PHYSICAL REVIEW D **95,** 096015 (2017)

Study on the reaction of $\gamma p \to f_1(1285)p$ in Regge-effective Lagrangian approach

Yan-Yan Wang, Li-Juan Liu, En Wang,* and De-Min Li†

Department of Physics, Zhengzhou University, Zhengzhou, Henan 450001, China

(Received 24 January 2017; published 31 May 2017)

The production of the $f_1(1285)$ resonance in the reaction of $\gamma p \to f_1(1285)p$ is investigated within a Regge-effective Lagrangian approach. Besides the contributions of the t-channel ρ and ω trajectories exchanges, we also take into account the contributions of s-/u-channel $N(2300)$ terms, s-/u-channel nucleon terms, and the contact term. By fitting to the CLAS data, we find that the s-channel $N(2300)$ term plays an important role in this reaction. We predict the total cross section for this reaction and find a clear bump structure around $W = 2.3$ GeV, which is associated with the $N(2300)$ state. The reaction of $\gamma p \to f_1(1285)p$ could be useful to further study the $N(2300)$ experimentally.

DOI: 10.1103/PhysRevD.95.096015

I. INTRODUCTION

It has been known since the 1970s that the nucleon is a bound state of three valence quarks. Many nucleon resonances, referred to as N^*, have been observed [1]; the properties of nucleon resonances are the important issues in hadron physics and attract lots of attention [2–4]. For the nucleon resonances with masses below 2 GeV, their properties have been widely investigated in the literature. However, the current knowledge on the properties of excited nucleon states with masses above 2 GeV is scarce. On the other hand, many missing N^* s, predicted by the constituent quark models, have not yet been found [5].

Recently, the CLAS Collaboration measured the $f_1(1285)$ meson for the first time in photoproduction from a proton target and presented the $f_1(1285)$ differential photoproduction cross section into $\eta\pi^+\pi^-$ final states from the threshold up to a c.m. energy of $W = 2.8$ GeV [6]. A cross section comparison for $\gamma p \to \eta'(958)p \to \eta\pi^+\pi^- p$ and $\gamma p \to f_1(1285)p \to \eta\pi^+\pi^- p$ at $W = 2.55$ GeV in Fig. 10 of Ref. [6] shows that the $\eta'(958)$ cross section exhibits much stronger t- and u-channel signatures in the angle dependence than does the one of $f_1(1285)$, which is quite flat. This may imply that the $f_1(1285)$ photoproduction mechanism is not dominated alone by t-channel production processes.

Before the experimental study on $\gamma p \to f_1(1285)p$ [6], there were several theoretical works on this reaction. Within the Regge model, considering the exchanges of t-channel ρ and ω trajectories, Kochelev *et al.* calculated the differential cross sections of $\gamma p \to f_1(1285)p$ [7]. Comparison of the Regge-model calculations and the CLAS data shows the t-channel production process alone does not reproduce the CLAS measurements. Within a model motivated by Chern-Simons-term-induced interactions in holographic QCD, Domokos *et al.* [8] predicted the differential cross sections of $\gamma p \to f_1(1285)p$. The predictions of Ref. [8] are much smaller than the CLAS data, even in the most forward region. Based on the effective-Lagrangian approach with tree-level ρ and ω exchanges in the t-channel [9], Huang *et al.* presented the differential cross sections as shown in Fig. 12 of Ref. [6]. The results of Huang *et al.* are also much smaller than the CLAS data. In order to describe the CLAS data, further model calculations are needed.

The differences between these model predictions and the CLAS data suggest that the s-channel intermediate baryon resonances may play an important role in the reaction of $\gamma p \to f_1(1285)p$. That is to say, the decay of the excited N^* intermediate states may be important, as pointed out by the CLAS Collaboration [6]. The reaction of $\gamma p \to f_1(1285)p$ filters the nucleon resonances with isospin $I = 1/2$ and provides a natural mode to investigate the higher excited nucleon resonance with a mass above 2.2 GeV and a sizeable coupling to the final states $f_1(1285)p$.

Among the possible nucleon resonances N^* [$N(2220)$ $9/2^+$, $N(2250)$ $9/2^-$, $N(2300)$ $1/2^+$],[1] the $N(2300)$ can couple to the $f_1(1285)p$ in the S wave, while the other two states $N(2220)$ and $N(2250)$ couple to the $f_1(1285)p$ in the F and E waves, respectively. is expected that the contributions of E and F waves would be strongly suppressed. Thus, we will consider the state $N(2300)$ as the intermediate state in the $\gamma p \to f_1(1285)p$ reaction.

*Corresponding Author: wangen@zzu.edu.cn.

†Corresponding Author: lidm@zzu.edu.cn.

[1]According to the PDG [1], there are three N^* [$N(2220)$ $9/2^+$, $N(2250)$ $9/2^-$, $N(2300)$ $1/2^+$] in the mass range of 2.2–2.5 GeV. The differential cross sections of $\gamma p \to f_1(1285)p$ above $W = 2.5$ GeV are very forward, which should be dominated by the t-channel mesons exchanges; as shown in Fig. 12 of Ref. [6], the s-channel nucleon resonances with masses above 2.55 GeV are not expected to give the dominant contributions.

In the present work, we shall study the reaction of $\gamma p \to f_1(1285)p$ within the Regge-effective Lagrangian approach by considering the t-channel ρ and ω trajectories exchanges, the s-/u-channel $N(2300)$ resonance mechanisms, the s-/u-channel nucleon terms, and the contact term.

Experimental information of the two-star[2] $N(2300)$ is very scarce [1]. Until now, it was observed only in the decay of $\psi(3686) \to p\bar{N}^*(\bar{p}N^*) \to p\bar{p}\pi^0(\bar{p}p\pi^0)$ by the BESIII Collaboration, and its mass and width have been determined to be 2300^{+40}_{-30} MeV and 340 ± 30 MeV, respectively [10]. Searching for the $N(2300)$ state in other processes, for instance the photoproduction, could be useful for providing more information about the properties of the $N(2300)$ state. As an isospin $1/2$ filter process, the $\gamma p \to f_1(1285)p$ is a potential mode to study the $N(2300)$ state.

This paper is organized as follows. In Sec. II, we discuss the formalism and the main ingredients of the Regge-effective Lagrangian approach. In Sec. III, the results and discussions are presented. Finally, a short summary is given in Sec. IV.

II. FORMALISM AND INGREDIENTS

A. Feynman amplitudes

For the process $\gamma p \to f_1(1285)p$, we will take into account the basic tree-level Feynman diagrams depicted in Fig. 1, where the t-channel ρ and ω exchanges, the s- and u-channel $N(2300)$ terms, the s- and u-channel nucleon terms, and the contact term are considered. The relevant effective Lagrangians of the vertices are given as [7,8,11,12].

$$\mathcal{L}_{VNN} = g_{VNN}\bar{\psi}_N\gamma_\mu\psi_N V^\mu + \frac{g_V^T}{2M_N}\bar{\psi}_N\sigma_{\mu\nu}\psi_N V^{\mu\nu}, \quad (1)$$

$$\mathcal{L}_{\gamma V f_1} = g_{\gamma V f_1} q_V^2 \epsilon_{\mu\nu\alpha\beta}\epsilon_V^\nu \xi^\beta \epsilon_\gamma^\alpha p_1^\mu, \quad (2)$$

$$\mathcal{L}_{\gamma NN^*} = \frac{e g_{\gamma NN^*}}{2M_N}\bar{\psi}_{N^*}\sigma_{\mu\nu}\partial^\nu A^\mu \psi_N + \text{H.c.}, \quad (3)$$

$$\mathcal{L}_{f_1 NN^*} = g_{f_1 NN^*}\bar{\psi}_{N^*}\gamma_5\sigma_{\mu\nu}\partial^\nu f_1^\mu \psi_N + \text{H.c.}, \quad (4)$$

$$\mathcal{L}_{\gamma NN} = -e\bar{\psi}_{N^*}\left[\gamma^\mu A_\mu - \frac{\kappa_N}{2M_N}\sigma_{\mu\nu}\partial^\nu A^\mu\right]\psi_N + \text{H.c.}, \quad (5)$$

$$\mathcal{L}_{f_1 NN} = g_{f_1 NN}\bar{\psi}_{N^*}\gamma^\mu\gamma_5 f_{1\mu}\psi_N + \text{H.c.}, \quad (6)$$

where $V^{\mu\nu} = \partial^\mu V^\nu - \partial^\nu V^\mu$, f_1^μ is axial-vector meson $f_1(1285)$ field, and A^μ and V^μ are the electromagnetic field and the vector meson (ρ or ω) field, respectively. q_V is the momentum of the exchanged vector meson, and $p_i (i = 1, 2, 3, 4)$ are the 4-momentum of the initial or final state, as shown in Fig. 1. ϵ_V, ξ, and ϵ_γ are the polarizations of the vector meson in the t-channel, $f_1(1285)$, and the photon, respectively.

[2]According to the PDG [1], the existence evidence of the baryon states with two stars is only fair.

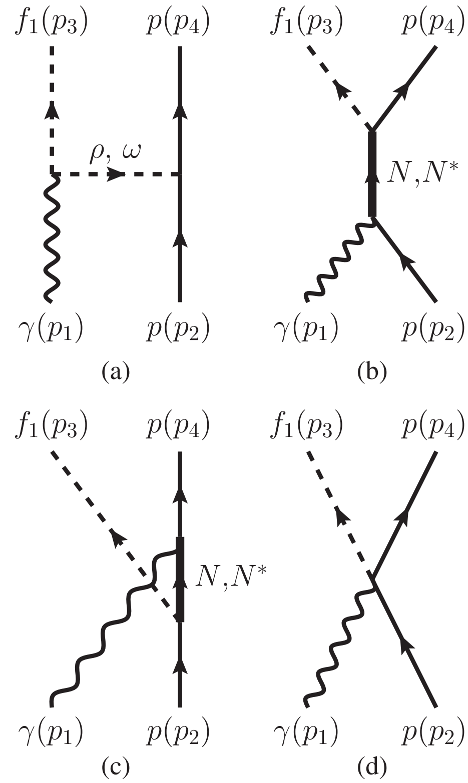

FIG. 1. Feynman diagrams for the $\gamma p \to f_1(1285)p$ reaction: (a) the t-channel ρ and ω exchanges, (b) the s-channel $N(2300)$ and proton terms, (c) the u-channel $N(2300)$ and proton terms, and (d) the contact term.

The numerical values of the coupling constants are taken from Ref. [13]:

$$g_\omega^T = 0, \quad (7)$$

$$g_\rho^T/g_{\rho NN} = \kappa_\rho = 6.1. \quad (8)$$

Since the hadrons are not pointlike particles, we need to include the form factors to describe the off-shell effects. We adopt here the form factors used in many previous works:

$$\mathcal{F}_{N^*}(q^2) = \frac{\Lambda_{N^*}^4}{\Lambda_{N^*}^4 + (q^2 - M_{N^*}^2)^2}, \quad (9)$$

$$\mathcal{F}_N(q^2) = \frac{\Lambda_N^4}{\Lambda_N^4 + (q^2 - M_N^2)^2}, \quad (10)$$

$$\mathcal{F}_{VNN}(q^2) = \frac{\Lambda_t^2 - M_V^2}{\Lambda_t^2 - q^2}, \quad (11)$$

$$\mathcal{F}_{Vf_1\gamma}(q^2) = \left(\frac{\Lambda_t^2 - M_V^2}{\Lambda_t^2 - q^2}\right)^2. \quad (12)$$

These form factors are similar to those used in Refs. [14,15], and the same cutoff Λ_t is used for the vertices of VNN and $Vf_1\gamma$.

Then, according to the Feynman rules, the scattering amplitudes for the $\gamma p \to f_1(1285)p$ reaction can be obtained straightforwardly with the above effective Lagrangians,

$$\begin{aligned}\mathcal{M}_{N^*}^s =& \frac{eg_{\gamma NN^*}g_{f_1NN^*}}{2M_N}\mathcal{F}_{N^*}(q_s^2)\bar{u}(p_4,s_4)\gamma_5(p_3^\nu - \not{p}_3\gamma^\nu)\\ &\times G_{N^*}(q_s^2)(p_1^\mu - \not{p}_1\gamma^\mu)u(p_2,s_2)\\ &\times \varepsilon_\mu(p_1,s_1)\xi_\nu^*(p_3,s_3), \end{aligned} \quad (13)$$

$$\begin{aligned}\mathcal{M}_u^{N^*} =& \frac{eg_{\gamma NN^*}g_{f_1NN^*}}{2M_N}\mathcal{F}_{N^*}(q_u^2)\bar{u}(p_4,s_4)(p_1^\mu - \not{p}_1\gamma^\mu)\\ &\times G_{N^*}(q_u^2)\gamma_5(p_3^\nu - \not{p}_3\gamma^\nu)u(p_2,s_2)\\ &\times \varepsilon_\mu(p_1,s_1)\xi_\nu^*(p_3,s_3), \end{aligned} \quad (14)$$

$$\begin{aligned}\mathcal{M}_s^N =& eg_{f_1NN}\mathcal{F}_N(q_s^2)\bar{u}(p_4,s_4)\gamma^\nu\gamma_5G_N(q_s^2)\\ &\times \left[\gamma^\mu - \frac{\kappa_N}{4M_N}(\gamma^\mu\not{p}_1 - \not{p}_1\gamma^\mu)\right]u(p_2,s_2)\\ &\times \varepsilon_\mu(p_1,s_1)\xi_\nu^*(p_3,s_3), \end{aligned} \quad (15)$$

$$\begin{aligned}\mathcal{M}_u^N =& eg_{f_1NN}\mathcal{F}_N(q_u^2)\bar{u}(p_4,s_4)\\ &\times \left[\gamma^\mu - \frac{\kappa_N}{4M_N}(\gamma^\mu\not{p}_1 - \not{p}_1\gamma^\mu)\right]G_N(q_u^2)\gamma^\nu\gamma_5\\ &\times u(p_2,s_2)\varepsilon_\mu(p_1,s_1)\xi_\nu^*(p_3,s_3), \end{aligned} \quad (16)$$

$$\begin{aligned}\mathcal{M}_t^V =& -g_{VNN}g_{\gamma Vf_1}\mathcal{F}_{VNN}(q_t^2)\mathcal{F}_{Vf_1\gamma}(q_t^2)\bar{u}(p_4,s_4)\\ &\times \left[\gamma_\sigma - \frac{\kappa_\rho}{2M_N}(\gamma_\sigma\not{q}_V - \not{q}_V\gamma_\sigma)\right]u(p_2,s_2)\\ &\times G^{\sigma\nu}(q_t^2)q_V^2\epsilon_{\mu\nu\alpha\beta}p_1^\mu\epsilon^\alpha(p_1,s_1)\xi^{*\beta}(p_3,s_3), \end{aligned} \quad (17)$$

where $q_s = p_1 + p_2$, $q_u = p_2 - p_3$, and $q_t = p_1 - p_3$. G_{N^*} and G_N are the propagators for the N^* and proton, and $G^{\sigma\nu}$ is the propagator for the ρ or ω meson. We also define $g_{N^*} \equiv \sqrt{4\pi}g_{\gamma NN^*} \times g_{f_1NN^*}$ and $g_t \equiv g_{VNN} \times g_{\gamma Vf_1}$ for convenience. With the SU(3) invariant Lagrangians and flavor symmetry, one can have $g_{\omega NN} = 3g_{\rho NN}$. On the other hand, we have $g_{f_1\omega\gamma} \approx \frac{e_u+e_d}{e_u-e_d}g_{f_1\rho\gamma} = \frac{1}{3}\times g_{f_1\rho\gamma}$ [7], and thus the g_t is same for the ρ and ω mesons.

The contact term is required to keep the full amplitude gauge invariant and can be written as

$$\begin{aligned}\mathcal{M}_c =& -eg_{f_1NN}\bar{u}(p_4,s_4)[\gamma^\nu\gamma_5G_N(q_s^2)\not{p}_1\mathcal{F}_N(q_s^2)\\ &-\not{p}_1G_N(q_u^2)\gamma^\nu\gamma_5\mathcal{F}_N(q_u^2)]\frac{p_3^\mu}{p_3\cdot p_1}\\ &\times u(p_2,s_2)\varepsilon_\mu(p_1,s_1)\xi_\nu^*(p_3,s_3). \end{aligned} \quad (18)$$

The propagator for the N^* and proton term can be written as

$$G_{N^*}(q^2) = i\frac{\not{q} + M_{N^*}}{q^2 - M_{N^*}^2 + iM_{N^*}\Gamma}, \quad (19)$$

$$G_N(q^2) = i\frac{\not{q} + M_N}{q^2 - M_N^2 + iM_N\Gamma}, \quad (20)$$

and the one for the vector meson ρ or ω is

$$G_V^{\mu\nu}(q^2) = -i\frac{g^{\mu\nu} - q^\mu q^\nu/M_V^2}{q^2 - M_V^2}. \quad (21)$$

The total amplitude for the process $\gamma p \to f_1(1285)p$ is the coherent sum of $\mathcal{M}_s^{N^*}$, $\mathcal{M}_u^{N^*}$, $\mathcal{M}_t^\rho$, $\mathcal{M}_t^\omega$, $\mathcal{M}_s^N$, $\mathcal{M}_u^N$, and $\mathcal{M}_c$,

$$\begin{aligned}\mathcal{M} =& \mathcal{M}_s^{N^*} + \mathcal{M}_u^{N^*} + \mathcal{M}_t^\rho + \mathcal{M}_t^\omega\\ &+ \mathcal{M}_s^N + \mathcal{M}_u^N + \mathcal{M}_c. \end{aligned} \quad (22)$$

The unpolarized differential cross section in the c.m. frame for the $\gamma p \to f_1(1285)p$ reaction is given as

$$\frac{d\sigma}{d\Omega} = \frac{M_N^2}{16\pi^2 s}\frac{|\vec{p}_3^{\,\rm cm}|}{|\vec{p}_1^{\,\rm cm}|}\overline{\sum}|\mathcal{M}|^2, \quad (23)$$

where s is the invariant mass square of the γp system, $d\Omega = 2\pi d\cos\theta$, θ denotes the angle of the outgoing meson $f_1(1285)$ relative to the beam direction in the c.m. frame, while $\vec{p}_1^{\,\rm c.m.}$ and $\vec{p}_3^{\,\rm c.m.}$ are the 3-momentum of the initial photon and final $f_1(1285)$ in the c.m. frame.

B. ρ and ω trajectories contributions

At high energies and forward angles, the Reggeon exchange mechanism plays a crucial role [16,17]. Therefore, in modeling the reaction amplitude for the $\gamma p \to f_1(1285)p$ reaction at high energies, instead of considering the exchange of a finite selection of individual particles, the exchange of entire Regge trajectories is taken into account, and this exchange can take place in the t-channel ρ and ω trajectories [18].

One can obtain the amplitude of the ρ or ω trajectory exchange $\mathcal{M}_V^{\rm Regge}$ from the Feynman amplitude $\mathcal{M}_t^V$ of Eq. (17) by replacing the usual vector meson propagator with a so-called Regge propagator [19],

$$\frac{1}{q^2 - M_V^2} \to \left(\frac{s}{s_0}\right)^{\alpha_V - 1} \frac{\pi \alpha'_V}{\sin(\pi\alpha_V)\Gamma(\alpha_V)} D_V, \quad (24)$$

where the mass scale constant $s_0 = 1$ GeV and α'_V is the slope of the trajectory. The ρ and ω trajectories are taken from Ref. [19],

$$\alpha_\omega(t) = 0.44 + 0.9t, \quad (25)$$

$$\alpha_\rho(t) = 0.55 + 0.8t, \quad (26)$$

and the signature factor $D_V(t)$ is taken from Refs. [7,20,21],

$$D_\omega(t) = \frac{-1 + \exp(-i\pi\alpha_\omega)}{2}, \quad (27)$$

$$D_\rho(t) = \exp(-i\pi\alpha_\rho). \quad (28)$$

In this work, we adopt a hybrid approach to describe the contributions of t-channel ρ and ω exchanges in the range of laboratory photon energies explored by the CLAS data. In the hybrid approach, the amplitude $\mathcal{M}_t^V$ ($\mathcal{M}_t^\rho$ and $\mathcal{M}_t^\omega$) in Eq. (22) is replaced by $\mathcal{M}_t^{\rm H}$ [18],

$$\mathcal{M}_t^{\rm H} = \mathcal{M}_V^{\rm Regge} \times \mathcal{R} + \mathcal{M}_t^V \times (1 - \mathcal{R}), \quad (29)$$

with

$$\mathcal{R} = \mathcal{R}_s \times \mathcal{R}_t, \quad (30)$$

$$\mathcal{R}_s = \frac{1}{1 + e^{-(W-W_0)/\Delta W}}, \quad (31)$$

$$\mathcal{R}_t = \frac{1}{1 + e^{(|t|-t_0)/\Delta t}}, \quad (32)$$

where we consider t_0 and Δt free parameters that will be fitted to experimental data, and $W_0 = 2.1$ GeV, $\Delta W = 0.08$ GeV from the qualitative comparison of the predictions of Ref. [7] with the CLAS measurement [6] and from the findings of Ref. [22].

From the Eq. (29), we can see that for the region of high energies ($W \equiv \sqrt{s} > W_0$) and forward angles ($|t| > t_0$), the Regge mechanism is dominant.

III. NUMERICAL RESULTS AND DISCUSSIONS

There are nine parameters in our model, (a) four relevant couplings $g_{N^*} = \sqrt{4\pi} g_{\gamma NN^*} \times g_{f_1 NN^*}$ for the $N(2300)$ term, the $g_t = g_{VNN} \times g_{\gamma V f_1}$ for the t-channel ρ and ω trajectories exchanges, $g_{f_1 NN}$, and κ_N; (b) three cutoff parameters Λ_{N^*}, Λ_N, and Λ_t; and (c) t_0 and Δt. We will obtain these parameters by fitting to the recent differential cross sections data from the CLAS experiment. Since the CLAS Collaboration presents the differential cross sections for $\gamma p \to f_1(1285) p \to \eta\pi^+\pi^- p$, our results for the total cross section and differential cross sections have been

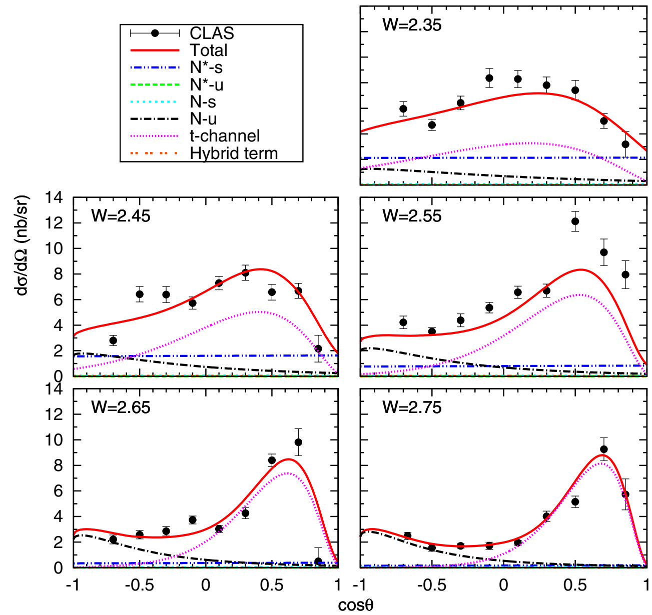

FIG. 2. Differential cross sections of the $\gamma p \to f_1(1285) p$ reaction as a function of $\cos\theta$. The black dots are the experimental data with statistical errors [6]. The blue dash-dot-dotted and green long dashed lines represent the contributions of the s-channel and u-channel $N(2300)$; the black dash-dotted and cyan short-dashed lines are the contributions of the s-channel and u-channel proton; the magenta dotted line describes the contribution of t-channel Reggeon exchanges; and the orange dash-dashed line depicts the contribution of the hybrid term. The red solid line stands for the total contributions.

scaled by the PDG branching fraction $\Gamma[f_1(1285) \to \eta\pi^+\pi^-]$ in the fit, $0.52 \times (2/3)$, which was used by the CLAS Collaboration [6]. In our fit, $M_N = 0.938$ Gev, $M_{N^*} = 2.30$ GeV, $\Gamma_{N^*} = 0.34$ GeV, $M_\rho = 0.775$ GeV, and $M_\omega = 0.783$ GeV [1].

There are a total of 45 CLAS experimental data, and the statistical and systematic uncertainties are taken into account. Considering all the contributions depicted in Fig. 1, we perform a fit to the CLAS data, and the corresponding results are shown in Table I (fit A). With these parameters in fit A, the calculated differential cross

TABLE I. The fitted parameters in this work.

	Fit A	Fit B
g_{N^*} (GeV^{-1})	-0.052 ± 0.006	$\cdots$
g_t (GeV^{-2})	0.335 ± 0.068	-0.443 ± 0.117
$g_{f_1 NN}$	0.347 ± 0.258	0.110 ± 0.016
κ_N	-4.034 ± 2.459	9.999 ± 9.801
Λ_{N^*} (GeV)	1.354 ± 0.269	$\cdots$
Λ_N (GeV)	1.285 ± 0.216	1.540 ± 0.157
Λ_t (GeV)	0.582 ± 0.219	0.610 ± 0.187
t_0 (GeV^2)	2.153 ± 0.445	1.612 ± 0.507
Δt (GeV^2)	0.736 ± 0.433	0.850 ± 0.344
χ^2/dof	1.05	1.89

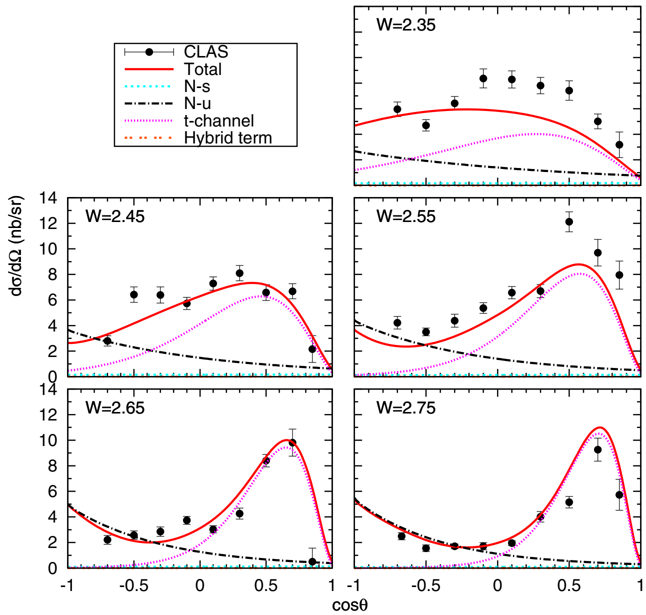

FIG. 3. Differential cross sections of the $\gamma p \to f_1(1285)p$ reaction as a function of $\cos\theta$, where $N(2300)$ effects are not considered. The explanation is the same as that of Fig. 2.

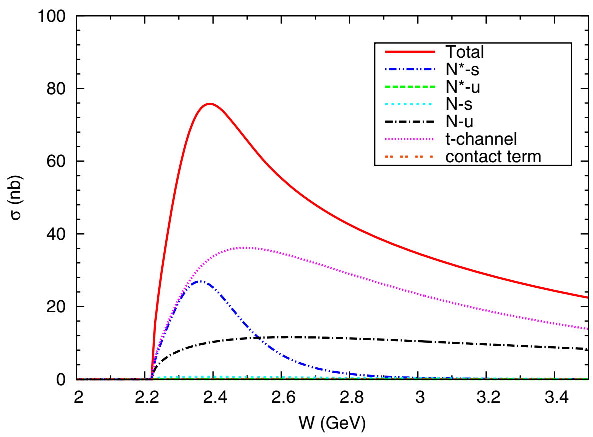

FIG. 4. Total cross section of the $\gamma p \to f_1(1285)p$ reaction vs the invariant mass $W = \sqrt{s}$ of the γp system, by including all the contributions depicted in Fig. 1. The explanation is the same as that of Fig. 2.

sections from $W = 2.35$ to $W = 2.75$ GeV as well as the 45 available data are depicted in Fig. 2, where the blue dash-dot-dotted and magenta dotted lines correspond to the contributions of the s-channel $N(2300)$ and t-channel exchanges, respectively; the black dash-dotted is the contribution of the u-channel proton; and other contributions are very small and can be neglected. The red solid lines stand for the total contributions. Only the statistical errors are shown in Fig. 2.

From Fig. 2, we can see that our model gives an overall reasonable description of the data in the range of $W = 2.35 \sim 2.75$ GeV. The $N(2300)$ provides a flat contribution for the differential cross sections, since the

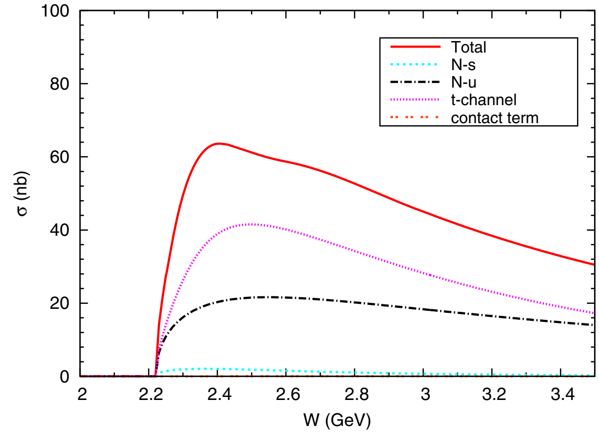

FIG. 5. Total cross section of the $\gamma p \to f_1(1285)p$ reaction vs the invariant mass $W = \sqrt{s}$ of the γp system, by excluding the contributions of the s-/u-channel N(2300) terms. The explanation is the same as that of Fig. 2.

$N(2300)$ couples to the final states $f_1(1285)p$ in the S-wave. Near the threshold, the s-channel $N(2300)$ gives a large contribution. At higher energies, the contributions of the t-channel ρ and ω trajectories exchanges are responsible for the shapes of the differential cross sections. The contribution of u-channel nucleon term is dominant at the backward angles, especially in the region of high energies. Other contributions are very small and can be neglected.

In order to study the role of the $N(2300)$ resonance in the $\gamma p \to f_1(1285)p$ reaction, we also perform a fit by excluding the s-/u-channel $N(2300)$ and allow the other terms to remain. The corresponding results are listed in Table I (fit B), and the differential cross sections are shown in Fig. 3. From Table I, one can see that the $\chi^2/\mathrm{dof} = 1.89$ in fit B is larger than $\chi^2/\mathrm{dof} = 1.05$ in fit A, which shows that the model including the $N(2300)$ contributions can better describe the CLAS data.

Finally, we present the total cross section of the $\gamma p \to f_1(1285)p$ reaction with and without $N(2300)$ terms, respectively, in Figs. 4 and 5. From Fig. 4, it can be seen that the s-channel $N(2300)$ term gives a clear peak structure around $W = 2.3$ GeV with the magnitude of order 30 nb, but there is no such structure for the case of excluding the $N(2300)$ contributions, which can be used to test our model.

IV. SUMMARY

In this work, we have performed the study of the $\gamma p \to f_1(1285)p$ reaction within the Regge-effective Lagrangian approach. Besides the contributions from the t-channel ρ and ω trajectories exchanges, we also consider the s-/u-channel $N(2300)$ terms, the s-/u-channel nucleon terms, and the contact term.

We extract the information about the intermediate states by fitting to the CLAS data. We find that the model including the $N(2300)$ contributions can better describe the CLAS data.

Our results indicate that the contributions of the u-channel $N(2300)$ term, the s-channel nucleon term, and the contact term are very small and can be neglected. However, the contribution of u-channel nucleon term is dominant at the backward angles, especially in the region of high energies. With the preferred parameters (fit A), we predict the total cross section. There is a clear bump structure around $W = 2.3$ GeV, which is associated with the $N(2300)$ state. Thus, the reaction of $\gamma p \to f_1(1285)p$ could be useful to further study the $N(2300)$ experimentally.

It should be noted that after we submitted this work to the arXiv Wang and He also discussed the $\gamma p \to f_1(1285)p$ reaction in a similar way [22], where the t-channel ρ and ω trajectories exchanges and the s- and u-channel nucleon term are considered and the s-channel nucleon resonances are not included. They suggested that the s-channel nucleon resonances are not very large. Our calculations show that the s-channel N(2300) term plays an important role in the $\gamma p \to f_1(1285)p$ reaction, and a clear bump structure in the total cross section around $\sqrt{s} = 2.3$ GeV is predicted. The current information about this reaction is not enough to distinguish our model from the one of Ref. [22]. To shed light on the relevant mechanisms of the $\gamma p \to f_1(1285)p$ reaction, further measurement of the total cross sections is called for.

ACKNOWLEDGMENTS

We would like to thank Dr. Ju-Jun Xie and Dr. Qi-Fang Lü for valuable discussions. This work is partly supported by the National Natural Science Foundation of China under Grant No. 11505158, the China Postdoctoral Science Foundation under Grant No. 2015M582197, the Postdoctoral Research Sponsorship in Henan Province under Grant No. 2015023, and the Startup Research Fund of Zhengzhou University under Grants No. 15113 17001 and No. 1511317002.

[1] C. Patrignani *et al.* (Particle Data Group Collaboration), Review of particle physics, Chin. Phys. C **40**, 100001 (2016).

[2] E. Klempt and J. M. Richard, Baryon spectroscopy, Rev. Mod. Phys. **82**, 1095 (2010).

[3] I. G. Aznauryan *et al.*, Studies of nucleon resonance structure in exclusive meson electroproduction, Int. J. Mod. Phys. E **22**, 1330015 (2013).

[4] M. F. M. Lutz *et al.*, Resonances in QCD, Nucl. Phys. **A948**, 93 (2016).

[5] S. Capstick and W. Roberts, Quark models of baryon masses and decays, Prog. Part. Nucl. Phys. **45**, S241 (2000).

[6] R. Dickson *et al.* (CLAS Collaboration), Photoproduction of the $f_1(1285)$ Meson, Phys. Rev. C **93**, 065202 (2016).

[7] N. I. Kochelev, M. Battaglieri, and R. De Vita, Exclusive photoproduction of $f_1(1285)$ meson off the proton in kinematics available at the Jefferson Laboratory experimental facilities, Phys. Rev. C **80**, 025201 (2009).

[8] S. K. Domokos, H. R. Grigoryan, and J. A. Harvey, Photoproduction through Chern-Simons term induced interactions in holographic QCD, Phys. Rev. D **80**, 115018 (2009).

[9] Y. Huang, J. J. Xie, X. R. Chen, J. He, and H. F. Zhang, The $\gamma p \to n a_2^+(1320) \to n\rho^0\pi^+$ reactions within an effective Lagrangian approach, Int. J. Mod. Phys. E **23**, 1460002 (2014).

[10] M. Ablikim *et al.* (BESIII Collaboration), Observation of two new N^* resonances in the decay $\psi(3686) \to p\bar{p}\pi^0$, Phys. Rev. Lett. **110**, 022001 (2013).

[11] N. I. Kochelev, D. P. Min, Y. Oh, V. Vento, and A. V. Vinnikov, New anomalous trajectory in Regge theory, Phys. Rev. D **61**, 094008 (2000).

[12] S. H. Kim, A. Hosaka, and H. C. Kim, Effects of $N(2000)5/2^+$, $N(2060)5/2^-$, $N(2120)3/2^-$, and $N(2190)7/2^-$ on $K^*\Lambda$ photoproduction, Phys. Rev. D **90**, 014021 (2014).

[13] C. Elster, A. Sibirtsev, S. Krewald, and J. Speth, Photoproduction of η'-mesons from the Proton, AIP Conf. Proc. **717**, 837 (2004).

[14] J. J. Xie, E. Wang, and J. Nieves, Re-analysis of the $\Lambda(1520)$ photoproduction reaction, Phys. Rev. C **89**, 015203 (2014).

[15] J. J. Xie and J. Nieves, Role of the $N^*(2080)$ resonance in the $\vec{\gamma}p \to K^+\Lambda(1520)$ reaction, Phys. Rev. C **82**, 045205 (2010).

[16] A. Donnachie and P. V. Landshoff, Exclusive rho production in deep inelastic scattering, Phys. Lett. B **185**, 403 (1987).

[17] V. Y. Grishina, L. A. Kondratyuk, W. Cassing, M. Mirazita, and P. Rossi, Comparative Regge analysis of $\Lambda, \Sigma\Lambda(1520)$ and Θ^+ production in $\gamma p, \pi p$ and pp reactions, Eur. Phys. J. A **25**, 141 (2005).

[18] E. Wang, J. J. Xie, and J. Nieves, Regge signatures from CLAS $\Lambda(1520)$ photoproduction data at forward angles, Phys. Rev. C **90**, 065203 (2014).

[19] J. M. Laget, The Primakoff effect on a proton target, Phys. Rev. C **72**, 022202 (2005).

[20] P. D. B. Collins, *An Introduction to Regge Theory and High-Energy Physics* (Cambridge University Press, Cambridge, England, 1977).

[21] M. Guidal, J. M. Laget, and M. Vanderhaeghen, Pion and kaon photoproduction at high energies: Forward and intermediate angles, Nucl. Phys. **A627**, 645 (1997).

[22] X. Y. Wang and J. He, Analysis of recent CLAS data on $f_1(1285)$ photoproduction, Phys. Rev. D **95**, 094005 (2017).