

Photoproduction of the Θ^+ and its vector and axial-vector structure*

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Abstract We present recent investigations on the vector and axial-vector transitions of the baryon antidecuplet within the framework of the self-consistent $SU(3)$ chiral quark-soliton model, taking into account the $1/N_c$ rotational and linear m_s corrections. The main contribution to the electric-like transition form factor comes from the wave-function corrections. This is a consequence of the generalized Ademollo-Gatto theorem. It is also found that in general the leading-order contributions are almost canceled by the rotational $1/N_c$ corrections. The results are summarized as follows: the vector and tensor $K^*N\Theta$ coupling constants, $g_{K^*N\Theta} = 0.74\text{--}0.87$ and $f_{K^*N\Theta} = 0.53\text{--}1.16$, respectively, and $\Gamma_{\Theta \rightarrow KN} = 0.71$ MeV, based on the result of the $KN\Theta$ coupling constant $g_{KN\Theta} = 0.83$. We also show the differential cross sections and beam asymmetries, based on the present results. We also discuss the connection of present results with the original work by Diakonov, Petrov, and Polyakov.

Key words Baryon antidecuplet, vector and axial-vector transition form factors, chiral quark-soliton model, Photoproduction of the Θ^+

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1 Introduction

We start with a brief summary of the present status about the pentaquark baryon Θ^+ . Since the LEPS collaboration announced the evidence of the Θ^+ ^[1], being motivated by Diakonov et al.^[2] (DPP), there has been a great deal of experimental and theoretical works on the Θ^+ (see, for example, reviews^[3, 4]). However, the CLAS collaboration reported null results of finding the Θ^+ ^[5–8] in various reactions. In this, we also want to mention the earlier work^[9]. These null results from the CLAS experiment imply that the total cross sections for photoproductions of the Θ^+ should be very small. The KEK-PS-E522 collaboration^[10] found a bump at around 1530 MeV but with only $(2.5\text{--}2.7)\sigma$ statistical significance. A later experiment at KEK (KEK-PS-E559), however, has observed no clear peak structure for the Θ^+ in the $K^+p \rightarrow \pi^+X$ reaction^[11].

In the meanwhile, the DIANA collaboration has recently brought news on a direct formation of a narrow K^0p peak with mass of (1537 ± 2) MeV. The width of $\Gamma_{\Theta \rightarrow K^0p} = (0.36 \pm 0.11)$ MeV was also found^[12]. Compared to the former measurement^[13], the decay width was more precisely measured, the statistics being doubled. The SVD experiment has also announced a narrow peak with the mass, $(1523 \pm 2_{\text{stat.}} \pm 3_{\text{syst.}})$ MeV in the inclusive reaction $pA \rightarrow pK_s^0 + X$ ^[14, 15]. Furthermore, the LEPS collaboration has reported again the evidence of the Θ^+ ^[16]: The mass of the Θ^+ is found at $(1525 \pm 2 + 3)$ MeV and the statistical significance of the peak turns out to be 5.1σ . The differential cross section was estimated to be (12 ± 2) nb/sr in the photon energy ranging from 2.0 GeV to 2.4 GeV in the LEPS angular range. In connection to the new LEPS results, Diakonov and Petrov recently discussed further theoretical aspects of the Θ^+ ^[17].

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Based on these experimental results, regardless of the existence of the Θ^+ or not, one can come to the following three main conclusions:

1. The decay width of the Θ^+ is very small ($\Gamma_{\Theta \rightarrow \text{KN}} < 1 \text{ MeV}$), which indicates that the $\text{KN}\Theta$ coupling should be tiny.

2. The total cross section of the Θ^+ photoproduction is small. It implies that the $\text{K}^*\text{N}\Theta$ coupling constant should be also very small.

3. Finding the Θ^+ may be reaction-dependent.

We need to understand this smallness of the $\text{KN}\Theta$ and $\text{K}^*\text{N}\Theta$ coupling constants theoretically. In this, we will present results of recent investigations on the two coupling constants from the chiral quark-soliton model (χQSM)^[18, 19] and of the application of these results to the photoproduction of the Θ^+ ^[20].

The present talk is sketched as follows: In Sec-

tion 2, we review briefly the general formalism of the χQSM to show how to calculate the vector and axial-vector form factors. In Section 3, we present the results and discuss them. We also predict the decay width of the Θ^+ . In Section 4, we discuss the connection of the present reported results to the original work by DPP. In Section 5, we describe the photoproduction of the Θ^+ using the results from the χQSM . The last section is devoted to summary and conclusions of the present reported work.

2 Vector and axial-vector transition form factors

We start with the Θ^+ -to-neutron transition matrix elements of the vector and axial-vector currents defined as:

$$\langle \Theta(p') | \bar{s}\gamma^\mu u | n(p) \rangle = \bar{u}_\Theta(\mathbf{p}') \left[F_1^{n\Theta}(Q^2)\gamma^\mu + \frac{F_2^{n\Theta}(Q^2)i\sigma^{\mu\nu}q_\nu}{M_\Theta + M_n} + \frac{F_3^{n\Theta}(Q^2)q^\mu}{M_\Theta + M_n} \right] u_n(\mathbf{p}), \quad (1)$$

$$\langle \Theta(p') | \bar{s}\gamma^\mu \gamma_5 u | n(p) \rangle = \bar{u}_\Theta(\mathbf{p}') \left[G_1^{n\Theta}(Q^2)\gamma^\mu + G_2^{n\Theta}(Q^2)q^\mu + G_3^{n\Theta}(Q^2)P^\mu \right] \gamma^5 u_n(\mathbf{p}), \quad (2)$$

where the $u_{\Theta(n)}$ denotes the spinor of the Θ^+ (neutron) with the corresponding mass $M_{\Theta(n)}$. The Q^2 stands for the momentum transfer $Q^2 = -q^2 = -(p' - p)^2$ and P represents the total momentum $P = p' + p$. $F_i^{n\Theta}$ and $G_i^{n\Theta}$ stand for real transition form factors that will be related to the strong coupling constants for the $\text{K}^*\text{N}\Theta$ and $\text{KN}\Theta$ vertices with the help of the vector-meson dominance (VMD)^[21, 22] and Goldberger-Treiman relation.

In the VMD, the vector-transition current can be expressed as the K^* current by the current field identity (CFI):

$$V^\mu(x) = \bar{s}(x)\gamma^\mu u(x) = \frac{m_{\text{K}^*}^2}{f_{\text{K}^*}} \text{K}^{*\mu}(x), \quad (3)$$

where m_{K^*} and f_{K^*} denote, respectively, the mass of

the K^* meson, $m_{\text{K}^*} = 892 \text{ MeV}$, and decay constant defined as

$$f_{\text{K}^*}^2 = \frac{m_{\text{K}^*}^2}{m_\rho^2} f_\rho^2. \quad (4)$$

The decay constant f_ρ for the rho meson can be determined as

$$f_\rho^2 = \frac{4\pi\alpha^2 m_\rho}{3\Gamma_{\rho^0 \rightarrow e^+e^-}}, \quad (5)$$

where α denotes the electromagnetic fine-structure constant. The f_{K^*} is determined by the experimental data for ρ -meson, $m_\rho = 770 \text{ MeV}$ and $\Gamma_{\rho^0 \rightarrow e^+e^-} = (7.02 \pm 0.11) \text{ keV}$ ^[23], for which we obtain the values $f_\rho \approx 4.96$ and $f_{\text{K}^*} \approx 5.71$.

Using the CFI, we can express the $\text{K}^*\text{N}\Theta$ vertex in terms of the transition form factors in Eqs. (1) and (2):

$$\langle \Theta(p') | \bar{s}\gamma^\mu u | n(p) \rangle = \frac{m_{\text{K}^*}^2}{f_{\text{K}^*}} \frac{1}{m_{\text{K}^*}^2 - q^2} \langle \Theta(p') | \text{K}^{*\mu} | n(p) \rangle, \quad (6)$$

$$\langle \Theta(p') | \text{K}^{*\mu} | n(p) \rangle = \bar{u}_\Theta(\mathbf{p}') \left[g_{\text{K}^*\text{n}\Theta}\gamma^\mu + f_{\text{K}^*\text{n}\Theta} \frac{i\sigma^{\mu\nu}q_\nu}{M_\Theta + M_n} + \frac{s_{\text{K}^*\text{n}\Theta}q^\mu}{M_\Theta + M_n} \right] u_n(\mathbf{p}), \quad (7)$$

where the $g_{\text{K}^*\text{n}\Theta}$ and $f_{\text{K}^*\text{n}\Theta}$ denote the vector and tensor coupling constants for the $\text{K}^*\text{N}\Theta$ vertex, respectively. These relations yield immediately the strong coupling constants as

$$g_{\text{K}^*\text{n}\Theta} = f_{\text{K}^*} F_1^{\Theta\text{n}}(0), \quad f_{\text{K}^*\text{n}\Theta} = f_{\text{K}^*} F_2^{\Theta\text{n}}(0). \quad (8)$$

Using the generalized Goldberger-Treiman relation, we can get the strong coupling constant $g_{\text{KN}\Theta}$ for the $\text{KN}\Theta$ vertex as follows:

$$g_{\text{KN}\Theta} = \frac{G_1^{\Theta\text{n}}(0)(M_\Theta + M_n)}{2f_{\text{K}}}, \quad (9)$$

where $f_{\text{K}} \approx 1.2f_\pi$ stands for the kaon decay constant.

In the rest frame of the Θ^+ , the form factors $F_1^{n\Theta}(Q^2)$, $F_2^{n\Theta}(Q^2)$ and $G_A^{n\Theta}(Q^2)$ of Eqs. (1, 2) can be expressed in terms of the matrix elements of the

vector and axial-vector currents with their time and space components decomposed in the Θ^+ rest frame, respectively

$$G_E^{m\Theta}(Q^2) = \int \frac{d\Omega_q}{4\pi} \langle \Theta(p') | \bar{s} \gamma^0 u | n(p) \rangle, \quad G_M^{m\Theta}(Q^2) = 3M_n \int \frac{d\Omega_q}{4\pi} \frac{q^i \epsilon^{ik3}}{i q^2} \langle \Theta(p') | \bar{s} \gamma^k u | n(p) \rangle, \quad (10)$$

$$G_1^{m\Theta}(Q^2) = -\frac{3}{2Q^2} \sqrt{\frac{2M_\Theta}{E_\Theta + M_\Theta}} \int \frac{d\Omega_q}{4\pi} \left[\mathbf{q} \times \left(\mathbf{q} \times \langle \Theta(p') | \bar{s} \gamma \gamma_5 u | n(p) \rangle \right) \right]_z, \quad (11)$$

where the electromagnetic-like Sachs form factors $G_E^{m\Theta}$ and $G_M^{m\Theta}$ are written as

$$G_E^{n\Theta}(Q^2) = F_1^{n\Theta}(Q^2) \quad (12)$$

$$G_M^{n\Theta}(Q^2) = F_1^{n\Theta}(Q^2) + F_2^{n\Theta}(Q^2) \quad (13)$$

The vector and tensor coupling constants are therefore obtained from Eq. (8) as:

$$g_{K^*n\Theta} = f_{K^*} G_E^{n\Theta}(0), \quad f_{K^*n\Theta} = f_{K^*} (G_M^{n\Theta}(0) - G_E^{n\Theta}(0)). \quad (14)$$

We are now in a position to evaluate the form factors within the self-consistent χ QSM. This model has the following virtues. There are only three free parameters among which two are fixed in the mesonic sector and just one remains for the whole baryon sector. This allows to calculate the Θ^+ transition form factors in the same frame as was used for the proton electromagnetic form factors.

The model is featured by the following effective low-energy partition function with quark fields ψ with the number of colors N_c and the pseudo-Goldstone boson field $U(x)$ in Euclidean space:

$$\mathcal{Z}_{\chi\text{QSM}} = \int \mathcal{D}\psi \mathcal{D}\psi^\dagger \mathcal{D}U \exp \left[- \int d^4x \psi^\dagger i D(U) \psi \right] = \int \mathcal{D}U \exp(-\mathcal{S}_{\text{eff}}[U]), \quad (15)$$

$$\mathcal{S}_{\text{eff}}(U) = -N_c \text{Tr} \ln i D(U), \quad (16)$$

where

$$D(U) = \gamma^4 (i \not{\partial} - \hat{m} - MU\gamma_5) = -i \not{\partial}_4 + h(U) - \delta m, \quad (17)$$

$$\delta m = \frac{m_s - \bar{m}}{3} \gamma^4 \mathbf{1}_{3 \times 3} + \frac{\bar{m} - m_s}{\sqrt{3}} \gamma^4 \lambda^8 = M_1 \gamma^4 \mathbf{1}_{3 \times 3} + M_8 \gamma^4 \lambda^8. \quad (18)$$

The current quark mass matrix is defined as $\hat{m} = \text{diag}(\bar{m}, \bar{m}, m_s) = \bar{m} + \delta m$. The \bar{m} stands for the average of the up and down current quark masses with isospin symmetry assumed. The M denotes the constituent-quark mass of which the best value for

the numerical results is $M = 420$ MeV. The pseudo-Goldstone boson field U^{γ_5} is defined as

$$U^{\gamma_5} = \exp(i\gamma_5 \lambda^a \pi^a) = \frac{1 + \gamma_5}{2} U + \frac{1 - \gamma_5}{2} U^\dagger \quad (19)$$

with $U = \exp(i\lambda^a \pi^a)$. For the quantization, we consider here Witten's embedding of $SU(2)$ soliton into $SU(3)$:

$$U_{SU(3)} = \begin{pmatrix} U_{SU(2)} & 0 \\ 0 & 1 \end{pmatrix}, \quad (20)$$

with the $SU(2)$ hedgehog chiral field

$$U_{SU(2)} = \exp[i\gamma_5 \hat{\mathbf{n}} \cdot \boldsymbol{\tau} P(r)], \quad (21)$$

Here, the $P(r)$ denotes the profile function of the chiral soliton $U_{SU(2)}$. We refer to Refs. [24, 25] as to how one can compute the form factors within the χ QSM.

3 $\text{KN}\Theta$ and $\text{K}^*\text{N}\Theta$ coupling constants

The results for the $\text{K}^*\text{N}\Theta$ and $\text{KN}\Theta$ coupling constant are listed in Table 1^[18, 19].

Table 1. The results for the $\text{K}^*\text{N}\Theta$ and $\text{KN}\Theta$ coupling constants at $Q^2 = 0$ with and without m_s corrections. The constituent-quark mass M is taken to be $M = 420$ MeV.

$m_s = 0$		$m_s = 180$ MeV		
$g_{\text{K}^*\text{N}\Theta}$	$f_{\text{K}^*\text{N}\Theta}$	$g_{\text{KN}\Theta}$	$f_{\text{K}^*\text{N}\Theta}$	$g_{\text{KN}\Theta}$
0	2.91	1.41	0.81	0.84
			0.84	0.83

The strong influence of the m_s corrections on these observables lies in a cancellation effect between the leading order and $1/N_c$ corrections. This effect was already observed in the work of DPP and led to the original prediction of the small Θ^+ decay width.

Note that the vector coupling constant $g_{\text{K}^*n\Theta}$ vanishes in exact $SU(3)$ symmetry due to the generalized Ademollo-Gatto theorem¹⁾, which will be explained below. The value of $g_{\text{K}^*n\Theta}$ with $SU(3)$ symmetry

1) We want to mention that the generalized Ademollo-Gatto theorem was first done by M.V. Polyakov.

breaking comes solely from the wavefunction corrections, so that the Dirac transition form factor turns out to be

$$F_1^{n\Theta}(0) = \sqrt{3}c_{10}^n(1 + \mathcal{O}(m_s)), \quad (22)$$

where c_{10}^n denotes the mixing parameter defined as

$$c_{10}^n = \frac{\langle n_{\overline{10}} | H_{sb} | n \rangle}{M_n - M_{n_{\overline{10}}}} \quad (23)$$

with a symmetry-breaking part of the Hamiltonian H_{sb} . $M_{n_{\overline{10}}}$ denotes the mass of the antidecuplet neutron. We call Eq. (22) as the generalized Ademollo-Gatto theorem. The results listed in Table 1 were obtained by using the value of the constituent-quark mass $M = 420$ MeV. However, if we calculate the coupling constants with M varied from 400 MeV to 450 MeV, we get the vector and tensor $K^*N\Theta$ coupling constants as $g_{K^*N\Theta} = 0.74 - 0.87$ and $f_{K^*N\Theta} = 0.53 - 1.16$, respectively. The smallness of these coupling constants can be understood by comparing them with the $K^*p\Lambda$ coupling constants

$$|g_{K^*p\Lambda}| = 6.97, \quad |f_{K^*p\Lambda}| = 10.15, \quad (24)$$

which were derived within the same framework. Thus, the $K^*n\Theta$ coupling constants are indeed very tiny, which is in agreement with the conclusion of recent experimental data^[10, 11, 16]. Using the value of $g_{K_n\Theta} = 0.83$, we immediately obtain the decay width of the Θ^+ as $\Gamma_{\Theta \rightarrow KN} = 0.71$ MeV which is in qualitative agreement with the data of the DIANA collaboration^[12].

The coupling constants for the proton can be obtained easily by considering isospin factors. Note that there is a sign difference in the coupling constants for the neutron and proton: $g_{K^*n\Theta} = -g_{K^*p\Theta}$ and the same for the $f_{K^*N\Theta}$ ^[19].

4 Discussion of the value of the Θ^+ decay width by Diakonov et al.

Diakonov et al.^[2] estimated the decay width of the Θ^+ : $\Gamma_{\Theta \rightarrow KN} \approx 15$ MeV, based on the experimental data for the πNN coupling constant and

$$g_{\pi NN} \approx \frac{7}{10} \left(G_0 + \frac{1}{2} G_1 \right) \approx 13.3, \quad (25)$$

where terms proportional to G_2 and c_{10}^n were neglected. However, the coupling constant $g_{K_n\Theta}$ is proportional to $G_0 - G_1$, so that it is not possible to determine it by the $g_{\pi NN}$ only. Thus, DPP^[2] have taken the results from the χ QSM calculations^[26, 27]. A recent work^[19] uses the same formalism as Refs. [26, 27] but several parts have been further elaborated. The

symmetry-conserving quantization^[28] was established after the publication of Ref. [2]. Since then, many observables of the baryon octet have been recalculated. The quark densities of the axial-vector current were also calculated^[29] and the ratio G_1/G_0 can be found to be 0.68.

Had DPP^[2] used the ratio $G_1/G_0 = 0.68$ instead of $G_1/G_0 = 0.4$, the decay width would have turned out to be $\Gamma_{\Theta \rightarrow KN} = 3.4$ MeV, which is much smaller than the value $\Gamma_{\Theta \rightarrow KN} < 15$ MeV published in Ref. [2], whereas $\Gamma_{\Delta \rightarrow \pi N}$ would remain unchanged. Even though we consider the criticism of Ref. [30] with $G_1/G_0 = 0.68$, one will get the decay width of the Θ^+ which is also smaller than predicted in Ref. [2]. Thus, we want to point out that the predicted physics in Ref. [2] by using the χ QSM is therefore unchanged.

5 Photoproduction of the Θ^+

The results of Ledwig et al.^[18, 19] enable us to proceed to investigate the photoproduction of the Θ^+ unambiguously. In Ref. [20], the $\gamma N \rightarrow K\Theta^+$ reaction has been revisited. We will briefly review several results of Ref. [20] in this Section.

Employing the coupling constants and cutoff masses obtained in Refs. [18, 19], observables for the $\gamma N \rightarrow K\Theta^+$ reaction were reexamined, based on an effective Lagrangian approach. The spin-parity quantum number of the Θ^+ has been assumed to be $1/2^+$ as predicted by the χ QSM. In this Section, we briefly summarize the results of Ref. [20].

In Fig. 1, we draw the total cross sections for the $\gamma n \rightarrow K^-\Theta^+$ and $\gamma p \rightarrow \bar{K}^0\Theta^+$ reactions with and without the K^* -exchange contribution, respectively, in the left and right panels. The K^* exchange contributes to the total cross section for the neutron target by about 30% whereas for the proton target it is almost everything. This is due to the fact that no K -exchange contributes to the $\gamma p \rightarrow \bar{K}^0\Theta^+$ reaction. The results for the neutron target is in qualitative agreement with the LEPS data^[16].

Figure 2 depicts the differential cross sections for the $\gamma n \rightarrow K^-\Theta^+$ (in the left panel) and $\gamma p \rightarrow \bar{K}^0\Theta^+$ (in the right one) reactions with and without K^* -exchange for three different photon energies 2.1 GeV, 2.2 GeV, and 2.3 GeV, respectively. Because of the K - and K^* -exchange contributions, the bump structures arise in the region $\lesssim 60^\circ$ for both the neutron and proton target cases. As in the case of the total cross sections, while the K^* -exchange contribution makes the differential cross section about 10% enhanced for the neutron target, its effects are remarkably large for

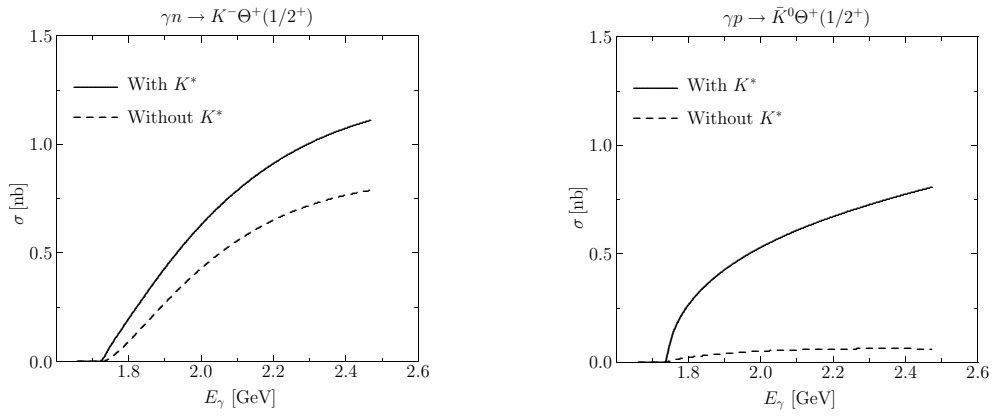


Fig. 1. Effects of the K^* -exchange on the total cross sections. The left panels represent those for the $\gamma n \rightarrow K^- \Theta^+$ reaction, while the right panels those for the $\gamma p \rightarrow \bar{K}^0 \Theta^+$. The solid curves indicate those with all contributions, whereas the dashed one those without the K^* -exchange.

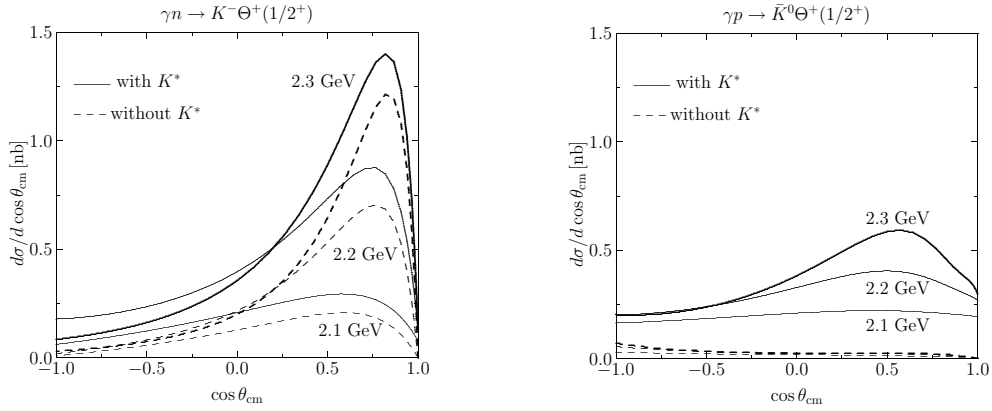


Fig. 2. Effects of the K^* -exchange on the differential cross sections. The left panels represent those for the $\gamma n \rightarrow K^- \Theta^+$ reaction, while the right panels those for the $\gamma p \rightarrow \bar{K}^0 \Theta^+$. The solid curves indicate those with all contributions, whereas the dashed one those without the K^* -exchange. The differential cross sections are drawn for three different photon energies E_γ , 2.1 GeV, 2.2 GeV, and 2.3 GeV.

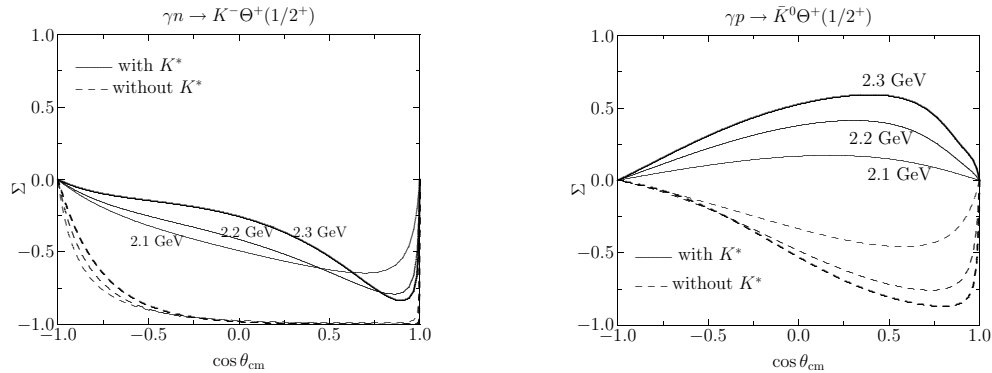


Fig. 3. Effects of the K^* -exchange on the photon-beam asymmetries. The left panels represent those for the $\gamma n \rightarrow K^- \Theta^+$ reaction, while the right panels those for the $\gamma p \rightarrow \bar{K}^0 \Theta^+$. The line styles are the same as those in Fig. 2.

the proton target. As the photon energy increases, the differential cross sections also increase consistently, as expected.

In the left and right panels of Fig. 3, we show the photon beam asymmetries for the $\gamma n \rightarrow K^- \Theta^+$ and $\gamma p \rightarrow \bar{K}^0 \Theta^+$ reactions. Without K^* -exchange, the photon beam asymmetry for the neutron target falls down drastically, starting from the backward direction, and goes down to almost $\Sigma = -1$ at around $\theta_{\text{cm}} = 90^\circ$. It is due to the electric meson-baryon coupling of the dominant K -exchange contribution. However, when we switch on the K^* -exchange one, the photon beam asymmetry decreases mildly from the backward direction to the forward direction, and then it increases sharply to $\Sigma = 0$. On the whole, the photon beam asymmetry is negative for the neutron target.

As for the proton target, K^* -exchange shows profound effects on the photon beam asymmetry. While the photon beam asymmetry becomes negative without the K^* -exchange contribution, it is changed into positive values in all the regions with the K^* -exchange contribution considered. The photon beam asymmetry starts to increase from the backward direction to the forward direction, and it gets brought down from around $\cos\theta_{\text{cm}} = 0.5$.

6 Summary and conclusions

In the present talk, we have reviewed recent works^[18, 19] on the $KN\Theta$ and $K^*N\Theta$ coupling constants based on the chiral quark-soliton model. The results are summarized as follows: the vector and tensor $K^*N\Theta$ coupling constants for the Θ^+ : $g_{K^*N\Theta} = 0.74 - 0.87$ and $f_{K^*N\Theta} = 0.53 - 1.16$, and $\Gamma_{\Theta \rightarrow KN} = 0.71$ MeV with the $KN\Theta$ coupling constant $g_{KN\Theta} = 0.83$. We also discussed the connection of the presently reported results to the original work by Diakonov et al.^[2]. If the present result had used in their work, they would have obtained $\Gamma_{\Theta \rightarrow KN} = 3.4$ MeV. These improvements even solidify the predicted physics in Ref. [2] regardless of the criticism by Jaffe^[30].

Using the coupling constants and cutoff masses obtained in Refs. [18, 19], we have reexamined the photoproduction of the Θ^+ . We found that the results of the total cross section for the neutron target is compatible with the LEPS data^[16].

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