Regge approach to the reaction of $\gamma N \to K^*\Lambda$

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Photoproduction of $K^*$ vector mesons off nucleon is investigated within the Regge framework where the electromagnetic vertex of $\gamma K^* K^*$ fully takes into account the magnetic dipole and electric quadrupole moments of spin-1 $K^*$ vector meson. The $t$-channel $K^*(892)$, $K(494)$ and $\kappa(800)$ meson exchanges are considered for the analysis of the production mechanism. The experimentally observed rapid decrease of the cross sections for the $\gamma p \to K^{*+}\Lambda$ reaction beyond the resonance region is well reproduced by the dominance of the exchange of $K$-meson trajectory. The role of the scalar $\kappa$-meson trajectory is found to be minor in both $\gamma p$ and $\gamma n$ reactions. The cross sections for the $\gamma n \to K^{*0}\Lambda$ reaction are predicted to be about twice those of the $\gamma p \to K^{*+}\Lambda$ reaction. The role of the $K^*$ electromagnetic multipoles and the proton anomalous magnetic moment is studied through the total and differential cross sections and spin/parity asymmetries. We suggest the measurement of the photon polarization asymmetry as a tool for identifying the role of the magnetic dipole and electric quadrupole moments of the $K^*$ vector meson.

PACS numbers: 11.55.Jy, 13.40.-f, 13.60.Le, 13.88.+e

Keywords: $K^*$ vector meson, photoproduction, electromagnetic multipoles, spin observables

Electromagnetic properties of hadrons are important to unravel the internal structure of hadrons. In the case of vector mesons, in particular, their magnetic moments and electric quadrupole moments are known to be $\mu = e_V/m_V$ and $Q = -e_V/m_V^2$, respectively, in the limit of point-like structure, where $e_V$ ($m_V$) is the charge (mass) of the vector meson. Therefore, any deviation from these canonical values implies nontrivial internal structure of vector meson and may give a clue on the properties of the constituents of vector mesons.

In this respect, the recent experimental data from the CLAS Collaboration on $K^*$ photoproduction at the Thomas Jefferson National Accelerator Facility draw attention as they provide information on the properties of vector mesons as well as on the production mechanisms of strangeness via the spin-1 vector meson. Nevertheless, only a few model calculations were attempted to analyze the reaction processes $\gamma p \to K^{*+}\Lambda$ and $\gamma n \to K^{*0}\Lambda$. Moreover, the former model calculations considered the electromagnetic interaction of the $K^*$ vector meson with the charge coupling only by dropping out other couplings. As stated above, however, spin-1 vector mesons have non-vanishing magnetic dipole and electric quadrupole moments. Therefore, investigating static properties of vector mesons through their production mechanisms is desirable and it is the main motivation of the present work.

In the recent publication, two of us studied photoproduction of charged $\rho$ meson, i.e., $\gamma N \to \rho^\pm N$ including the electromagnetic multipoles of vector mesons. We found that the existing data of Refs. on these processes could be reasonably reproduced. Encouraged by this observation, in the present work, we study the reaction processes $\gamma p \to K^{*+}\Lambda$ and $\gamma n \to K^{*0}\Lambda$ in order to see the role of the structure of the $\gamma K^* K^*$ vertex for a description of existing data reported in Refs.

As discussed in Ref. the validity of the Ward identity for the $\gamma K^* K^*$ vertex is crucial to provide a reliable prescription for gauge invariance in charged-meson photoproduction. The most general form of the electromagnetic $\gamma K^* K^*$ vertex $\Gamma_{\gamma K^* K^*}(q, Q)$ which satisfies the Ward identity is given by

$$
\eta_\nu^* \Gamma_{\gamma K^* K^*}(q, Q) \eta_\alpha \epsilon_\mu = -\eta_\nu^*(q) \left\{ e_{K^*} \left[ (q + Q)^\mu g^{\alpha \nu} - Q^\nu g^{\alpha \nu} - Q^\alpha g^{\mu \nu} \right] + e_{K^*} (k^\nu g^{\alpha \nu} - k^\alpha g^{\mu \nu}) \right\} \eta_\alpha(Q) \epsilon_\mu,
$$

(1)
where $k_{\mu}$ is the photon momentum and $Q_{\mu}$ and $q_{\mu}$ are the incoming and outgoing $K^*$ momenta, respectively, with $Q_{\mu} = q_{\mu} - k_{\mu}$. The polarization vectors of the photon and $K^*$ are denoted by $e_{\mu}$ and $\eta_{\mu}$, respectively. Here $e_{K^*}$ is the charge of the $K^*$ vector meson, and the magnetic dipole and electric quadrupole moments of the $K^*$ are given as

$$\mu_{K^*} = (\hat{e}_{K^*} + \kappa_{K^*}) \left( \frac{e}{2m_{K^*}^2} \right),$$

$$Q_{K^*} = \lambda_{K^*} \left( \frac{e}{m_{K^*}^2} \right).$$

Theoretical estimates on the magnetic dipole and electric quadrupole moments of the $K^*$ vector meson are reported in various models inspired by QCD [15, 16]. In the present work, we adopt the values predicted in Ref. [16], namely, $\hat{e}_{K^*} = +1$, $\kappa_{K^*} = 1.23$ (therefore, $\mu_{K^*} = 2.23$) and $\lambda_{K^*} = -0.38$ for the $K^{*+}$ and $\hat{e}_{K^*} = 0$, $\kappa_{K^*} = -0.26$ (therefore, $\mu_{K^*} = -0.26$) and $\lambda_{K^*} = 0.01$ for the $K^{*0}$. We also use $g_{K^{*+}N\Lambda} = -4.5$ and $g_{K^{*0}N\Lambda} = -10$ obtained by using the flavor SU(3) relations with the ratios $\alpha_{\nu} = 1$ and $\alpha_{T} = 0.4$ from $g_{pNN} = 2.6$ and $g_{\rho NN} = 9.62$ following Refs. [10, 17].

With these in mind we write the production amplitude as consisting of ka on, and scalar meson $\kappa$ and $K^*$-channel Regge-pole exchange in the $t$-channel, whereas $K^*$ of nonzero spin and $K^*_0$ as well should be suppressed in the region over the resonance peak.

We now consider the $t$-channel Regge-pole exchange in production amplitudes. Given the Born amplitude for the process $\gamma(k) + N(p) \rightarrow K^{*}(q) + Y(p')$, where the momentum of each particle is denoted in the parenthesis, the meson exchange in the $t$-channel is reggeized by replacing the $t$-channel pole with the Regge-pole in the form of

$$R^\nu(s,t) = \frac{\pi\alpha'_{\gamma}}{\Gamma[\alpha'_{\gamma}(t) + 1 - J]\sin[\pi\alpha'_{\gamma}(t)]} \left( \frac{s}{s_0} \right)^{\alpha'_{\gamma}(t) - J}$$

written collectively for a meson $\varphi$ of spin-$J$ with the phase $\frac{1}{2}[(J^2 - 1)^{J} + e^{-\pi\alpha'_{\gamma}(t)}]$ assigned to the exchange-non-degenerate single meson.

Recalling that the energy dependence of total cross sections is given as $\sigma \sim s^{\alpha'_{\gamma}(0)-1}$, the steep decrease of the cross section for the $\gamma p \rightarrow K^{*+}\Lambda$ reaction with increasing photon energy, as observed by the CLAS Collaboration [4], implies the dominance of the exchange of the kaon trajectory, whereas $K^*$ of nonzero spin and $K^*_0$ as well should be suppressed in the region over the resonance peak.

\[ \alpha_{\kappa}(t) = 0.7 \ (t - m_{K^*}^2), \]

\[ \alpha_{K^*}(t) = 0.83 t + 0.25. \]
of the $\gamma n \rightarrow K^{*0}\Lambda$ process, however, only the $t$-channel $\kappa + K + K^{*0}$ exchanges are included with the magnetic dipole and electric quadrupole moments of $K^{*0}$ which are by themselves gauge-invariant. In Eq. (9), the phase of the $K$ exchange is to be read for the $\gamma p \rightarrow K^{*+}\Lambda$ (upper) and $\gamma n \rightarrow K^{*0}\Lambda$ (lower) in consistent with the phase relations in the $p^\pm$ and $\pi^\pm$ photoproductions [10]. In the reggeization of $K^{*+}$ exchange in the $t$-channel we preserve the proton magnetic moment in the $s$-channel Born term for the $\gamma p$ reaction because of the expected role of the magnetic interactions between the particles for non-zero spin.

For the estimate of the kaon-trajectory exchange, we use $g_{K\pi A} = -13.24$ in consistent with the SU(3) prediction with $\alpha = 0.365$ and $g_{\pi NN} = 13.4$, and the couplings $g_{\gamma KK^{*+}} = 0.254$ and $g_{\gamma KK^{*0}} = -0.388$ are determined from the measured decay widths $\Gamma_{K^{*+} \rightarrow K^+ + \gamma} = 50.3$ keV and $\Gamma_{K^{*0} \rightarrow K^0 + \gamma} = 116.6$ keV, respectively. The negative sign for $g_{\gamma KK^{*0}}$ follows the quark model prescription.

The radiative decay constants relevant to the scalar meson $\kappa$ is unknown at present and we use the prediction of Ref. [20], which gives the width of $K^{*0}$ as

$$\Gamma(K^{*0} \rightarrow \kappa\gamma) = \frac{1}{96\pi} \frac{e^2}{g_\rho^2} \left( \frac{m_{K^*}^2 - m_\kappa^2}{m_\kappa^2} \right)^3 \left| -\frac{8}{3} \beta_A \right|^2,$$

supposing that the $K^*$ mass larger than the $\kappa$ mass. The values of $\beta_A = 0.72$ GeV$^{-1}$ and $\tilde{g} = 4.04$ are estimated in Ref. [20]. In this work we consider $m_\kappa = 800$ MeV and $g_{\gamma\kappa K^{*0}} = 0.144$ GeV$^{-1}$, which gives $\Gamma(K^{*0} \rightarrow \kappa\gamma) \approx 0.411$ keV. The SU(3) relation $g_{\gamma\kappa K^{*+}} = -2g_{\gamma\kappa K^{*0}}$ is kept through the present work, which gives $g_{\gamma\kappa K^{*+}} = -0.072$ [21]. For the scalar meson $\bar{K} \pi$-baron coupling constant we adopt $g_{K\pi N} = -14.7$ using a recent result of QCD sum rule calculation [22].

Shown in Fig. [1] are the total cross sections for the reactions of $\gamma p \rightarrow K^{*+}\Lambda$ and $\gamma n \rightarrow K^{*0}\Lambda$ as functions of the photon energy $E_\gamma$ in the laboratory frame. The contributions from $K$, $\kappa$ and $K^*$ exchanges are displayed by the dashed, dot-dot-dashed and dot-dashed lines in order. The red dotted line is from the gauge-invariant $K^*$ exchange $M_{K^*N}$ in Eq. [5] which contains the $s$-channel proton pole and contact terms. The experimental data are from the CLAS collaboration [4] for $\gamma p \rightarrow K^{*+}\Lambda$ and from the ABHHM collaboration [14] for $\gamma n \rightarrow K^{*0}\Lambda$, respectively. These results show that the $K^*\Lambda$ production in the $\gamma p$ reaction exhibits the dominance of $K$ plus $K^*$ exchanges which are comparable to each other, while the $\gamma n$ process is totally governed by the $K$ exchange. As a result, the cross section for the $\gamma n$ reaction is about double the size of the $\gamma p$ cross section. But the effect of $K^*$ electromagnetic multipole is suppressed in the $\gamma n$ reaction.

As stated before, since the process involves the production of spin-1 vector meson, the effects of magnetic interactions are expected. In the present work, we examine the role of the electromagnetic multipoles of $K^*$ as well as of the proton pole term in the case of the $\gamma p$ process. Figure [2] shows the role of the $\kappa K^*$ and $\lambda K^*$ terms in the cross sections for the $\gamma p$ process with and without the proton anomalous magnetic moment $\kappa_p$ term. We adopt $(\kappa_{K^*}, \lambda_{K^*}) = (1.23, -0.38)$ following Ref. [10]. We first note that the difference of the cross section $\sigma$ between the cases of $(\kappa_{K^*}, \lambda_{K^*}) = (1.23, -0.38)$ by the solid line and $(\kappa_{K^*}, \lambda_{K^*}) = (0, 0)$ by the dash-dotted line is noticeable in the case of $\kappa_p = 0$ as shown in Fig. [2]b). This tendency disappears, however, in the presence of $\kappa_p = 1.79$ as can be seen in Fig. [2]a), which shows a nontrivial role of the proton anomalous magnetic moment $\kappa_p$. Therefore, this signifies that the $\kappa_p$ in the proton pole term should be activated in the reggeization of the production amplitude in case of the vector meson not only for a theoretical consistency but also for the phenomenological consequences just we have demonstrated.

The observed differential cross sections for both reaction processes are reasonably reproduced by the present model calculations as shown in Fig. [3]. Enhancement at forward angles in both cases illustrates the dominance of $K$ exchange shown by the blue dashed lines in Fig. [3] for $E_\gamma = 2.35$ GeV (2.2 GeV) in the case of $\gamma p (\gamma n)$ reaction. As in the case of total cross section, the contribution of $K^*$ without multipoles does not significantly alter the differential cross section in the presence of $\kappa_p$. Although contributions of $K^*$ multipoles, i.e., $\kappa_{K^*}$ and $\lambda_{K^*}$ terms, are small in cross sections, their effects may be found in spin asymmetries. Furthermore, since the contributions of $N^*$ resonances in the $\gamma p \rightarrow K^{*+}\Lambda$ process are found to be rather insignificant [7], the process is of benefit to the measurement of such observables on a clear background. Presented in Fig. [4] are the pho-

FIG. 1. Total cross section (a) for $\gamma p \rightarrow K^{*+}\Lambda$ and (b) for $\gamma n \rightarrow K^{*0}\Lambda$. Blue dashed, green dot-dot-dashed, and red dot-dashed lines are the contributions from the exchanges of $K$, $\kappa$, and $K^*$ with $(\kappa_{K^*}, \lambda_{K^*}) = (1.23, -0.38)$, respectively. The gauge-invariant $K^*$ exchange $M_{K^*N}$ in Eq. [5] is given by the red dotted line. The solid lines show the results of the full calculation. Experimental data for the $\gamma p$ reaction are from Ref. [4] (filled circles) and those for the $\gamma n$ reaction are from Ref. [14] (open square).
FIG. 2. Total cross sections for $\gamma p \to K^{*+}\Lambda$ (a) with and (b) without $\kappa_\gamma$. In (a), the red dashed line is the $K^*$ exchange contribution with $(\kappa_{K^*}, \lambda_{K^*}) = (1.23, 0)$ and the corresponding cross section is given by the red solid line. The blue dash-dotted line is the cross section from the $K^*$ exchange with $(\kappa_{K^*}, \lambda_{K^*}) = (0, 0)$ which is given by blue dotted line. In (b), full calculations for cross sections with $(\kappa_{K^*}, \lambda_{K^*}) = (1.23, -0.38)$ and $(0, 0)$ are shown by the same notation as in (a), respectively.

FIG. 3. Differential cross sections for $\gamma p \to K^{*+}\Lambda$ and $\gamma n \to K^{*0}\Lambda$ reactions. Dotted lines are the results without $\kappa_{K^*}$ and $\lambda_{K^*}$ terms. The respective contributions of $K$ and $K^*$ exchanges are shown with the same notation as in Fig. 1 Experimental data are taken from Ref. [4] (filled circles) and from Ref. [2] (open squares).

The photon polarization observable ($\Sigma$) together with the parity asymmetry ($P_\sigma$) and the recoil polarization ($P_\Lambda$) for both processes. Following the convention and definitions of Refs. [24, 25], the photon polarization asymmetry is given by

$$\Sigma = \frac{\sigma(\|,0,0,0) - \sigma(\perp,0,0,0)}{\sigma(\|,0,0,0) + \sigma(\perp,0,0,0)},$$

(10)

where we define $\sigma(B,T,Y,V)$ for the differential cross section $d\sigma/d\Omega$, where the superscripts $(B,T,Y,V)$ denote the polarizations of photon beam, target proton, produced hyperon, and produced $K^*$ vector-meson, respectively. The superscript 0 means unpolarized state and $\perp$ (or $\|\perp$) corresponds to a photon linearly polarized parallel (perpendicular) to the reaction plane but normal to the photon beam direction. The negativity of $\Sigma$ in $\gamma p$ reaction is largely due to the $K^*$-exchange, which reveals a sizable dependence on $\kappa_{K^*}$ and $\lambda_{K^*}$. Thus, measuring this observable is desirable to verify the role of the $K^*$ magnetic moment and electric quadrupole moment.

The parity asymmetry defined as

$$P_\sigma = 2\rho_1^p - \rho_0^p,$$

(11)

measures the asymmetry between the natural and unnatural parity of exchanged mesons in terms of density matrix elements [26]. In particular, the predicted value $P_\sigma \approx -1$ for the $\gamma n$ reaction is understood by the dominance of the $K$ exchange of the unnatural-parity over the natural-parity exchanges of $\kappa$ and $K^*$. Recently $P_\sigma$ of the $\gamma p \to K^{*0}\Sigma^+$ reaction was reported [23] and the comparison of $P_\sigma$ in various channels for the $K^*$ production will be useful to understand the production mechanism of strangeness via the spin-1 vector meson.

The observation of the recoil polarization, $P_\Lambda$, is also interesting since the produced $\Lambda$ hyperon in the final state is self-analyzing [23]. The asymmetry between the spin polarizations of the final $\Lambda$ along with the $y'$-axis as de-
which can be measured by the subsequent weak decay of the final Λ through the \( \Lambda \to p\pi \) decay. Viewed from the different spin structure of the final state \( K^*+\Lambda \) from the case of the \( K^+\Lambda \) in the final state of the reaction process \( \gamma p \to K^+\Lambda \), it is informative to compare \( P_\Lambda \) asymmetry in both reactions. The dashed line for the \( P_\Lambda \) in the latter process is estimated from Ref. [18] with the experimental data of Ref. [23], which shows a quite different spin polarization of \( \Lambda \) from the \( K^*+\Lambda \) production process, as expected. The experimental measurements of these observables, therefore, will be a testing ground to confirm models for the electromagnetic production of strangeness through spin-1 vector mesons with electromagnetic multipoles.

In summary, we have investigated photoproduction reactions of \( \gamma N \to K^*\Lambda \) focusing on the role of electromagnetic multipoles of \( K^* \) vector meson. With the \( \gamma K^*K^* \) vertex that fully accounts magnetic dipole and electric quadrupole moments of \( K^* \) satisfying the Ward identity, analysis of existing data was performed based on the Regge approach. We found that the \( \gamma p \to K^{*+}\Lambda \) process is dominated by \( K^+ \) plus \( K^* \) exchanges, while \( \gamma n \to K^{*0}\Lambda \) process can be understood by the dominance of \( K \) exchange. Although the dependence of total and differential cross sections on the \( K^* \) electromagnetic multipoles cannot be easily verified, we found that the photon beam asymmetry may be useful to unravel the role of \( K^* \) multipoles in the production of \( K^* \) vector meson. Our predictions for spin observables would be tested by future measurements at current electron/photon beam facilities.

ACKNOWLEDGMENTS

This work was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (Grant Nos. NRF-2013R1A1A2010504 and NRF-2015R1D1A1A01059603).

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