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

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The interaction mechanism of the $\Sigma(1385)$ photoproduction from proton $\gamma p \rightarrow K^{*}\Sigma(1385)$ 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 to the behaviors of differential cross sections at forward and backward angles, respectively. The contributions from nucleon resonances including $N^*$ and $\Delta^*$, which are determined by the predicted decay amplitudes in the constituent quark model, are found small, but the $F_{35}$ state $\Delta(2000)$ is essential to reproduce 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 “missing resonance” is very small in the usual experimental detected channels, such as $pN$ and strange channels, attract much attentions.

A mount of experimental data of the kaon photoproduction companied by a ground strange baryon $\Lambda$ or $\Sigma$ have been accumulated in the recent years [4]. However, the study about 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 $\Lambda(1405)$ with kaon meson have been studied in the CQM [3]. Combined with the theoretical prediction about the radiative decay [7], one can make a rough estimation 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 analysis 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 $\Sigma(1385)K$ decay channel [6]. Hence it is interesting to study the roles played by such states in the $\Sigma(1385)$ photoproduction.

There only exist some old experimental data about the $\Sigma(1385)$ photoproduction with low precision, which were obtained before last seventies [10,11]. The LEPS Collaboration also released some results in this channel but only at extreme forward angles [12]. Correspondingly, the 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, we 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 introduction, we will present the effective Lagrangian used in this work and Reggeized treatment for $t$ channel. The gauge invariance will be also discussed in this section. The numerical results for the cross section will be given and compared with the experimental data in Section 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 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,

$$L_{\gamma KK} = ieA_{\mu}(K^{*}\partial^{\mu}K^{*} - \partial^{\mu}K^{*}K^{*}),$$

$$L_{KNN} = \frac{f_{KNN}}{m_{K}}\partial_{\mu}K^{*}\Sigma^{\mu\nu} \cdot \tau N + H.c.,$$

$$L_{\gamma NN} = -\epsilon_{N}^{\mu}(\epsilon_{N}^{\nu} - \frac{K_{N}}{2M_{N}}\partial^{\nu}\partial_{\nu})A_{\mu}N,$$
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]

\[ M_{i}^{\gamma\nu} = \frac{ie f_{K^{*}N^{*}}}{m_{K}} \left[ g_{\mu\nu} k_{i}^{\nu}(2k_{2} - k_{1}) (F_{i} - 1) \left| 1 - h(1 - F_{i}) \right| \right] \left| \frac{m_{K}^{2} - t}{m_{K}^{2} - \frac{1}{2} M_{i}^{2}} \right| \]

(6)

where \( h \) 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 from,

\[ F_{i}(q^{2}) = \left( \frac{n \Lambda_{i}^{4}}{n \Lambda_{i}^{4} + (q^{2} - M_{i}^{2})^{2}} \right)^{n}, \]

(7)

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

\[ F_{i}(q^{2}) = \frac{\Lambda_{i}^{2} - M_{i}^{2}}{\Lambda_{i}^{2} - q^{2}}, \]

(8)

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

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

\[ \frac{1}{t - m_{K}^{2}} \to D_{K} = \left( \frac{s}{s_{\text{scale}}} \right)^{\alpha_{K}} \frac{\pi \alpha_{K}}{\Gamma(1 + \alpha_{K})} \sin(\pi \alpha_{K}), \]

(9)

where \( \alpha_{K} \) is the slope of the trajectory and the scale factor \( s_{\text{scale}} \) is fixed at 1 GeV\(^2\). \( \alpha_{K} \) 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 \( f_{K^{*}N^{*}} \) and \( f_{K^{*}N^{*}} \) are 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. We 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. [22] and Nam and Kao [17] by introducing a weighting function \( R \). Here we adopt the treatment as,

\[ \frac{F_{t}}{t - m_{K}^{2}} \to \frac{F_{t}}{t - m_{K}^{2}} R = D_{R} R + \frac{F_{t}}{t - m_{K}^{2}} (1 - R), \]

(10)

where \( R = R, R_{s} \) with

\[ R_{s} = \frac{1}{2} \left[ 1 + \tanh \left( \frac{\delta - s_{\text{reg}}}{s_{0}} \right) \right], \]

\[ R_{t} = 1 - \frac{1}{2} \left[ 1 + \tanh \left( \frac{|t| - t_{\text{reg}}}{t_{0}} \right) \right], \]

(11)
The free parameters \( s_{\text{Reg}}, s_0, t_0 \) and \( t_0 \) will be fitted with the differential cross section.

As inclusion of the from factor \( F_t \), the Reggeized treatment will violate the gauge invariance and current conservation also. To restore the current conservation, we redefine the relevant amplitudes,

\[
iM^{\mu\nu} = i\mathcal{M}^{\mu\nu} + i\mathcal{M}^{\mu\nu}\rightarrow \left(i\mathcal{M}^{\mu\nu} + i\mathcal{M}^{\mu\nu}\right)\mathcal{R}
\]

(12)

With such definition, the relation \( k_i^0 \mathcal{M}^{\mu\nu} = 0 \) is satisfied.

For the nucleon resonance contributions, we adopt the Lagrangians for the radiative decay,

\[
\mathcal{L}_{\gamma NR(4^+)} = \frac{e_f^2}{2M_N} \mathcal{N} \Gamma^{(\pm)} \sigma_{\mu\nu} F^{\mu\nu} R + \text{h.c.},
\]

\[
\mathcal{L}_{\gamma NR(J^+)} = -\frac{f_f^2}{2M_N} \mathcal{N} \gamma_{\mu} \partial_{\mu} \partial_{\nu} F_{\mu\nu} \Gamma^{(\pm)} R \mathcal{P} \partial_{\mu\nu} \mathcal{P} - \text{h.c.},
\]

(13)

where \( F^{\mu\nu} = \partial^{\mu} A^{\nu} - \partial^{\nu} A^{\mu} \) with \( \mathcal{R} \partial_{\mu\nu} \mathcal{R} \) 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

\[
\mathcal{L}_{\rho NR(4^+)} = \frac{h_{\rho}}{2M_K} \partial_{\mu} \mathcal{K} \mathcal{P} \partial_{\mu} \mathcal{R}, \text{h.c.},
\]

\[
\mathcal{L}_{\rho NR(J^+)} = -\frac{f_{\rho}}{2M_K} \mathcal{K} \mathcal{P} \partial_{\mu} \mathcal{P} \partial_{\mu} \mathcal{R} + \text{h.c.},
\]

(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. [8, 13] for further information.

In this work the nucleon resonances \( R \) including \( N^* \) and \( \Delta^* \) 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,

\[
\mathcal{R} \Sigma^* \cdot R K = p^0 K^* \cdot n^0 + \sqrt{2} m^0 K^* + \sqrt{2} p^0 \Sigma^* K^0, \quad (15)
\]

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

\[
\mathcal{R} \Sigma^* \cdot R K = \sqrt{3} \Delta^{0+} \Sigma^+ K^* - \sqrt{2} \Delta^{0+} \Sigma^0 K^* - \Delta^{0+} \Sigma^0 K^* - \sqrt{3} \Delta^{0-} \Sigma^- K^0. \quad (16)
\]
The largest contribution is from the nucleon resonances in the mass frame. The contributions from the nucleon resonances are smaller in comparison to the contributions from other resonances even the Born terms. The resonances with small $\lambda$ is negligible, we stop here. If not, more resonances would be added. According to such criterion nine resonances survived with $\lambda_0 = 0.1$ are listed in Table II.

For the masses of the nucleon resonances, the values suggested in the Particle Data Group (PDG) [23] are adopted and for the nucleon resonances not listed in PDG, the prediction by the CQM will be adopted [6, 7]. To prevent the proliferation of the free parameters, the Breit-Wigner widths for the nucleon resonances not listed in 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 $\Lambda(2000)$ and $\Delta(1940)$ obtained in the multichannel partial-wave analysis [24, 25]. As shown in Table II the fitted value of 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 $n \to \infty$.

In Fig. 2 we 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 have largest $\lambda$ about 3. The three nucleon resonances listed in the PDG, $N(2120)$, $\Delta(1940)$ and $\Delta(2000)$ have relatively large contributions among all nucleon resonances considered. The $N(2095)$ with largest decay width in the $\Sigma(1385)K$ channel has much smaller contribution than $\Delta(2000)$ due to its relative small radiatively decay width.

In Table II we list $\delta \chi^2$ and $\delta \chi^2_\ell$, which are the variations of the $\chi^2$ 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 $\chi^2$ is consistent with the value of $\lambda$. The resonances with $\lambda > 1$, $N(2120)$, $N(2095)$ and $\Delta(2000)$, give $\delta \chi^2$ about or larger than 0.1 [0.7]. The $\Delta(2000)$ not only provides largest contribution to total cross section as shown in Fig. 2 but also has largest influence on the $\chi^2$ with $\delta \chi^2_\ell = 0.7$ [4.5] after refitting. The influences of other resonances including the $N(2095)$ are much smaller than $\Delta(2000)$. The $\lambda$ of $N(2095)$ is large, about 1.7, while the $\delta \chi^2_\ell$ 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 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.

### Table II: The nucleon resonances considered.

| State | PDG   | $A_{1/2}^0$ | $A_{3/2}^0$ | $G(f_1)$ | $G(f_2)$ | $\lambda$ | $\delta \chi^2$ | $\delta \chi^2_\ell$ |
|-------|-------|-------------|-------------|----------|----------|-----------|----------------|----------------|
| $|N_{3/2}^{-}\rangle_1(1960)$ | $N(2120)D_{13}$ | 36 | -43 | 1.3 $^{+0.4}_{-0.4}$ | 1.4 $^{+1.3}_{-1.3}$ | 1.1 | 0.2 [0.8] | 0.1 [0.4] |
| $|N_{3/2}^{-}\rangle_1(2055)$ | 16 | 0 | $-2.5^{+1.0}_{-1.0}$ | $-2.5^{+2.3}_{-1.9}$ | 0.3 | 0.0 [0.0] | 0.0 [0.0] |
| $|N_{3/2}^{-}\rangle_1(2095)$ | -9 | -14 | 7.7 $^{+1.2}_{-1.2}$ | $-0.8^{+0.7}_{-1.0}$ | 1.7 | 0.4 [3.3] | 0.1 [0.1] |
| $|N_{3/2}^{-}\rangle_1(1910)$ | -21 | -27 | $-1.9^{+0.9}_{-0.3}$ | 0.0 | 0.0 | 0.4 | 0.0 [0.5] | 0.0 [0.1] |
| $|N_{3/2}^{-}\rangle_1(2030)$ | -9 | 15 | 2.2 $^{+1.0}_{-0.3}$ | $-0.2^{+0.1}_{-0.1}$ | 0.2 | 0.0 [0.0] | 0.0 [0.0] |
| $|N_{3/2}^{-}\rangle_1(1980)$ | -11 | -6 | $-3.6^{+2.5}_{-3.0}$ | $-0.1^{+0.1}_{-0.3}$ | 0.2 | 0.2 [0.5] | 0.1 [0.3] |
| $|\Delta_{3/2}^-\rangle_1(2080)$ | $\Delta(1940)D_{33}$ | -20 | -6 | $-4.1^{+4.0}_{-1.5}$ | $-0.5^{+2.2}_{-0.3}$ | 1.5 | 0.1 [1.1] | 0.0 [0.0] |
| $|\Delta_{1/2}^-\rangle_1(2145)$ | 0 | 10 | 5.2 $^{+0.4}_{-0.4}$ | $-1.9^{+1.2}_{-4.0}$ | 0.6 | 0.2 [1.0] | 0.0 [0.0] |
| $|\Delta_{1/2}^-\rangle_1(1990)$ | -10 | -28 | 4.0 $^{+4.5}_{-4.0}$ | $-0.1^{+0.1}_{-0.4}$ | 2.8 | 1.5 [14.7] | 0.7 [4.5] |

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

B. The Contact term and the Reggeized treatment

In this section we 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 most dominant role at energies up to about 3 GeV. For $t$ channel, the $K$
exchange is dominant in low energies while the Regge contribution becomes dominant at energies higher than 2.5 GeV as we expected.

C. Differential cross section

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

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

D. Total cross section

We also present the theoretical results of total cross section compared with the CLAS data in Fig. 5. One can find that our 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 $E_{\gamma}$ 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 mech-
anism and 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 have much smaller contribution for total cross section and smaller influence on the reproduction of differential cross section than $F_{35}$ 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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