29 ± 0.27	$\sqrt{t_{\rm Reg}}$	4.95 ± 3.62
t_0	0.88 ± 0.48	$f_{KN\Sigma^*}^{\rm Reg}$	-4.74 ± 0.02		

TABLE II. The nucleon resonances considered. The mass m_R, helicity amplitudes $A_{1/2,3/2}$, and partial wave decay amplitudes $G(\ell)$ are in units of MeV, $10^{-3}/\sqrt{\text{GeV}}$, and $\sqrt{\text{MeV}}$, respectively. The explanation about λ, $\delta\chi^2$, and $\delta\chi_r^2$ can be found in the text. In the full model $\chi^2 = 0.8[2.5]$ per degree of freedom. The values in brackets are obtained after excluding the systematic uncertainties.

State	PDG	$A_{1/2}^p$	$A_{3/2}^p$	$G(\ell_1)$	$G(\ell_2)$	λ	$\delta\chi^2$	$\delta\chi_r^2$
$[N\frac{3}{2}^-]_3(1960)$	$N(2120)D_{13}**$	36	−43	$1.3\,^{+0.4}_{-0.4}$	$1.4\,^{+1.3}_{-1.3}$	1.1	0.2 [0.8]	0.1 [0.4]
$[N\frac{3}{2}^-]_4(2055)$		16	0	$-2.5\,^{+1.0}_{-1.0}$	$-2.5\,^{+2.3}_{-1.9}$	0.3	0.0 [0.0]	0.0 [0.0]
$[N\frac{3}{2}^-]_5(2095)$		−9	−14	$7.7\,^{+1.2}_{-1.2}$	$-0.8\,^{+0.7}_{-1.0}$	1.7	0.4 [3.3]	0.1 [0.1]
$[N\frac{3}{2}^+]_3(1910)$		−21	−27	$-1.9\,^{+1.9}_{-7.3}$	$0.0\,^{+0.0}_{-0.4}$	0.4	0.0 [0.5]	0.0 [0.1]
$[N\frac{3}{2}^+]_5(2030)$		−9	15	$2.2\,^{+1.0}_{-1.9}$	$-0.2\,^{+0.1}_{-0.3}$	0.2	0.0 [0.0]	0.0 [0.0]
$[N\frac{5}{2}^+]_2(1980)$		−11	−6	$-3.6\,^{+2.5}_{-3.0}$	$-0.1\,^{+0.1}_{-0.3}$	0.2	0.2 [0.5]	0.1 [0.3]
$[\Delta\frac{3}{2}^-]_2(2080)$	$\Delta(1940)D_{33}**$	−20	−6	$-4.1\,^{+4.0}_{-1.5}$	$-0.5\,^{+0.5}_{-2.2}$	1.5	0.1 [1.1]	0.0 [0.0]
$[\Delta\frac{3}{2}^-]_3(2145)$		0	10	5.2 ± 0.4	$-1.9\,^{+1.2}_{-4.0}$	0.6	0.2 [1.0]	0.0 [0.0]
$[\Delta\frac{5}{2}^+]_2(1990)$	$\Delta(2000)F_{35}**$	−10	−28	$4.0\,^{+4.5}_{-4.0}$	$-0.1\,^{+0.1}_{-0.4}$	2.8	1.5 [14.7]	0.7 [4.5]

factor 10^5 is introduced to make the largest value of λ in the order of 10^0. The isospin factor $I = 1$ for N^* and $\sqrt{2}$ for Δ^*. First I choose several nucleon resonances in descending order of λ. If the contributions and influences of the nucleon resonances with small λ are negligible, I stop here. If not, more resonances would be added. According to such criteria the nine resonances which survived with $\lambda_0 = 0.1$ are listed in Table II.

For the masses of the nucleon resonances, the values suggested by the Particle Data Group (PDG) [22] are adopted and for the nucleon resonances not listed by the PDG, the prediction by the CQM will be adopted [6,7]. To prevent the proliferation of the free parameters, the Breit-Wigner widths for all nucleon resonances are set to 500 MeV, which is consistent to the widths for the $\Delta(2000)$ and $\Delta(1940)$ obtained in the multichannel partial-wave analysis [23,24]. As shown in Table I, the fitted value of the cutoff for the nucleon resonances $\Lambda_R = 1.19$ GeV with Gaussian from factor, that is, the form of from factor in Eq. (7) with $n \to \infty$.

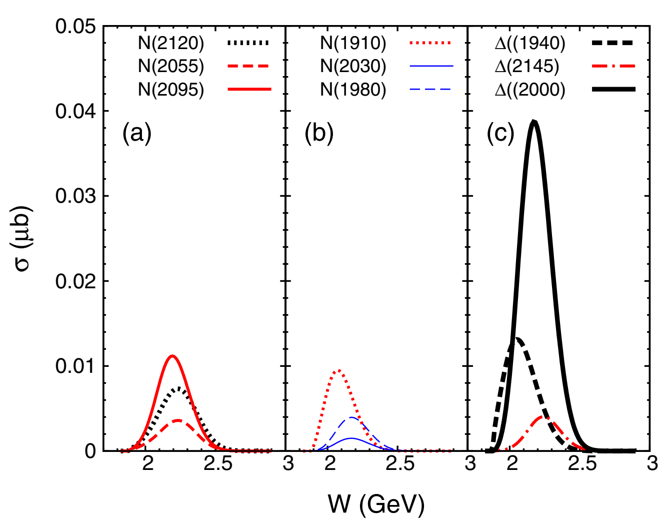

FIG. 2. (Color online) Total cross section σ for corresponding nucleon resonance as a function of the photon energy W in center-of-mass frame.

In Fig. 2, I present the total cross section of each nucleon resonance listed in Table II to give an image of the magnitude of the corresponding nucleon resonance. Generally, the contributions from the nucleon resonances are smaller in the $\Sigma(1385)$ photoproduction compared with the contributions of nucleon resonances in the $\Lambda(1520)$ photoproduction [9]. The largest contribution is from $\Delta(2000)$ which has the largest λ at about 3. The three nucleon resonances listed by the PDG, $N(2120)$, $\Delta(1940)$, and $\Delta(2000)$ have relatively large contributions among all nucleon resonances considered. The $N(2095)$ with the largest decay width in the $\Sigma(1385)K$ channel has a much smaller contribution than $\Delta(2000)$ due to its relative small radiative decay width.

In Table II, I list $\delta\chi^2$ and $\delta\chi_r^2$, which are the variations of the χ^2 after turning off the corresponding resonance without and with refitting, respectively. It reflects the influence of the corresponding resonance on the reproduction of the experimental differential cross section. Generally, the variation of the χ^2 is consistent with the value of λ. The resonances with $\lambda > 1$, $N(2120)$, $N(2095)$, and $\Delta(2000)$, give $\delta\chi_r^2$ about or larger than 0.1 [0.7]. The $\Delta(2000)$ not only provides the largest contribution to total cross section as shown in Fig. 2, but also has the largest influence on the χ^2 with $\delta\chi_r^2 = 0.7[4.5]$ after refitting. The influences of other resonances including the $N(2095)$ are much smaller than $\Delta(2000)$. The λ of $N(2095)$ is large, about 1.7, while the $\delta\chi_r^2$ after refitting is about 0.1 which is much smaller than $\Delta(2000)$. It is due to the compensation effect from other resonances and (even) the Born terms in refitting. After a nucleon resonance is turned off, the variation of the parameters after refitting will lead to the variation of the contributions from other resonances even the Born terms. The absence of the $N(2095)$ is smeared by such variation.

B. The contact term and the Reggeized treatment

In this section I will present more explicit information about the contact term and Reggeized treatment. As shown in Fig. 3, the first term of the contact term in Eq. (6), which comes from the Lagrangians given by Eq. (4), play a most dominant role at energies up to about 3 GeV. For the t channel, the K exchange is dominant in low energies while the Regge

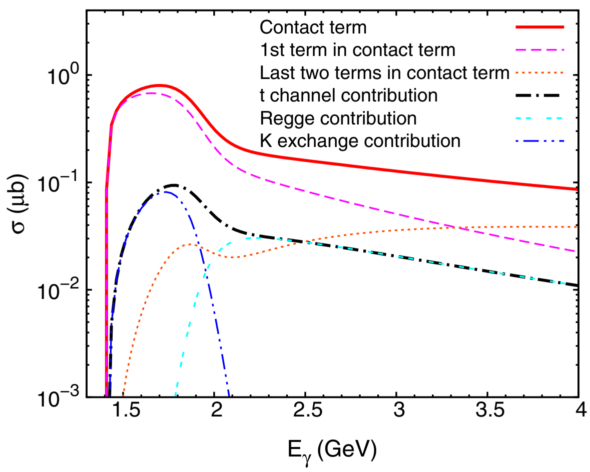

FIG. 3. (Color online) Total cross section σ as a function of the photon energy E_γ for the contact term and Reggeized treatment.

contribution becomes dominant at energies higher than 2.5 GeV as I expected.

C. Differential cross section

With the nucleon resonance contributions and the Born terms given in the previous subsections, the results of the differential cross section for the $\Sigma(1385)$ photoproduction from the proton compared with the CLAS data are shown in Fig. 4. As shown in the figure, the experimental data are well reproduced in my model. The contributions from the u channel and the contact term are dominant and are responsible for the behaviors of the differential cross section at backward and forward angles, respectively. The t channel contribution is smaller but gives a considerable contribution at forward angles. The Born s channel contribution is very small.

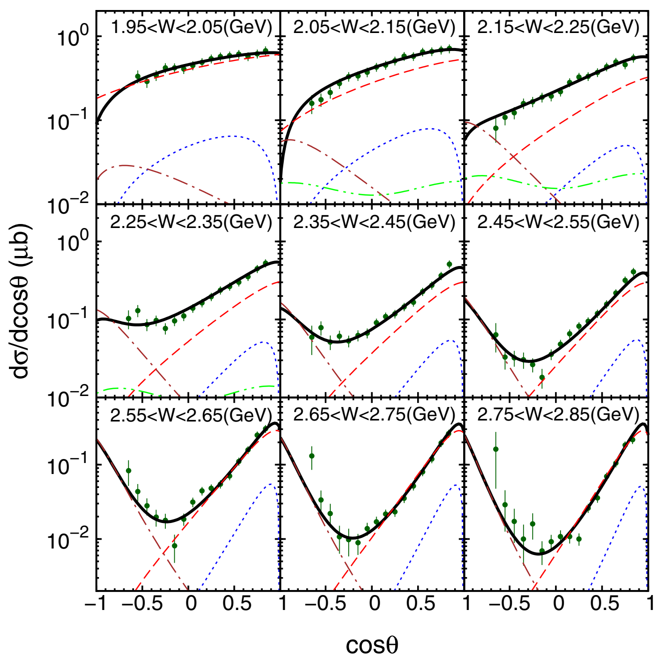

FIG. 4. (Color online) The differential cross section $d\sigma/d\cos\theta$ for the $\Sigma(1385)$ photoproduction from the proton as a function of $\cos\theta$. The full (black), dashed (red), dash-dotted (brown), dotted (blue), and dash-dot-dotted (green) lines are for the full model, the contact term, the u channel, the t channel, and $\Delta(2000)$, respectively. The data are from [5].

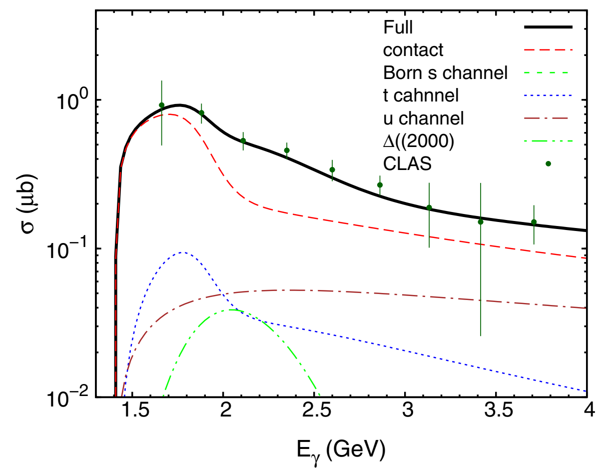

FIG. 5. (Color online) Total cross section σ as a function of the photon energy E_γ. The data are from Ref. [5].

Compared with the plausible results at forwards angles, the results at backward angles are not as satisfactory. I have tried to introduce the Reggeized treatment u channel contribution. But as mentioned in Sec. II, the large uncertainty at backward angles make it difficult to give a meaningful determination of the extra five parameters required by Reggeized treatment. Hence, I keep the Λ intermediate u channel in this work. The further experimental data at extreme backward angle with high precision will be helpful to deepen the understanding about the interaction mechanism in the u channel.

D. Total cross section

I also present the theoretical results of the total cross section compared with the CLAS data in Fig. 5. One can find that my result is well comparable with the CLAS data. At all energies, the contact term provides most important contribution, and the Reggeized t channel contribution is large near threshold and decreases rapidly at higher energies. The u channel contribution becomes important at higher energies. The contributions from the nucleon resonances are small. But as shown in Table II, it is essential to reproduce the differential cross section. The $\Delta(2000)$ has magnitude comparable to the t channel and the u channel at E_γ about 2.1 GeV.

IV. SUMMARY

The $\Sigma(1385)$ photoproduction in the $\gamma p \rightarrow K^+\Sigma^0(1385)$ reaction is investigated within a Regge-plus-resonance approach. The contact term is dominant in the interaction mechanism and the Reggeized t channel is important at energies near threshold at forward angles. The u channel is responsible for the behavior of differential cross section at backward angles.

The contributions of nucleon resonances are determined by the radiative and strong decay amplitudes predicted from the CQM. The results show that the contributions from nucleon resonances are small compared with the contact term, u and t channel contributions but essential to reproduce the experimental data. The D_{13} state $N(2095)$ which is expected to be important in $\Sigma(1385)$ photoproduction has a much smaller contribution for the total cross section and smaller influence on the reproduction of the differential cross section than the F_{35} state $\Delta(2000)$. The resonance $\Delta(2000)$ is the most important nucleon resonance in $\Sigma(1385)$ photoproduction as suggested by CQM [6,7], which is also consistent with the results in Ref. [13].

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[1] T. P. Vrana, S. A. Dytman, and T. S. H. Lee, Phys. Rep. **328**, 181 (2000).
[2] N. Isgur and G. Karl, Phys. Rev. D **18**, 4187 (1978).
[3] S. Capstick and N. Isgur, Phys. Rev. D **34**, 2809 (1986).
[4] E. Klempt and J.-M. Richard, Rev. Mod. Phys. **82**, 1095 (2010).
[5] K. Moriya *et al.* (CLAS Collaboration), Phys. Rev. C **88**, 045201 (2013).
[6] S. Capstick and W. Roberts, Phys. Rev. D **58**, 074011 (1998).
[7] S. Capstick, Phys. Rev. D **46**, 2864 (1992).
[8] J. J. Xie and J. Nieves, Phys. Rev. C **82**, 045205 (2010).
[9] J. He and X.-R. Chen, Phys. Rev. C **86**, 035204 (2012).
[10] Cambridge Bubble Chamber Group, Phys. Rev. **156**, 1426 (1967).
[11] R. Erbe *et al.*, Phys. Rev. **188**, 2060 (1969).
[12] M. Niiyama *et al.*, Phys. Rev. C **78**, 035202 (2008).
[13] Y. Oh, C. M. Ko, and K. Nakayama, Phys. Rev. C **77**, 045204 (2008).
[14] P. Gao, J.-J. Wu, and B. S. Zou, Phys. Rev. C **81**, 055203 (2010).
[15] T. Corthals, J. Ryckebusch, and T. Van Cauteren, Phys. Rev. C **73**, 045207 (2006).
[16] K. Ohta, Phys. Rev. C **40**, 1335 (1989).
[17] S. I. Nam and C. W. Kao, Phys. Rev. C **81**, 055206 (2010).
[18] H. Haberzettl, K. Nakayama, and S. Krewald, Phys. Rev. C **74**, 045202 (2006).
[19] A. I. Titov, B. Kampfer, S. Date, and Y. Ohashi, Phys. Rev. C **72**, 035206 (2005); **72**, 049901(E) (2005).
[20] M. Guidal, J. M. Laget, and M. Vanderhaeghen, Nucl. Phys. A **627**, 645 (1997).
[21] H. Toki, C. Garcia-Recio, and J. Nieves, Phys. Rev. D **77**, 034001 (2008).
[22] J. Beringer *et al.* (Particle Data Group), Phys. Rev. D **86**, 010001 (2012), and the 2013 partial update for the 2014 edition.
[23] M. Shrestha and D. M. Manley, Phys. Rev. C **86**, 055203 (2012).
[24] A. V. Anisovich *et al.*, Eur. Phys. J. A **48**, 15 (2012).