Charged K^* photoproduction in a Regge model

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(Received 15 October 2009; published 19 March 2010)

We investigate the $\gamma p \to K^{*+}\Lambda$ reaction within a Regge approach. For the gauge invariance of the scattering amplitude, we reggeize the s channel and contact-term amplitudes as well as the t-channel amplitude. We obtain a decreasing behavior of the total cross section as the CLAS's preliminary data show. We also calculate spin density matrices and find clear differences between our Regge model and the previous Feynman (isobar) model.

DOI: 10.1103/PhysRevC.81.035206 PACS number(s): 13.60.Le, 11.55.Jy, 25.20.Lj, 12.40.Vv

Recently strangeness photoproduction has been of interest in hadron physics. Several photon facilities such as CLAS, LEPS, SAPHIR, and CBELSA/TAPS provide accurate data on strangeness photoproduction. In these data there are very interesting phenomena, for instance, pentaquark production [1,2] and peak structures near the threshold in ϕ photoproduction [3] and, also, in Λ resonance photoproduction [4,5]. To understand those phenomena, we have to understand a fundamental mechanism of open strangeness photoproduction.

From a theoretical point of view, Regge phenomenology is very successful in strangeness photoproduction above 2 GeV. The model reproduces the energy and t dependence of cross sections and spin observables of several strangeness photoproductions in the forward-angle region. What we pay special attention to is the energy dependence of cross sections predicted by this model. The Regge phenomenology successfully reproduces the decreasing behavior of cross sections of the kaon photoproduction in terms of kaon and K^* trajectories [6–9]. On the other hand, in ϕ photoproduction, the experimental data show a monotonically increasing behavior of the cross section. This behavior is explained by the Pomeron exchange [10,11].

Originally, however, the Regge model is applied in high-energy hadron reactions. The relevant question is then at what energy and beyond we can apply the Regge model. From the successful application of the model in strangeness photoproduction, one can expect that it is valid in the energy region where open strangeness is produced. To test this, we study charged K^* photoproduction using the Regge approach. The feature of charged K^* photoproduction is that K^* (vector meson) exchange is allowed, whereas it is forbidden in the neutral K^* photoproduction. Because the exchange of a higher-spin particle including a vector meson leads to s^J behavior of a Feynman amplitude, where s stands for the Madelstam variable and J stands for the spin of the exchanged particle, the amplitude increases with the energy faster than $\log^2 s$. Therefore, the Feynman (isobar) model violates the Froissart bound (unitarity) in the high-energy region. Figure 1 shows CLAS's preliminary data on $\gamma p \to K^{*+}\Lambda$ and the result of the Feynman model. Because the K^* (vector meson) exchange amplitude shows monotonically increasing behavior, it is difficult to reproduce the decreasing behavior of the data if one applies the Feynman model naively. The contradiction between the data and the results of the Feynman model may indicate that we need to employ the Regge approach in this energy region. Instead of one meson exchange, the Regge model takes into account the exchange of an entire family of hadrons with the same quantum number expect spin. The resulting amplitude satisfies the Froissart bound. Because of the slope parameters of the kaon, κ, and K^* trajectories, one would expect that the Regge model naturally reproduces the decreasing behavior. In this paper we apply the Regge model in the charged K^* photoproduction and compare the results of our Regge model with those of the previous Feynman model.

In previous studies, Oh *et al.* investigated K^* photoproduction that was based on the Feynman model [13,14]. Their model nicely reproduced the experimental data. In Ref. [14], the authors pointed out that κ exchange plays an important role in neutral K^* photoproduction. Therefore we take κ exchange into account in the charged K^* photoproduction $\gamma p \to K^{*+}\Lambda$. The exact form of the interaction Lagrangians and the amplitudes in the model are given in Refs. [13] and [14]. We use the same values of coupling constants and κ parameters as in Refs. [13] and [14], which are determined as follows. K^* couplings are fixed in terms of Nijmegen potential [15]: $g_{K^*N\Lambda} = -4.26$, $\kappa_{K^*N\Lambda} = 2.66$ (NSC97a). The photon coupling $g_{\gamma KK^*}$ can be determined by K^* radiative decay. From experimental data, in the case of charged K^* production, $g_{\gamma KK^*} = 0.254\ \text{GeV}^{-1}$, where the sign is fixed by using the quark model. The strong interaction coupling of kaon and baryon vertices is determined from flavor $SU(3)$ symmetry, $g_{KN\Lambda} = -\frac{1}{\sqrt{3}}(1+2\alpha)g_{\pi NN} = -13.24$, with $\alpha = 0.365$ and $g^2_{\pi NN}/4\pi = 14.0$. Parameters for κ meson mass and width are $m_\kappa = 700 \sim 900$ MeV and $\Gamma_\kappa = 400 \sim 770$ MeV. Here we employ $m_\kappa = 750$ MeV, $\Gamma_\kappa = 550$ MeV, and $|g_{\gamma K\kappa} g_{\kappa N\Lambda}| = 1.1e\ \text{GeV}^{-1}$ [13,14]. We include the nucleon pole in the s channel, while we take into account $\Lambda(1116)$, $\Sigma(1193)$, and $\Sigma(1385)$ in the u channel. We do not consider nucleon resonances, for simplicity. Inclusion of the nucleon resonances, however, will modify the cross section near the threshold region as in other production reactions (e.g., kaon production), as discussed later. Coupling constants for s and u channels are given in Refs. [13] and [14]. In the model the hadronic form

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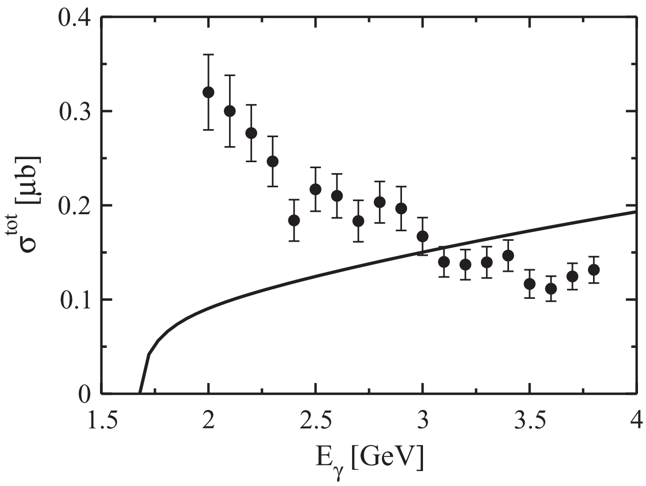

FIG. 1. Total cross section of the $\gamma p \to K^{*+}\Lambda$ reaction as a function of the photon energy E_γ in the laboratory frame. The solid line is the result of the Feynman model (see text for details), and the data are taken from Refs. [12] and [13].

factors are used at each vertex to take into account size effects of hadrons phenomenologically:

$$F(t) = \frac{\Lambda_t^2 - m^2}{\Lambda_t^2 - t}, \quad F(x) = \frac{\Lambda_x^4}{(x - M^2)^2 + \Lambda_x^4}, \quad x = s, u, \tag{1}$$

where m and M are masses of an exchanged meson and baryon. The sum of the electric term of the s channel, contact term, and K^* exchange term forms a set of gauge-invariant terms, and therefore, the common form factor $F_c = 1 - [1 - F(s)][1 - F_{K^*}(t)]$ was employed for them [16]. Figure 2(a) shows contributions from each channel in the Feynman model with a cutoff $\Lambda_t = 1.15$ GeV for all t channels and a cutoff $\Lambda_x = 0.9$ GeV for s and u channels. As shown in this figure, the origin of the monotonically increasing behavior is the K^* exchange and also the contact term contribution. Therefore if we use the same value of the cutoff parameter Λ_t for all t-channel contributions, we obtain increasing-energy-behavior as shown in Fig. 1. To explain the decreasing behavior in the Oh *et al.* model, K^* exchange and the contact term contributions were quite suppressed by tuning the cutoff parameter of the form factor [Fig. 2(b)]. Then kaon exchange became a dominant contributor. This is a unique feature of this model. If one wants to reproduce charged K^* photoproduction in terms of the Feynman model, one should suppress contributions of the vector meson exchange and the contact term and enhance the scalar or pseudoscalar meson exchange terms.

Now we introduce the Regge model for charged K^* photoproduction. The reggeization is done by replacing the t-channel propagator in the Feynman amplitudes with the Regge propagator as [7–9]

$$\frac{1}{t - m_K^2} \to \mathcal{P}_{\rm regge}^K = \left(\frac{s}{s_0}\right)^{\alpha_K(t)} \frac{1}{\sin[\pi\alpha_K(t)]} \frac{\pi\alpha_K'}{\Gamma[1 + \alpha_K(t)]}, \tag{2}$$

$$\frac{1}{t - m_\kappa^2} \to \mathcal{P}_{\rm regge}^\kappa = \left(\frac{s}{s_0}\right)^{\alpha_\kappa(t)} \frac{1}{\sin[\pi\alpha_\kappa(t)]} \frac{\pi\alpha_\kappa'}{\Gamma[1 + \alpha_\kappa(t)]}, \tag{3}$$

$$\frac{1}{t - m_{K^*}^2} \to \mathcal{P}_{\rm regge}^{K^*} = \left(\frac{s}{s_0}\right)^{\alpha_{K^*}(t)-1} \frac{1}{\sin[\pi\alpha_{K^*}(t)]} \frac{\pi\alpha_{K^*}'}{\Gamma[\alpha_{K^*}(t)]}. \tag{4}$$

Formally one can reggeize the t-channel amplitude by multiplying the t-channel Feynman amplitude by $(t - m_{K^*}^2)\mathcal{P}_{\rm regge}$. Here we assume degenerate trajectories because there are no dip structures (wrong-signature zeros) in kaon photoproduction [7,8] or in the reaction $\gamma p \to K^{*0}\Sigma^+$ [17,18]. We choose constant phases for all trajectories and set $s_0 = 1$ GeV. Phase dependence will be discussed in Ref. [19]. The following discussion, however, is not affected by this phase factor. Meson trajectories are given by

$$\alpha_K(t) = 0.70\ {\rm GeV}^{-2}\big(t - m_K^2\big), \tag{5}$$

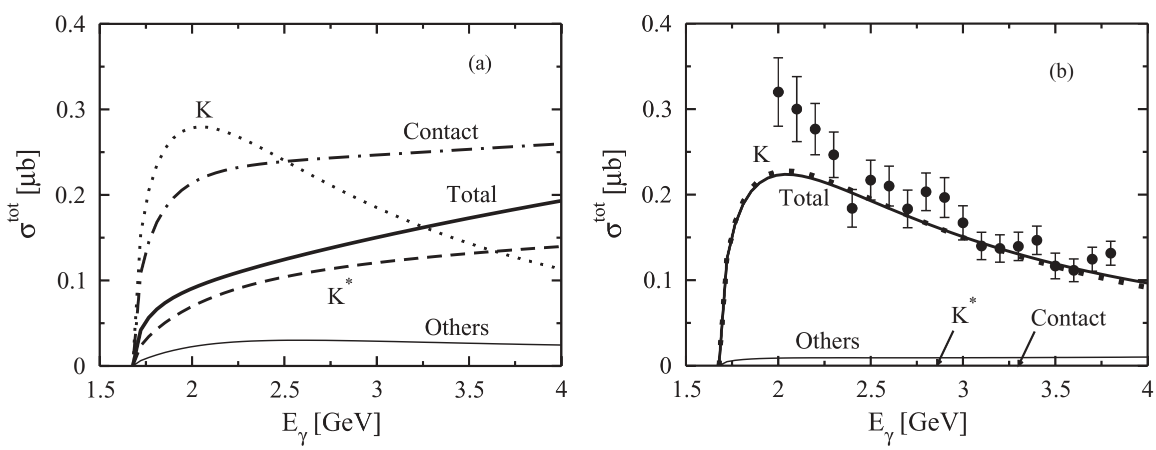

FIG. 2. (a) Separate contributions of each channel to the total cross section in the Feynman model. The solid line is the total cross section, the dashed line is K^* exchange, the dotted line is kaon exchange, the dot-dashed line is the contact term, and the thin solid line is other-channel contributions including κ exchange. (b) Previous results with the Feynman model from Ref. [13], where the cutoff parameters $\Lambda_{K,\kappa} = 1.1$ GeV and $\Lambda_{K^*} = 0.9$ GeV were used. Contributions of various terms are shown separately. Conventions are as in (a).

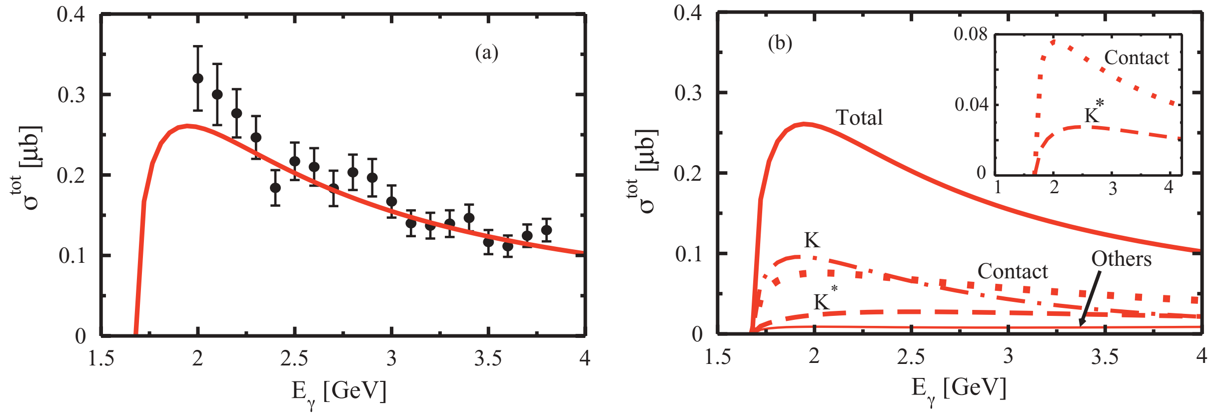

FIG. 3. (Color online) (a) The total cross section of the reaction $\gamma p \to K^{*+}\Lambda$ in the Regge model. The cutoff for the t channel is $\Lambda_t = 1.55$ GeV. (b) Various contributions to the total cross section. Conventions are as in Fig. 2(a).

$$\alpha_\kappa(t) = \alpha_\kappa^{'}\left(t - m_\kappa^2\right), \quad (6)$$

$$\alpha_{K^*}(t) = 1 + 0.85\ \text{GeV}^{-2}\left(t - m_{K^*}^2\right), \quad (7)$$

where $\alpha_\kappa^{'}$ is fixed by the κ trajectory. In PDG [20], $K_0^*(800)$ (or κ), $K_1^*(1410)$, and $K_2^*(1980)$ can be identified as members of the κ family. Other mesons have not been found yet. We can fit the κ trajectory with $\alpha_\kappa^{'} = 0.70\ \text{GeV}^{-2}$. To maintain the gauge invariance, we need to reggeize the set of gauge-invariant terms of the electric s-channel, contact, and K^* exchange terms simultaneously. This means that, in accordance with Eq. (4), we perform the following replacement:

$$\left(\mathcal{M}_s^{\text{elec}} + \mathcal{M}_c\right) \to \left(\mathcal{M}_s^{\text{elec}} + \mathcal{M}_c\right) \times \left(t - m_{K^*}^2\right)\mathcal{P}_{\text{regge}}^{K^*}. \quad (8)$$

This procedure has been shown to be important for reproducing very forward-angle behavior ($\theta \sim 0$) in charged kaon photoproduction [6,7,9].

Let us now discuss the result of our approach. First, we calculate the total cross section. Because the Regge amplitude has a forward peak structure and decreases rapidly as $|t|$ is increased, in the forward region the main contribution comes from Regge amplitudes, while in intermediate- and high-$|t|$ regions the main contribution comes from s-channel and u-channel amplitudes. Therefore we expect that our present formalism with the Regge amplitude can also be used for estimation of the total cross section, although the Regge model is reliable in the low-$|t|$ region at high energy. As shown in Fig. 3(a), we find that our Regge model can reproduce the experimental data very well except in the region near the threshold and describe the decreasing behavior of the total cross section. Here we apply the monopole form factor $F(t)$ for K and κ trajectory, while we use F_c for K^* trajectory as well as for the electric part of the s channel and the contact term owing to the gauge invariance. We use the common cutoff parameter $\Lambda_t = 1.55$ GeV for the t-channel Regge amplitudes. As anticipated, the slight underestimate of the total cross section in Fig. 3(a) is expected to be improved by including nucleon resonances. Figure 3(b) shows each contribution of our model. In this model the K^* trajectory and the reggeized contact term contributions both decrease as the energy is increased. Here the gauge-invariant prescription, Eq. (8), plays a crucial role in explaining the decreasing behavior. Although both the Regge and the Feynman models reproduce the decreasing-energy behavior, their reaction mechanisms are different.

To see the difference more clearly, we calculate spin observables in the reaction $\gamma p \to K^{*+}\Lambda$. Spin observables

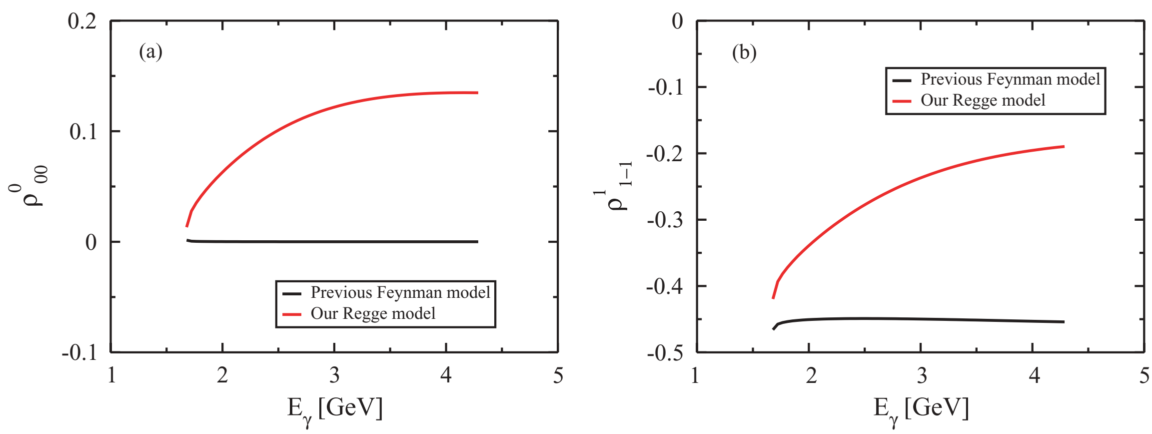

FIG. 4. (Color online) Spin density matrices of the $\gamma p \to K^{*+}\Lambda$ reaction: (a) ρ_{00}^0 and (b) ρ_{1-1}^1. In the calculation, the K^* angle was fixed at $\theta = 20^\circ$. The upper (red) line is our Regge model result, and the lower (black) line is the previous Feynman model result.

are very important for understanding the reaction mechanism; for instance, Refs. [21] and [22] pointed out the importance of chiral anomaly in kaon photoproduction by using the photon beam asymmetry. To focus on the t-channel contributions, we study spin density matrices at a forward angle, $\theta = 20^{\mathrm{o}}$. Figure 4(a) shows ρ^0_{00}, which represents the spin-1 flip process in the Gottfried-Jackson system [23]. In this system, a scalar or pseudoscalar exchange makes this matrix element exactly 0, but a vector meson exchange makes a finite contribution to this matrix element. Because in the Oh *et al.* model the dominant contribution is the kaon (pseudoscalar meson) exchange, ρ^0_{00} is almost zero. On the other hand, in our Regge model, ρ^0_{00} is finite owing to the sizable contribution of the K^* trajectory. Figure 4(b) shows ρ^1_{1-1}, which represents the naturalness or unnaturalness of the exchanged particles. The previous model makes this matrix element almost $-1/2$, owing to the kaon exchange (unnatural parity exchange) dominance. Because the K^* contribution is positive and increases with energy, in the Regge model the negative value of ρ^1_{1-1} decreases as the energy is increased. We verify that the significantly different behaviors in the two models of spin density matrices do not depend on the choice of the phase factors for the Regge trajectories qualitatively, and the differences are expected to be observed in future experiments, which will give us important information on the K^* photoproduction mechanism.

In summary, we have studied charged K^* photoproduction using the Regge model and compared the results of the Regge model versus the previous one. Both results reproduce the monotonically decreasing behavior of the total cross section, but their reaction mechanisms are very different. In the Feynman model, the dominant contribution is from kaon (pseudoscalar meson) exchange, and K^* (vector meson) exchange and the contact term are greatly suppressed, to reproduce the decreasing behavior of the total cross section. On the contrary, in the Regge model the K^* trajectory and the reggeized contact term contributions are naturally decreasing and provide sizable contributions. Consequently we have found decreasing behavior of the total cross section as the experimental data show. Owing to these features of the two models, we have found clear differences in the spin density matrices. These differences in spin density matrices can be used in comparison with experimental data to test the Regge model for open strangeness production.

ACKNOWLEDGMENTS

S.O. was supported by Grant for Scientific Research No. 21-4269 from the JSPS. A.H. was supported in part by Grant for Scientific Research No. (C) 19540297 from the Ministry of Education, Culture, Science and Technology (MEXT) of Japan.

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