

Scalar κ meson in K^* photoproduction

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We propose that the scalar $\kappa(800)$ meson may play an important role in K^* photoproduction. In the reactions of $\gamma p \rightarrow K^{*+}\Lambda$ and $\gamma p \rightarrow K^{*0}\Sigma^+$, we consider the production mechanisms including t -channel K^* , K , κ exchanges, s -channel N , Δ diagrams, and u -channel Λ , Σ , Σ^* diagrams within the tree level approximation, and find that the κ -meson exchange may contribute significantly to $K^*\Sigma$ photoproduction, while it is rather supplementary in $K^*\Lambda$ photoproduction. We demonstrate how the observables of K^* photoproduction can be used to constrain the κ meson properties. In particular, the parity asymmetry can separate the κ meson contribution in K^* photoproduction.

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Recently, the CLAS Collaboration at Thomas Jefferson National Accelerator Facility reported preliminary cross section data for $K^*(892)$ photoproductions, namely, $\gamma p \rightarrow K^{*0}\Sigma^+$ [1] and $\gamma p \rightarrow K^{*+}\Lambda$ [2]. In the baryon sector, K^* vector meson photoproduction can be used to search for the nucleon resonances which couple strongly to the K^*Y channel, where Y stands for a hyperon [3]. This reaction is interesting in the meson sector as well since it can offer an opportunity to study the scalar $\kappa(800)$ meson whose exchange is prohibited in K meson photoproduction.

Since the Pomeron exchange is absent in the photoproduction of strange mesons, the main production mechanisms of K^* photoproduction should be different from the case of nonstrange neutral vector mesons (ρ^0 , ω , ϕ) [4]. In Ref. [5], Zhao *et al.* have studied $K^*\Sigma$ photoproduction within a quark model. Some assumptions were made on the quark-meson couplings and parameters, which should be further tested by experiments. We have studied the $\gamma N \rightarrow K^*\Lambda$ reaction in Ref. [6], and found that the t -channel K exchange dominates the production amplitudes at small scattering angles and it can describe quite well the total cross section data of Ref. [2].

The two preliminary experimental data of CLAS for $K^{*+}\Lambda$ and for $K^{*0}\Sigma^+$ photoproductions [1,2] show a very challenging aspect that requires careful examination. Namely, the two production processes have very similar cross sections, not only in the magnitude but also in the angular distribution at forward scattering region [7]. This contradicts with a naive expectation based on the kaon exchange process which predicts that the cross section for $K^{*+}\Lambda$ production would be larger than that for $K^{*0}\Sigma^+$ production by a factor of ~ 3 , since $R_K \equiv (g_{K^*K\gamma}^c g_{KN\Lambda} / \sqrt{2} g_{K^*K\gamma}^0 g_{KN\Sigma})^2 = [g_{K^*K\gamma}^c (1 + 2\alpha) / \sqrt{6} g_{K^*K\gamma}^0 (1 - 2\alpha)]^2 \simeq 1.7^2$ with $\alpha = f / (f + d) \approx 0.365$ [8]. (Here $\sqrt{2}$ is the isospin factor.) To compensate for this difference, it is necessary to have

different production mechanisms for $K^*\Sigma$ production from the $K^*\Lambda$ production case, unless we assume a large value of $g_{KN\Sigma}$ to have $R_K \sim 1$. Sizable s -channel nucleon resonance effects, which could be responsible for the similarities between $K^+\Lambda$ and $K^+\Sigma^0$ photoproductions at low energies [9], are not sufficient to explain the similarities in K^* photoproductions at *forward* angles with relatively high energies. In order to have similar differential cross sections at forward angles, we expect to have other t -channel mechanisms that contribute significantly to $K^*\Sigma$ production but give supplementary contribution to $K^*\Lambda$ production. In this paper, we propose that the light scalar $\kappa(800)$ meson can have this role, which can actually explain the observed similarities between the cross sections for $\gamma p \rightarrow K^{*+}\Lambda$ and for $\gamma p \rightarrow K^{*0}\Sigma^+$.

The nature of the scalar mesons is yet to be clarified and there are many models on the structure of scalar meson nonet [10]. In the case of scalar $\kappa(800)$ meson, the situation is even worse since its existence is still controversial [11] as can be seen in many pros and cons [12–14]. Accordingly, the predicted or estimated mass and width of the κ are in a broad range: $M_\kappa = 600 \sim 900$ MeV and $\Gamma_\kappa = 400 \sim 770$ MeV [11]. Here, we do not address the issue whether such a light κ exists in nature, but instead we demonstrate how one can explain the similarities observed in K^* photoproductions by introducing light κ meson and how one can identify its role through some observables of this reaction.

For K^* photoproduction, we consider t -channel K^* , K , κ exchanges, s -channel N , Δ , and u -channel Λ , Σ , $\Sigma^*(1385)$ diagrams as shown in Fig. 1. [The t -channel K^* exchange and the contact diagram Fig. 1(d) are absent in K^{*0} photoproduction.] For the t -channel diagrams, which are expected to be dominant at small $|t|$ region, the electromagnetic interactions are

$$\begin{aligned} \mathcal{L}_{K^*K^*\gamma} &= -ieA^\mu (K^{*-v} K_{\mu\nu}^{*+} - K_{\mu\nu}^{*-} K^{*+v}), \\ \mathcal{L}_{K^*K\gamma} &= g_{K^*K\gamma} e^{\mu\nu\alpha\beta} \partial_\mu A_\nu \partial_\alpha K_\beta^* \bar{K} + \text{H.c.}, \\ \mathcal{L}_{\kappa K^*\gamma} &= eg_{\kappa K^*\gamma} A^{\mu\nu} \bar{\kappa} K_{\mu\nu}^* + \text{H.c.}, \end{aligned} \quad (1)$$

where A_μ is the photon field, $A_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$, and $K_{\mu\nu}^* = \partial_\mu K_\nu^* - \partial_\nu K_\mu^*$. The decay width for $K^{*0} \rightarrow K^0\gamma$

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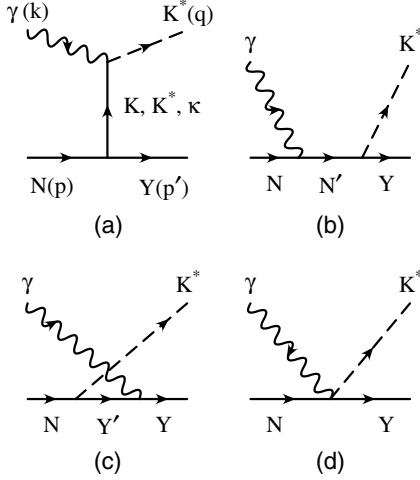


FIG. 1. Tree diagrams for $\gamma N \rightarrow K^* Y$ ($Y = \Lambda, \Sigma$), which include (a) t -channel exchanges, (b) s -channel N, Δ , (c) u -channel $\Lambda, \Sigma, \Sigma^*$, and (d) contact diagrams.

($K^{*\pm} \rightarrow K^\pm \gamma$) gives $g_{K^* K \gamma}^0 = -0.388 \text{ GeV}^{-1}$ ($g_{K^* K \gamma}^c = 0.254 \text{ GeV}^{-1}$). The κ meson couplings will be discussed later.

The t -channel hadronic interactions read

$$\begin{aligned} \mathcal{L}_{K^* N Y} &= -g_{K^* N Y} \bar{N} \left(\gamma_\mu Y - \frac{\kappa_{K^* N Y}}{2M_N} \sigma_{\mu\nu} Y \partial^\nu \right) K^{*\mu} + \text{H.c.}, \\ \mathcal{L}_{K N Y} &= -i g_{K N Y} \bar{N} \gamma_5 Y K + \text{H.c.}, \\ \mathcal{L}_{\kappa N Y} &= -g_{\kappa N Y} \bar{N} Y \kappa + \text{H.c.}, \end{aligned} \quad (2)$$

where $Y = \Lambda$ or $\tau \cdot \Sigma$. The pseudoscalar coupling used for $\mathcal{L}_{K N Y}$ is equivalent to the pseudovector coupling as the baryons are on-shell in our case. Then SU(3) relations are used to obtain $g_{K N \Lambda} = -13.24$ and $g_{K N \Sigma} = 3.58$, with $\alpha = 0.365$ and $g_{\pi N N}^2/4\pi = 14$. For the K^* couplings, the Nijmegen potential [8] gives ($g_{K^* N Y} = -4.26, \kappa_{K^* N Y} = 2.66$) for $Y = \Lambda$ and $(-2.46, -0.47)$ for $Y = \Sigma$. The Lagrangians and their coupling constants for the s - and u -channel $N, \Delta, \Lambda, \Sigma$, and Σ^* diagrams, Figs. 1(b) and 1(c), are fully discussed in Refs. [6,16] and will not be repeated here. The contact diagrams, Fig. 1(d), are required to have charge conservation in charged K^* production and can be calculated from the K^* interaction Lagrangian by minimal substitution.

One may also consider the axial-vector $K_1(1270)$ and $K_1(1400)$ exchanges. However, there are several comments for the interactions of the axial-vector mesons. Firstly, the $AV\gamma$ interaction like the $K_1 \rightarrow K^* \gamma$ decay is an anomalous interaction [17,18], which does not exist in the Bardeen subtracted anomalous action [19]. (See, however, Ref. [20] for the hidden gauge approach.) Although the $f_1 \rightarrow \rho\gamma/\phi\gamma$ decays are seen, the other decays like $a_1 \rightarrow \rho\gamma/\omega\gamma$ have not been observed so far [11]. Thus it is not yet clear whether the observed f_1 decays indicate the existence of the $AV\gamma$ anomaly for the axial-vector meson nonet or just reflect some peculiar internal structure of the f_1 . Secondly, the $K_1 N Y$ couplings suffer from the lack of information. (For the $a_1 N N$ coupling, see, e.g., Ref. [21].) In addition, the large mass of K_1 mesons leads to an expectation that the K_1 exchange contribution would be small. Indeed, the total cross section data for $K^* \Lambda$

production indicate suppressed contribution from high-spin meson exchanges in the considered energy region [6]. Since there is no observation for the $K_1 \rightarrow K^* \gamma$ decay so far, we leave the K_1 exchange for a future study.

Form factors are included to dress the vertices of the diagrams. The following two forms are considered:

$$F_M(p_{\text{ex}}^2) = \frac{\Lambda^2 - M_{\text{ex}}^2}{\Lambda^2 - p_{\text{ex}}^2}, \quad F_G(p_{\text{ex}}^2) = \frac{\Lambda^4}{\Lambda^4 + (p_{\text{ex}}^2 - M_{\text{ex}}^2)^2}, \quad (3)$$

where M_{ex} and p_{ex} are the mass and momentum of the exchanged particle, respectively, and Λ is the cutoff parameter. Including form factors can violate the charge conservation condition. In fact, in $\gamma p \rightarrow K^{*+} \Lambda$, the sum of the t -channel K^* exchange, s -channel nucleon, and the contact term respects the charge conservation when there is no form factor, but they separately violate the condition [6]. So introducing form factors depending on the exchanged particle can easily break the charge conservation. Following Ref. [22], charge conservation is restored by taking the common form factor, $F = 1 - (1 - F_{K^*})(1 - F_N)$, for the three terms, where F_{K^*} denotes the K^* exchange form factor, etc. In $\gamma p \rightarrow K^{*0} \Sigma^+$, we have the same situation with the s -channel nucleon and the u -channel Σ terms, and we take their common form factor as $F = 1 - (1 - F_N)(1 - F_\Sigma)$.

In Ref. [6], considering all the diagrams of Fig. 1, it was shown that the cross sections for $\gamma p \rightarrow K^{*+} \Lambda$ could be well explained by the dominance of K meson exchange. Here, the t -channel amplitudes have the form factors of the monopole type F_M with $\Lambda_{K^*} = 0.9 \text{ GeV}$ and $\Lambda_K = \Lambda_\kappa = 1.1 \text{ GeV}$. The s - and u -channel form factors take the form of F_G with $\Lambda = 0.9 \text{ GeV}$ following Ref. [16]. In Ref. [6], $M_\kappa = 900 \text{ MeV}$ and $\Gamma_\kappa = 550 \text{ MeV}$ were used following Ref. [15]. This is our model (I), where the κ exchange was found to be small for $K^* \Lambda$ production. If we apply this model to $\gamma p \rightarrow K^{*0} \Sigma^+$, however, we evidently underestimate the data as shown by the dashed lines in Fig. 2. This is consistent with the expectation with the K exchange dominance and indicates that the main production mechanisms of $K^* \Lambda$ and $K^* \Sigma$ productions should be quite different.

In this paper, by observing the similarities in the differential cross section data for $K^* \Lambda$ and for $K^* \Sigma$ productions, we propose a different model where the scalar meson exchange plays a more important role, especially in $K^* \Sigma$ case. In fact, the mass and coupling constants of the κ are not firmly established, and model (I) uses

$$\begin{aligned} |g_{K^* K^* \gamma}^c g_{\kappa N \Lambda}| &= 1.1 \text{ GeV}^{-1}, \\ |g_{K^* K^* \gamma}^c g_{\kappa N \Sigma}| &= 0.7 \text{ GeV}^{-1}, \end{aligned} \quad (4)$$

which are in the range of Refs. [8,15], i.e., $|g_{K^* K^* \gamma}^c g_{\kappa N \Lambda}| = (1.0 \sim 1.2)$ and $|g_{K^* K^* \gamma}^c g_{\kappa N \Sigma}| = (0.6 \sim 0.8)$ in GeV^{-1} unit [6]. Also the SU(3) relation, $g_{\kappa K^* \gamma}^0 = -2g_{K^* K^* \gamma}^c$, was used. Because of the uncertainties in the couplings as well as in the mass of the κ , we vary them within the acceptable ranges and look for their values that reproduce the data for $K^* \Sigma$ photoproduction.

A successful description of the preliminary data of Ref. [1] was achieved with $M_\kappa = 750 \text{ MeV}$ and the coupling constants

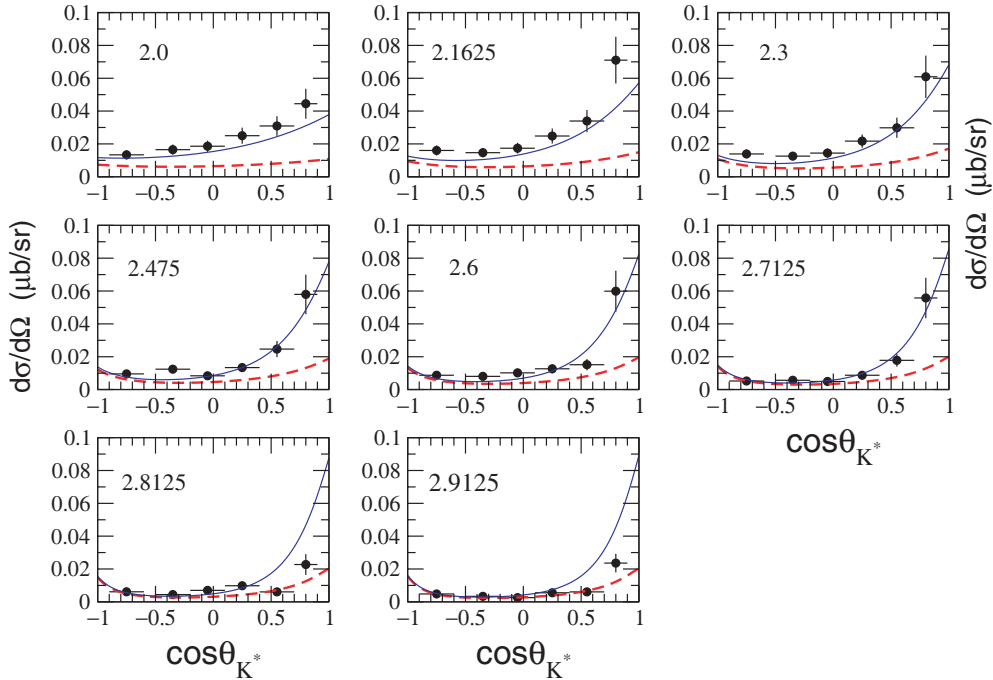


FIG. 2. (Color online) Differential cross sections for $\gamma p \rightarrow K^{*0}\Sigma^+$. The dashed and solid lines are the results for models (I) and (II), respectively. The number in each box denotes the photon energy E_γ in GeV. The preliminary data are from Ref. [1].

(4) by employing the form factor for the κ exchange in the form of F_G with $\Lambda_\kappa = 1.2$ GeV, while keeping the other production amplitudes as in model (I). This is our model (II). We use $\Gamma_\kappa = 550$ MeV, whose uncertainty, however, does not have significant influence. The obtained results are given by the solid lines in Fig. 2, which imply that the off-shell κ meson favors the form factor in the form of F_G over the monopole type F_M . The main difference between the two form factors is that F_G is harder for small $|p_\kappa^2|$ and softer for large $|p_\kappa^2|$ compared with F_M . Therefore, microscopic studies on the behavior of the off-shell κ meson couplings are highly desirable for understanding the internal structure of the scalar mesons and the κ meson exchange for K^* photoproduction. Since the scalar κ meson exchange does not interfere with the K meson exchange, the unknown phases of the κ meson couplings (4) do not change our results. However, it should also be mentioned that there can be other choices for the κ meson parameters to describe $K^*\Sigma$ photoproduction. For example, in model (II), by taking $M_\kappa = 900$ MeV with $|g_{\kappa K^*\gamma}^c g_{\kappa N\Sigma}| = 1.2$ GeV $^{-1}$ or $M_\kappa = 600$ MeV with $|g_{\kappa K^*\gamma}^c g_{\kappa N\Sigma}| = 0.4$ GeV $^{-1}$, we could obtain the results that are very close to the solid lines of Fig. 2. This shows that the uncertainties of the κ meson parameters [11] cannot be reduced by the current analyses on K^* production, and hence we do not make a fine tuning of the κ parameters here. In addition, in order to check whether such a role can be ascribed to a more massive scalar meson, $K_0(1430)$, we simply increased the κ mass to 1430 MeV and found that its contribution is suppressed due to the large mass. Therefore, the K^* photoproduction data can be used to constrain the κ meson parameters and a light scalar κ meson with $M_\kappa < 900$ MeV is favored.

In model (II), we have shown that the scalar κ meson exchange might be crucial in the $K^*\Sigma$ production mechanisms. Since the κ meson parameters are different from those of model (I), the previous results for $K^*\Lambda$ photoproduction should be reexamined. We found that in model (II) the K meson exchange is still dominant for $K^*\Lambda$ production. This is mainly due to the large value of $g_{KN\Lambda}$. Furthermore, since $\alpha \simeq 1.1$ for the scalar mesons [8], the coupling constant ratio of κ exchange, $R_\kappa \equiv (g_{\kappa K^*\gamma}^c g_{\kappa N\Lambda} / \sqrt{2} g_{\kappa K^*\gamma}^0 g_{\kappa N\Sigma})^2 \simeq 0.3$, implies a mild role of the κ exchange in $K^*\Lambda$ production. In SU(6) limit, $\alpha = 1$ for the scalar mesons and for the vector couplings of the vector mesons, while $\alpha = 2/5$ for the other mesons [23]. Thus, at least in this limit, the scalar meson is unique in giving a larger contribution to the $K^{*0}\Sigma^+$ channel than to the $K^{*+}\Lambda$ channel, since K^* exchange is absent in K^{*0} production. The obtained total cross sections for $K^*\Lambda$ production are given in Fig. 3 with those for $K^*\Sigma$ case. This shows that the difference between models (I) and (II) for $K^*\Sigma$ photoproduction is substantial, while it is small for $K^*\Lambda$ case and is in the range of experimental errors.

The scalar κ meson has natural parity and the pseudoscalar K meson has unnatural parity. The relative strength of the natural/unnatural t -channel exchanges can be unambiguously estimated by measuring the parity asymmetry [24],

$$P_\sigma \equiv \frac{d\sigma^N - d\sigma^U}{d\sigma^N + d\sigma^U} = 2\rho_{1-1}^1 - \rho_{00}^1, \quad (5)$$

where ρ 's are the K^* density matrix elements, and $d\sigma^N$ ($d\sigma^U$) is the cross section from the natural (unnatural) parity exchanges. Therefore, we roughly expect that P_σ is close

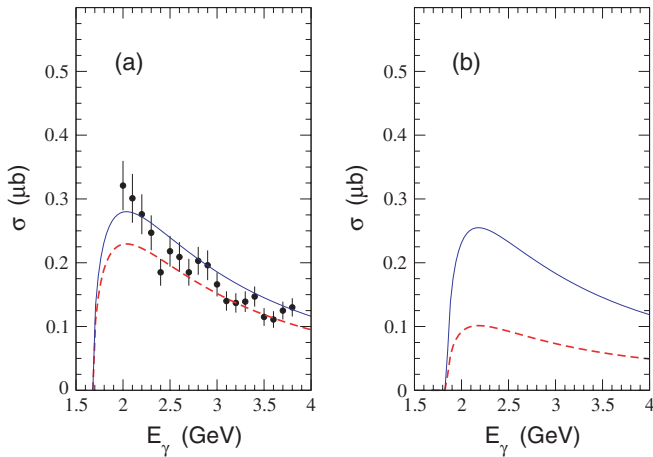


FIG. 3. (Color online) Total cross sections for (a) $\gamma p \rightarrow K^{*+} \Lambda$ and for (b) $\gamma p \rightarrow K^{*0} \Sigma^+$. The dashed and solid lines are the results for models (I) and (II), respectively. The data are from Ref. [2].

to -1 when the kaon exchange dominates, and its deviation from -1 shows the relative size of the κ and K^* meson exchanges. In order to avoid the contamination due to the s - and u -channel amplitudes, it should be measured at relatively high energies and at small scattering angles. Shown in Fig. 4 are the results for P_σ at $E_\gamma = 3.0$ GeV. This shows the sensitivity of P_σ on the scalar κ meson exchange, especially, in $K^{*0} \Sigma^+$ production since it excludes natural-parity K^* exchange. Measuring the parity asymmetry is, therefore, highly required for identifying the role of light κ meson. The same conclusion can be drawn for the photon beam asymmetry $\Sigma_V \equiv (\rho_{11}^+ + \rho_{1-1}^+)/(\rho_{11}^0 + \rho_{1-1}^0)$ [24].

In summary, we have investigated photoproduction mechanisms for $K^* \Sigma$ and $K^* \Lambda$ within the tree level approximation, especially focusing on the role driven by the scalar κ meson

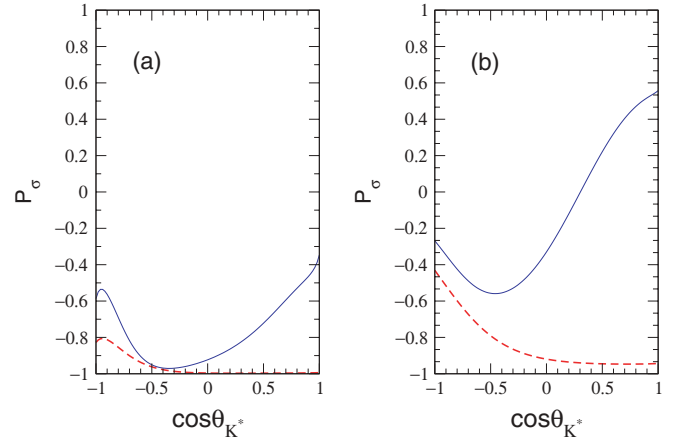


FIG. 4. (Color online) Parity spin asymmetry P_σ for (a) $\gamma p \rightarrow K^{*+} \Lambda$ and for (b) $\gamma p \rightarrow K^{*0} \Sigma^+$ at $E_\gamma = 3.0$ GeV. Notations are the same as in Fig. 3.

exchange. We found that the contribution from the light κ meson with a mass around $600 \sim 900$ MeV could be substantial for the $K^* \Sigma$ production, while it is supplementary in $K^* \Lambda$ production. Therefore, $K^* \Sigma$ photoproduction provides a nice tool for studying the controversial scalar κ meson: specifically the parity asymmetry and the photon beam asymmetry can be outstanding probes to separate the κ meson exchange in K^* photoproduction, which can be verified at current experimental facilities.

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