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Exclusive photoproduction of $f_1(1285)$ meson off the proton in kinematics available at the Jefferson Laboratory experimental facilities

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We calculated the exclusive $f_1(1285)$ meson photoproduction cross section at an energy of a few GeV within the Regge approach. The calculation shows that the cross section is sizable, being in the range of 100 nb, and much larger than the expected cross section of the $\eta(1295)$ meson photoproduction at the same energy. These two facts make it possible to use this reaction to study the poor known properties of the $f_1(1285)$ meson in the JLab kinematics.

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I. INTRODUCTION

Investigation of hadron properties is nowadays a hot topic, being the subject of several studies within nonperturbative QCD approaches. The existence of possible exotic hadron states is the subject of both theoretical [1–4] and experimental activity [5–7]. The $f_1(1285)$ meson, with quantum numbers $I^G(J^{PC}) = 0^+(1^{++})$, is usually considered a member of the axial vector meson nonet. However, it was argued that this resonance may have a rather large mixture of gluons in its wave function [8]. In Ref. [9], the special role of the $f_1(1285)$ trajectory in spin-dependent high energy cross sections, based on the deep relation of the properties of this meson with the $U(1)_A$ gluon axial anomaly in QCD, was discussed. The alternative approach to treat $f_1(1285)$ as a dynamically generated resonance through the interaction of vector and pseudoscalar mesons in the $K^*\bar{K}$ channel was suggested in Ref. [10]. It is worth noticing that the $f_1(1285)$ meson has a large branching ratio (∼36% [16]) to $a_0(980)\pi$. Therefore the production of this meson gives also a unique opportunity to study the properties of the $a_0(980)$ meson, a well-known candidate for the exotic four-quark state (see discussion and references in Refs. [1] and [2]).

Photoproduction is a very powerful tool to investigate meson properties. The experimental program of the CLAS Collaboration at Jefferson Laboratory (JLab) includes various photoproduction reactions with mesonic final states. In light of the importance of the $f_1(1285)$ meson, we report on an estimate of the cross section for the reaction $\gamma p \to p f_1(1285)$ at a photon energy of a few GeV, within the Regge approach.

II. ESTIMATE OF THE $f_1(1285)$ MESON EXCLUSIVE PHOTOPRODUCTION CROSS SECTION

The Regge model for meson photoproduction is being widely used to calculate cross sections for different reactions in the kinematic region $s \gg -t$ (see Refs. [13,17] and references therein). Within this approach, the main contribution to the $f_1(1285)$ photoproduction cross section at small momentum transfer ($-t \leqslant 1$ GeV^2) and a photon energy range of a few GeV is related to the t-channel exchange of ρ and ω meson trajectories (see Fig. 1).

Propagators of ρ and ω mesons are given by [13]

$$P_V = \left(g^{\mu\nu} - \frac{k_V^\mu k_V^\nu}{m_V^2}\right)\left(\frac{s}{s_0}\right)^{\alpha_V(t)-1} \times \frac{\pi\alpha'_V}{\sin(\pi\alpha_V(t))\Gamma(\alpha_V(t))} D_V(t), \quad (1)$$

where $D_V(t)$ is the signature factor. It is well known that Regge trajectories can be either nondegenerate or degenerate [11]. In Ref. [12], a detailed analysis of high energy pion photoproduction data within the Regge approach was performed. It was argued that the ρ meson trajectory should be degenerate in order to describe the ratio of cross sections of charged pions photoproduction. However, the ω trajectory should be nondegenerate to reproduce the dip around $t \approx -0.6$ GeV^2 observed in high energy exclusive π^0 photoproduction. Using the results of this study, we adopted the following expressions for the signature related factors:

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

$$D_\rho(t) = \exp(-i\pi\alpha_\rho(t)), \quad (3)$$

where k_V is the meson momentum, $s_0 = 1$ GeV, and α'_V is the slope of the trajectory. For the ρ trajectory the rotating phase was chosen [13][1] to be

$$\alpha_\omega(t) = 0.44 + 0.9t, \quad (4)$$

$$\alpha_\rho(t) = 0.55 + 0.8t. \quad (5)$$

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[1] We have checked that the choice of a constant value for the phase of the ρ trajectory leads to very similar numerical results for the differential photoproduction cross sections of the $f_1(1285)$, $\eta(1295)$, and $\eta(548)$ mesons.

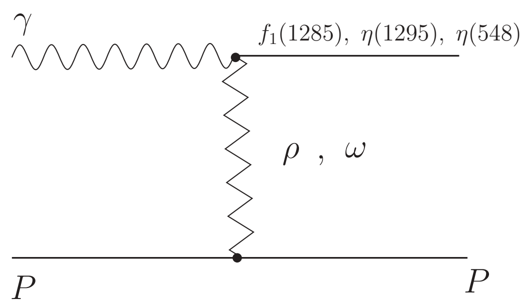

FIG. 1. The dominant diagram in $f_1(1285)$, $\eta(1295)$, and $\eta(548)$ meson exclusive photoproduction off the proton within the Regge model.

The vector meson (VM)-proton coupling is given by the standard expression

$$\mathcal{L} = g_V \bar{N}\gamma_\mu N V_\mu + \frac{g_V^T}{2m_N}\bar{N}\sigma_{\mu\nu} N V_{\mu\nu}, \tag{6}$$

where $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$. The numerical value of the coupling constants was taken from Ref. [17]:

$$g_{\omega NN} = 10.6, \tag{7}$$

$$g_\omega^T = 0, \tag{8}$$

$$g_{\rho NN} = 3.9, \tag{9}$$

$$g_\rho^T / g_\rho = 6.1. \tag{10}$$

The f_1-VM-photon vertex has the following form [9]:

$$V_{Vf_1\gamma} = g_{Vf_1\gamma} k_V^2 \epsilon_{\mu\nu\alpha\beta}\xi^\beta \epsilon_V^\nu \epsilon_\gamma^\alpha q^\mu, \tag{11}$$

where q is photon momentum, ξ, ϵ_V, and ϵ_γ are the polarization vectors of the f_1, the vector meson and the photon, respectively.

The coupling in Eq. (11) corresponds to the AVV Lagrangian obtained in Ref. [14] by using the hidden gauge approach. We should also mention that this coupling satisfies the Landau-Yang theorem [15] and leads to a vanishing value for an axial vector meson coupling to two massless vector particles (e.g., in the limit $k_V^2 \to 0$).

The coupling $g_{\rho f_1 \gamma} = 0.94\ \text{GeV}^{-2}$ was fixed from the measured width

$$\Gamma_{f_1\to\rho\gamma} = \frac{m_\rho^2\left(m_{f_1}^2 + m_\rho^2\right)\left(m_{f_1}^2 - m_\rho^2\right)^3}{96\pi m_{f_1}^5} g_{\rho f_1\gamma}^2, \tag{12}$$

assuming $\Gamma_{f_1\to\rho\gamma} \simeq 1.3$ MeV [16].

There is no experimental information about the $f_1\omega\gamma$ vertex. However, this coupling can be estimated within the quark model through the known value of $g_{\rho f_1\gamma}$ by using a quite general flavor decomposition of the f_1 wave function

$$f_1 = \alpha(\bar{u}u + \bar{d}d) + \beta\bar{s}s + \gamma gg, \tag{13}$$

where the parameters β and γ describe a possible mixture of strange quark and gluons in f_1. In the $SU(2)_f$ limit we have

$$g_{\omega f_1\gamma} \approx \frac{e_u + e_d}{e_u - e_d} g_{\rho f_1 \gamma}, \tag{14}$$

where e_q is the electric charge of the correspondent quark.

To further proceed in the calculation, we need an estimate of the two form factors in the $Vf_1\gamma$ and VNN vertices. In the spirit of vector meson dominance, we derived F_{VNN} from the Bonn model [17]:

$$F_{VNN}(t) = \frac{\Lambda_1^2 - m_V^2}{\Lambda_1^2 - t}, \tag{15}$$

with $\Lambda_1 = 1.5$ GeV, and we chose $F_{Vf_1\gamma}$ in the form

$$F_{Vf_1\gamma} = \left(\frac{\Lambda_2^2 - m_V^2}{\Lambda_2^2 - t}\right)^2, \tag{16}$$

with $\Lambda_2 = 1.04$ GeV. This form follows from the recent results of the $L3$ Collaboration about the $f_1(1285)$ production in the $\gamma\gamma^*$ interaction [18] and the assumption on the similarity of the heavy photon and vector meson vertices.

The resulting differential cross section for $E_\gamma = 3.1$ GeV is plotted as a solid line in Fig. 2 (left). As shown in the plot, the cross section has its maximum at $-t \sim 0.5$ GeV. Both values, E_γ and $-t$, are well matched to the kinematics accessible with the CLAS detector at JLab. The size of the cross section, $\sim$100 nb, makes the measurement feasible with such a detector.

III. ESTIMATE OF THE η(1295) EXCLUSIVE PHOTOPRODUCTION CROSS SECTION

Experimentally, the main problem to measure the exclusive $f_1(1285)$ photoproduction cross section comes from the background of the $\eta(1295)$ meson. A separation of the two mesons could be achievable performing a partial wave analysis that distinguishes the different quantum numbers. On the other hand, the small production cross section results in low statistics that limits the accuracy of these analysis. Another approach is to extract the cross section through the inclusive measurement of the reaction $\gamma p \to pX$, where mesons are identified as peaks in the spectrum of the proton missing mass. In the case of the $f_1(1285)$ and $\eta(1295)$ meson, their similar mass and width makes it practically impossible to distinguish them. The measurement of the $f_1(1285)$ cross section would be still possible if the $\eta(1295)$ cross section was found to be much lower, assuming therefore, that the observed signal is dominated by the $f_1(1285)$ meson production.

In Regge theory, the $\eta(1295)$ meson exclusive photoproduction is described by the same diagram as for $f_1(1285)$ meson (see Fig. 1). In the spirit of the vector meson dominance model, the $\eta(1295)$ meson photoproduction cross section can be estimated knowing the strength of the vertex $\eta(1295) \to \gamma\gamma$. Unfortunately, the are no direct measurements of this width. We then used an indirect way to estimate the width relying on the constituent quark model. Assuming that the $\eta(1475)$ and $\eta(1295)$ mesons are the first radial excitations of the $\eta'(980)$ and $\eta(548)$, respectively, we correlated the existing data on the $\eta(1475) \to \gamma\gamma$ width using the constituent quark model relationships for a two-photon width of the pseudoscalar meson [19]:

$$\Gamma(0^{-+} \to 2\gamma) \propto m_{0^{-+}}^3 \sum_q e_q^2, \tag{17}$$

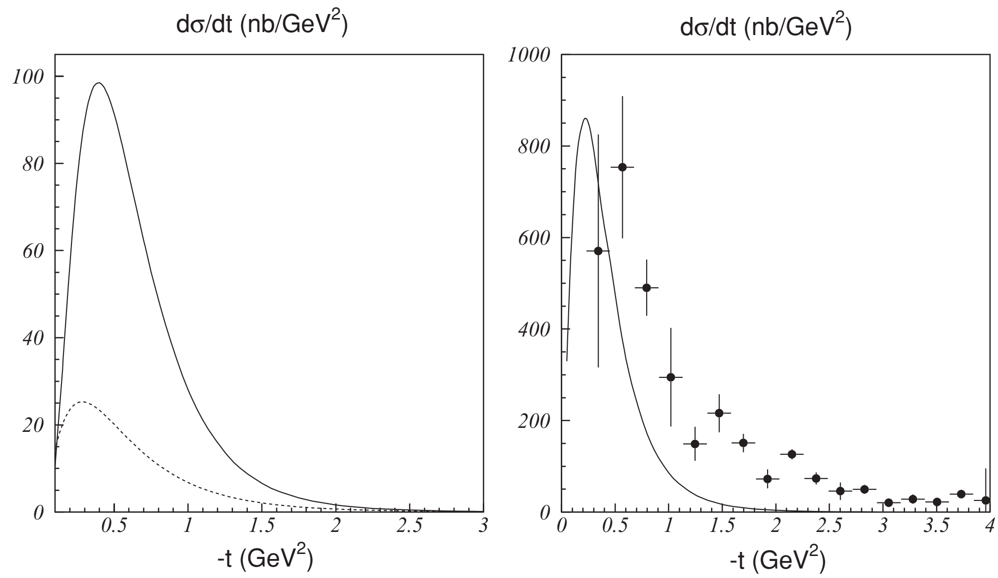

FIG. 2. Estimated cross sections for the reactions: $\gamma p \to f_1(1285)p$ (left panel, solid line), $\gamma p \to \eta(1295)p$ (left panel, dotted line), and $\gamma p \to \eta(548)p$ (right panel) at $E_\gamma = 3.1$ GeV. In the right panel, the SAPHIR data [21] for the $\eta(548)$ cross section at $E_\gamma = 2.8$–3 GeV are also shown.

where $\sum_q e_q^2$ represents the sum of the electric charges of quarks in meson, and therefore

$$\Gamma(\eta(1295) \to 2\gamma) \approx \frac{\Gamma(\eta(1475) \to 2\gamma)\Gamma(\eta \to 2\gamma)m_{\eta'}^3 m_{1295}^3}{\Gamma(\eta' \to 2\gamma)m_\eta^3 m_{1475}^3} \approx 0.091 \text{ KeV}, \quad (18)$$

where we used $\Gamma(\eta(1475) \to 2\gamma) \approx 0.212$ KeV [16] with the assumption that $K\bar{K}\pi$ is the $\eta(1475)$ dominant decay mode.

The η-VM-photon vertex has the following form:

$$V_{V\eta\gamma} = g_{V\eta\gamma}\epsilon_{\mu\nu\alpha\beta}\epsilon_V^\nu \epsilon_\gamma^\alpha q^\mu k_\eta^\nu, \quad (19)$$

where k_η is the η meson momentum. Using Eq. (19) and the vector meson dominance model, we obtained the following expression for the $\rho\eta\gamma$ coupling:

$$g^2_{\rho\eta(1295)\gamma} \approx \frac{96\pi m_\rho^3 m_\eta^3 \Gamma(\rho \to \eta\gamma)\Gamma(\eta(1295) \to 2\gamma)}{\left(m_\rho^2 - m_\eta^2\right)^3 m^3{}_{\eta(1295)}\Gamma(\eta \to 2\gamma)} \approx 0.0032 \text{ GeV}^{-2}, \quad (20)$$

where $\eta \equiv \eta(548)$. The $\eta(1295)$-ω coupling has been estimated with a similar equation as in Eq. (14):

$$g_{\omega\eta(1295)\gamma} \approx \frac{e_u + e_d}{e_u - e_d} g_{\rho\eta(1295)\gamma}. \quad (21)$$

The Brodsky-Lepage form of the transition form factor in the $V\eta\gamma$ vertex was used [20]:

$$F_{V\eta\gamma} = \frac{1}{1 - t/\left(8\pi^2 f_{PS}^2\right)}, \quad (22)$$

where f_{PS} is the pseudoscalar decay constant, related to the $\Gamma_{\gamma\gamma}$ partial width by

$$f_{PS} = \frac{\alpha}{\pi}\sqrt{\frac{M_{PS}^3}{64\pi\Gamma_{\gamma\gamma}}}. \quad (23)$$

The resulting differential cross section for the reaction $\gamma p \to p\eta(1295)$ at $E_\gamma = 3.1$ GeV is plotted as a dotted line in Fig. 2 (left). Integrating the two differential cross sections in the whole $-t$ range, we obtained

$$\sigma_{f_1(1285)} = 68 \text{ nb},$$
$$\sigma_{\eta(1295)} = 18 \text{ nb}.$$

The $\eta(1295)$ cross section was found to be smaller (about 25%) than the $f_1(1285)$ cross section suggesting that the extraction of the exclusive $f_1(1285)$ photoproduction is possible without complicated partial wave analysis in the JLab kinematics.

As a check of the model, we repeated the same calculation to derive the differential cross section for the exclusive reaction $\gamma p \to \eta(548)p$. In this case the $\eta(548)$-VM-gamma coupling was obtained using the formula

$$g_{V\eta\gamma} = \sqrt{\frac{96\pi M_V^3 \Gamma_{V\to\eta\gamma}}{\left(m_V^2 - m_\eta{}^2\right)^3}}. \quad (24)$$

Results of the calculation are shown in Fig. 2 (right) compared to the experimental points for the same reaction measured by the SAPHIR Collaboration [21] in a similar photon energy range ($E_\gamma = 2.8$–3 GeV). Data are described rather well by our model. The deviation between theory and experiment, especially at low $-t$, remains within a factor 2 and it is typical for such simple implementation of the Regge theory. More sophisticated models and, in particular a better treatment of the shape of the form factors, would result in a better agreement.

IV. SUMMARY

In summary, we calculated the cross section for the exclusive $f_1(1285)$ meson photoproduction off proton above the baryon resonance region. The chosen kinematics matches the typical Jefferson Lab, Hall-B, photon experiments. Using the Regge model with some phenomenological input for the unknown parameters, we obtained a cross section of the order of 100 nb. In the same framework, we also evaluated the cross section for the exclusive $\eta(1295)$ meson photoproduction, which represents the main background for the $f_1(1285)$ meson extraction from a photoproduction experiment. The small value we found for such background suggests that a measurement of the $f_1(1285)$ exclusive photoproduction cross section with a detector such as CLAS is possible.

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