Pentaquark Θ^+ production from the reaction $\gamma p \rightarrow \pi^+ K^- \Theta^+$ W. Liu,¹ C. M. Ko,¹ and V. Kubarovsky²¹*Cyclotron Institute and Physics Department, Texas A&M University, College Station, Texas 77843-3366, USA*²*Rensselaer Polytechnic Institute, Troy, New York 12180-3590, USA and Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA*

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The cross section for Θ^+ production from the reaction $\gamma p \rightarrow \pi^+ K^- \Theta^+$, which was observed in the CLAS experiment at the Jefferson National Laboratory, is evaluated in a hadronic model that includes couplings of Θ^+ to both KN and K^*N . With their coupling constants determined from the empirical $\pi NN(1710)$ and $\rho NN(1710)$ coupling constants using the $SU(3)$ symmetry, the cross section for this reaction has been evaluated by taking Θ^+ to have spin 1/2 and isospin 0 but either positive or negative parity. We find that if Θ^+ has positive parity as predicted by the chiral soliton model and the correlated quark model, the cross section is 50–110 nb, depending on the value of the $K^*N\Theta$ coupling. The cross section is reduced by more than a factor of 10 if Θ^+ has negative parity as given by lattice QCD studies and the uncorrelated quark model. For both parities, the differential cross section peaks at small negative four-momentum transfer when the reaction is dominated by the t -channel kaon-exchange diagram that involves only the coupling of Θ^+ to KN . After decreasing with increasing negative four-momentum transfer, the differential cross section increases again when the u -channel contribution due to intermediate Θ^+ propagation becomes important at large negative four-momentum transfer.

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I. INTRODUCTION

One of the most exciting recent experiments in hadron spectroscopy is the detection of a narrow baryon state from the invariant mass spectrum of K^+n or K^0p in nuclear reactions induced by photons [1–4] or kaons [5]. The extracted mass of about 1.54 GeV and width of less than 21–25 MeV are consistent with those of the pentaquark baryon Θ^+ consisting of $uudd\bar{s}$ quarks and predicted in the chiral soliton model [6]. Its existence has also been verified in the Skyrme model [7–12], the constituent quark model [13–15], the chiral quark model [16,17], the QCD sum rules [18–20], and the lattice QCD [21,22]. Although most models predict that Θ^+ has spin 1/2 and isospin 0, their predictions on Θ^+ parity vary widely. While the soliton model gives a positive parity and the lattice QCD studies favor a negative parity, the quark model can give either positive or negative parities, depending on whether quarks are correlated or not. Since the quantum numbers of the detected Θ^+ are not yet determined in experiments, studies have therefore been carried out to predict its decay branching ratios based on different assignments of the Θ^+ quantum numbers [23,24].

To evaluate the cross sections for Θ^+ production from these reactions, we have employed a hadronic model that is based on gauged $SU(3)$ flavor symmetric Lagrangians with the photon introduced as a $U_{em}(1)$ gauged particle [25]. The symmetry breaking effects are taken into account phenomenologically by using empirical hadron masses and coupling constants as well as empirical form factors. For the reaction $\gamma p \rightarrow \bar{K}^0 \Theta^+$, in which Θ^+ was detected in the SAPHIR experiment at Bonn University's ELSA accelerator [4], the predicted cross section reaches a value of about 40 nb at photon energy $E_\gamma \sim 3.5$ GeV if the parity of Θ^+ is taken to be positive. This value is about an order of magnitude smaller than the 300 nb measured in the experiment. On the other hand,

the reaction $\gamma n \rightarrow K^- \Theta^+$, which corresponds to the one seen in the LEPS experiment at SPring-8 [1] and the CLAS experiment at the Thomas Jefferson National Laboratory (JLab) [2], is predicted to have a peak value of about 280 nb at $E_\gamma \sim 2.2$ GeV, comparable to that obtained in Ref. [26] using similar hadronic Lagrangians. The much larger cross section for the reaction $\gamma n \rightarrow K^- \Theta^+$ than that for the reaction $\gamma p \rightarrow \bar{K}^0 \Theta^+$ is due to coupling of the photon to the virtual K^- accompanied with the produced Θ^+ [27], which is absent in the latter reaction. It was also pointed out in Ref. [27] that if Θ^+ is allowed to couple to K^*N with a coupling constant similar to the $KN\Theta$ coupling and if one further includes the photon anomalous parity interactions with kaons, which are responsible for the decay of K^* to $K\gamma$, then the cross section for the reaction $\gamma p \rightarrow \bar{K}^0 \Theta^+$ is increased to about 350 nb, comparable to that quoted in the SAPHIR experiment, although that for the reaction $\gamma n \rightarrow K^- \Theta^+$ is only somewhat enhanced. In these studies, photon interactions with the anomalous magnetic moment of nucleons are, however, not considered. Including this contribution and using empirical form factors extracted from photoproduction of Λ from protons, the cross sections for these reactions have been evaluated in Ref. [28] and were again found to be a few hundred nanobarn except that the one on protons is somewhat larger than the one on neutrons. In both Refs. [26] and [28], it was further found that the Θ^+ production cross section is significantly reduced if its parity is negative.

Besides the reactions $\gamma p \rightarrow \bar{K}^0 \Theta^+$ and $\gamma n \rightarrow K^- \Theta^+$, the Θ^+ was also observed in the reaction $\gamma p \rightarrow \pi^+ K^- \Theta^+$ by the CLAS Collaboration at JLab [3]. It was suggested in Ref. [3] that this process is likely to result from the decay of $\bar{K}^{*0}$ in the reaction $\gamma p \rightarrow \bar{K}^{*0} \Theta^+$. Since this cross section has not been considered in previous studies, we shall evaluate it in this paper using the hadronic Lagrangians introduced in

FIG. 1. Diagrams for Θ^+ production from the reaction $\gamma p \rightarrow \bar{K}^{*0}\Theta^+$.

Refs. [25,27] but with improved considerations of the Θ^+ coupling constants and the form factors at strong interaction vertices. Our results show that the magnitude of the cross section is sensitive to the parity of Θ^+ and is thus useful in the experimental determination of Θ^+ parity.

II. Θ^+ PRODUCTION FROM THE REACTION

$$\gamma p \rightarrow \pi^+ K^- \Theta^+$$

The diagrams that contribute to the reaction $\gamma p \rightarrow \bar{K}^{*0}\Theta^+$ are shown in Fig. 1. If we take Θ^+ to have spin 1/2, isospin 0, and positive parity, then the following interaction Lagrangians are needed to evaluate the amplitudes for these diagrams:

$$\mathcal{L}_{KN\Theta} = i g_{KN\Theta} \bar{N} \gamma_5 \Theta K + \text{H.c.},$$

$$\mathcal{L}_{K^*N\Theta} = g_{K^*N\Theta} \bar{N} \gamma_\mu \Theta K^{*\mu} + \text{H.c.},$$

$$\mathcal{L}_{\gamma NN} = -e \bar{N} \left\{ \gamma_\mu \frac{1 + \tau_3}{2} - \frac{1}{4m_N} \right. \\ \left. \times [\kappa_p + \kappa_n + \tau_3(\kappa_p - \kappa_n)] \sigma_{\mu\nu} \partial^\nu \right\} A^\mu N,$$

$$\mathcal{L}_{\gamma\Theta\Theta} = -e \bar{\Theta} \gamma_\mu \Theta A^\mu,$$

$$\mathcal{L}_{\gamma K K^*} = g_{\gamma K K^*} \epsilon_{\alpha\beta\mu\nu} \partial^\alpha A^\beta [\partial^\mu \bar{K}^{*\nu} K + \bar{K} \partial^\mu K^{*\nu}]. \quad (1)$$

In the above, A denotes the photon field while N , K , and K^* are the isospin doublet nucleon, kaon, and vector kaon fields, respectively; γ_μ and γ_5 are Dirac matrices while τ_3 is the Pauli spin matrix; and $\epsilon_{\alpha\beta\mu\nu}$ represents the antisymmetric tensor with the usual convention $\epsilon_{0123}=1$.

The coupling constant $g_{KN\Theta}$ can in principle be determined from the width Γ_Θ of Θ^+ . Unfortunately, Γ_Θ is not well known due to limitation of experimental resolution. In our previous studies [25,27], we have taken the experimental upper limit of $\Gamma_\Theta=20$ MeV and obtained $g_{KN\Theta}=4.4$ using

$$\Gamma_\Theta = \frac{g_{KN\Theta}^2 k (\sqrt{m_N^2 + k^2} - m_N)}{2\pi m_\Theta}, \quad (2)$$

where k is the momentum of nucleon with mass m_N or kaon with mass m_K in the rest frame of Θ^+ . In the present study, we use SU(3) symmetry to relate $g_{KN\Theta}$ to $g_{\pi NN_{1710}}$

between the coupling of pentaquark N_{1710} $[(uudd\bar{d} + \sqrt{2}uuds\bar{s})/\sqrt{3}, (uudd\bar{u} + \sqrt{2}udds\bar{s})/\sqrt{3}]$ and $N\pi$, i.e., $g_{KN\Theta} = \sqrt{6} g_{\pi NN_{1710}}$ [29], with $g_{\pi NN_{1710}}$ determined from the decay width of N_{1710} to $N\pi$, given by an expression similar to Eq. (1) with $g_{KN\Theta}$, m_Θ , and m_K replaced by $\sqrt{3}/2$ times the πNN_{1710} coupling $g_{\pi NN_{1710}}$, the N_{1710} mass m_{1710} , and the pion mass m_π , respectively.

If we assume that the pentaquark N_{1710} is the $N(1710)$ published by the Particle Data Group [30], we then obtain $g_{\pi NN_{1710}} \sim 1.0$ and thus $g_{KN\Theta} \sim 2.5$ from $\Gamma_{N(1710) \rightarrow N\pi} \sim 100 \times 0.15 = 15$ MeV, where 100 MeV is the total decay width of $N(1710)$ and 0.15 is the branching ratio for decaying to $N\pi$ [30]. However, it was pointed out in Ref. [29] that $N(1710)$ cannot be a pure antidecuplet pentaquark baryon as it then cannot have the large decay branching ratio to $\Delta\pi$ seen empirically. Following Ref. [29], we assume that antidecuplet pentaquark baryons are mixed ideally with octet pentaquark baryons. In this case, the Θ^+ remains a pure antidecuplet pentaquark baryon but the mixed pentaquark baryons $[(\sqrt{2}N_{1710} - N_8)/\sqrt{3} = (uuds\bar{s}, udds\bar{s})]$, where N_8 $[(\sqrt{2}uudd\bar{d} - uuds\bar{s})/\sqrt{3}, (\sqrt{2}uudd\bar{u} - udds\bar{s})/\sqrt{3}]$ are octet pentaquark baryons, can be identified with the $N(1710)$ published by the Particle Data Group. This then leads to the coupling constant $g_{\pi NN_{1710}} \sim 1.0 \times \sqrt{3}/2 \sim 1.2$ and thus $g_{KN\Theta} = 3g_{\pi NN_{1710}} \sim 3.0$. According to Eq. (2), this would give a Θ^+ width of $\Gamma_\Theta \sim 9$ MeV, which is smaller than that seen in photonucleon reactions [1–4] but is larger than that in kaon-nucleon reactions [5].

The coupling constant $g_{K^*N\Theta}$ between Θ^+ and K^* can be similarly determined from the SU(3) relation $g_{K^*N\Theta} = 3g_{\rho NN(1710)}$. Since the ρ meson has a large decay width, the decay width of N_{1710} to $N\rho$ is given differently from that for its decay to $N\pi$, i.e.,

$$\Gamma_{N(1710) \rightarrow N\rho} = \frac{3g_{\rho NN(1710)}^2}{4\pi} \int dm M(m) \frac{k}{m_{N(1710)}} \times \left[\sqrt{m_N^2 + k^2} \right. \\ \left. - 3m_N + \frac{\sqrt{m^2 + k^2}}{m^2} (m_{N(1710)}^2 - m^2 - m_N^2) \right], \quad (3)$$

where k is the three-momentum of nucleon or ρ meson with mass m in the rest frame of $N(1710)$. In the above,

$$M(m) = \frac{\alpha\Gamma(m)}{2\pi[(m - m_\rho)^2 + \Gamma^2(m)/4]} \quad (4)$$

is the ρ meson mass distribution with mass-dependent width $\Gamma(m) = \Gamma_\rho(k/k_\rho)^3 (m_\rho/m)^3$, where $\Gamma_\rho = 150$ MeV is the em-

pirical width of ρ meson when its mass is $m_\rho = 770$ MeV, and $k_\rho = \sqrt{m_\rho^2/4 - m_\pi^2}$ and $k = \sqrt{m^2/4 - m_\pi^2}$. The constant $\alpha = 1.256$ is introduced to normalize the ρ mass distribution, i.e., $\int dm M(m) = 1$. Using the empirical value $\Gamma_{N(1710) \rightarrow N\rho} \sim 15$ MeV, we obtain $g_{K^*N\Theta} \sim 1.8$. As the sign of $g_{K^*N\Theta}$ relative to that of $g_{KN\Theta}$ cannot be fixed by SU(3) symmetry, we shall consider both signs for the coupling constant $g_{K^*N\Theta} = \pm 1.8$ as well as the case of $g_{K^*N\Theta} = 0$.

For photon coupling to nucleon, we include also its interaction with the anomalous magnetic moment of nucleons with empirical values of $\kappa_p = 1.79$ and $\kappa_n = -1.91$. Since the anomalous magnetic moment of Θ^+ is not known, we neglect its coupling to photon.

The coupling constant $g_{\gamma K K^*}$ denotes the photon anomalous parity interaction with kaons and has the dimension of inverse of energy. Its value is $g_{\gamma K^0 K^{*0}} = 0.388$ GeV $^{-1}$ using the decay width $\Gamma_{K^{*0} \rightarrow K^0 \gamma} = 0.117$ MeV of K^{*0} to kaon and photon [27]. Although the sign of $g_{\gamma K K^*}$ relative to other coupling constants in the interaction Lagrangians is not known either, it is not relevant for our study as both constructive and destructive interferences among the three diagrams in Fig. 1 are automatically taken into account by using different signs for the coupling constant $g_{K^*N\Theta}$.

The amplitudes for the three diagrams shown in Fig. 1 for the reaction $\gamma p \rightarrow \bar{K}^{*0} \Theta^+$ are then given by

$$\mathcal{M}_t = i g_{\gamma K^0 K^{*0}} g_{KN\Theta} \bar{\Theta}(p_3) \gamma_5 \frac{\epsilon_{\alpha\beta\mu\nu} p_2^\alpha \epsilon_2^\beta p_4^\mu \epsilon_4^\nu}{t - m_K^2} p(p_1),$$

$$\begin{aligned} \mathcal{M}_s = & -e g_{K^*N\Theta} \bar{\Theta}(p_3) \epsilon_4 \cdot \gamma \frac{(p_1 + p_2) \cdot \gamma + m_N}{s - m_N^2} \\ & \times \left[1 + \frac{\kappa_p}{2m_N} p_2 \cdot \gamma \right] \epsilon_2 \cdot \gamma p(p_1) \end{aligned}$$

$$\mathcal{M}_u = -e g_{K^*N\Theta} \bar{\Theta}(p_3) \epsilon_2 \cdot \gamma \frac{(p_1 - p_4) \cdot \gamma + m_\Theta}{u - m_\Theta^2} \epsilon_4 \cdot \gamma p(p_1). \quad (5)$$

In the above, we have introduced the usual Mandelstam variables $s = (p_1 - p_2)^2$, $t = (p_1 - p_3)^2$, and $u = (p_1 - p_4)^2$, with p_1 , p_2 , p_3 , and p_4 denoting the momenta of proton, photon, Θ^+ , and K^{*0} , respectively. The polarization vectors of photon and K^{*0} are given, respectively, by ϵ_2 and ϵ_4 .

To take into account the internal structure of hadrons, form factors are needed at strong interaction vertices. In our previous studies of Θ^+ production in the reactions $\gamma N \rightarrow \bar{K} \Theta$, we have used the same form factor $F(\mathbf{q}^2) = \Lambda^2 / (\Lambda^2 + \mathbf{q}^2)$, where $\mathbf{q}$ is the three-momentum of photon in the center-of-mass frame, for all amplitudes in order to keep the total amplitude gauge invariant. The cutoff parameter $\Lambda = 0.75$ GeV used in these studies is obtained from fitting the empirical charmed hadron production cross section in photon-proton reactions at 6 GeV with similar interaction Lagrangians based on SU(4) flavor symmetry with empirical hadron masses and coupling constants [31]. Although this form factor suppresses the growth of total cross section with

increasing center-of-mass energy, it does not damp sufficiently the increasing contribution of t -channel diagram to the differential cross section at large four-momentum transfer. This can be improved by using a form factor for the t -channel amplitude that depends on the momentum of the exchanged particle instead of the momentum of the photon. Since the t -channel amplitude is gauge invariant by itself, the total amplitude remains gauge invariant even the form factor for the t -channel amplitude is different from those for the s - and u -channel amplitudes. In the present study, we follow, however, the method of Ref. [32] for photoproduction of Λ from protons by introducing different covariant form factors for the s -, t -, and u -channel amplitudes, and they are given by

$$F(x) = \frac{\Lambda^4}{\Lambda^4 + (x - m_x^2)^2}, \quad (6)$$

where $x = s$, t , and u with corresponding masses $m_x = m_N$, m_K , and m_Θ of the off-shell particles at strong interaction vertices. The cutoff parameter Λ characterizes the off-shell momentum above which hadron internal structure becomes important, and its value will be determined empirically. Although the t -channel amplitude M_t after including the form factor $F(t)$ remains gauge invariant, adding form factors $F(s)$ and $F(t)$, respectively, to the s - and t -channel amplitudes M_s and M_u leads to terms that violate the gauge invariance. The gauge violation can, however, be removed by introducing a contact term in the interaction Lagrangian that gives an additional amplitude of the form

$$\begin{aligned} \mathcal{M}_c = & -2e g_{K^*N\Theta} \bar{\Theta}(p_3) \epsilon_4 \cdot \gamma \left[\frac{\epsilon_2 \cdot p_1}{s - m_N^2} [\hat{F} - F(s)] \right. \\ & \left. + \frac{\epsilon_2 \cdot p_3}{u - m_\Theta^2} [\hat{F} - F(u)] \right] p(p_1), \quad (7) \end{aligned}$$

with $\hat{F} = 1$ [33], $a_s F(s) + a_u F(u)$ with $a_s + a_u = 1$ [34], or $\hat{F} = F(s) + F(u) - F(s)F(u)$ [35]. Here, we adopt the last $\hat{F}$ in order to maintain both crossing symmetry and the pole structure of original amplitude. To determine the value of cutoff parameter Λ , we again use similar interaction Lagrangians based on the SU(4) flavor symmetry with empirical masses and coupling constants to study charmed hadron production from photon-proton reactions at center-of-mass energy of 6 GeV [31]. Comparisons with the available experimental data gives $\Lambda \approx 1.2$ GeV, which is between the soft (0.8 GeV) and hard (1.8 GeV) form factors considered in Ref. [32] for describing experimental data on Λ production in photoproton reactions.

The resulting differential cross section for the reaction $\gamma p \rightarrow \bar{K}^{*0} \Theta^+$ is then

$$\frac{d\sigma_{\gamma p \rightarrow \bar{K}^{*0} \Theta^+}}{dt} = \frac{1}{256\pi s p_i^2} |F(t)M_t + F(s)M_s + F(u)M_u + M_c|^2, \quad (8)$$

where p_i is the magnitude of the three momenta of initial-state particles in the center-of-mass frame, i.e., $p_i = (s - m_N^2)/2\sqrt{s}$.

FIG. 2. Total cross section for the production of positive parity Θ^+ from the reaction $\gamma p \rightarrow \pi^+ K^- \Theta^+$ as a function of photon energy obtained without form factors and for the coupling constant $g_{K^*N\Theta} = 1.8$ (dotted curve), 0 (solid curve), and -1.8 (dashed curve).

Since $\bar{K}^{*0}$ can decay into either $\pi^+ K^-$ or $\pi^0 \bar{K}^0$ with a branching ratio of 2 to 1, the differential cross section for the reaction $\gamma p \rightarrow \pi^+ K^- \Theta^+$ is thus 2/3 of that given by Eq. (8).

III. RESULTS

A. Positive parity Θ^+

We first show in Fig. 2 the total cross section for the production of a positive parity Θ^+ in the reaction $\gamma p \rightarrow \pi^+ K^- \Theta^+$ obtained without form factors but with different values of 1.8 (dotted curve), 0 (solid curve), and -1.8 (dashed curve) for the coupling constant $g_{K^*N\Theta}$. It is seen that for photon energies $E_\gamma \leq 3$ GeV the cross section with $g_{K^*N\Theta}=0$, which corresponds to including only the t -channel diagram (a) of Fig. 1, lies between those with nonzero $g_{K^*N\Theta}$, indicating that contributions from the s - and u -channel diagrams (b) and (c) are as important. Since the one with positive $g_{K^*N\Theta}$ is larger than that with negative $g_{K^*N\Theta}$, the interference between the t -channel diagram and the s - and u -channel diagrams is constructive for positive $g_{K^*N\Theta}$ but destructive for negative $g_{K^*N\Theta}$. For larger photon energies, the cross section with $g_{K^*N\Theta}=0$ becomes smaller than those with nonzero $g_{K^*N\Theta}$. This implies that the s - and u -channel contributions due to $K^*N\Theta$ coupling are most important when the photon energy is large.

Including form factors at strong interaction vertices according to the method described in the preceding section, the resulting total cross sections are shown in Fig. 3 for the coupling constant $g_{K^*N\Theta}=1.8$ (dotted curve), 0 (solid curve), and -1.8 (dashed curve). In this case, the cross sections are much smaller than corresponding ones shown in Fig. 2 without form factors by about an order of magnitude at low photon energies but two orders of magnitude at high photon energies. Furthermore, unlike the case without form factors, the cross section with $g_{K^*N\Theta}=0$ is always between those with positive or negative nonzero $g_{K^*N\Theta}$ until to photon energy $E_\gamma \sim 6$ GeV, when it has a similar value as that with $g_{K^*N\Theta} = -1.8$. This implies that the effect of form factors on the s -

FIG. 3. (Color online) Same as Fig. 2 with form factors.

and u -channel diagrams is stronger than on the t -channel diagram, leading to similar contributions from all three diagrams at large E_γ . Depending on the value of $g_{K^*N\Theta}$, the total cross section obtained with form factors has a peak value of 50–110 nb at photon energy $E_\gamma \sim 3.2$ GeV.

In Fig. 4, we show the differential cross section for producing a positive parity Θ^+ in the reaction $\gamma p \rightarrow \pi^+ K^- \Theta^+$ as a function of negative four-momentum transfer $-t$ for photon energies of $E_\gamma=3, 4, 5$, and 6 GeV, using different values of 1.8 (dotted curves), 0 (solid curves), and -1.8 (dashed curves) for the coupling constant $g_{K^*N\Theta}$. In all cases, the differential cross section peaks at small negative four-momentum transfer as expected from the dominance of t -channel diagram in Fig. 1 when $-t$ is small. At large $-t$, the contribution from the u -channel diagram becomes important, leading to an increase of the differential cross section with $-t$ for nonzero $g_{K^*N\Theta}$.

B. Negative parity Θ^+

We have assumed in the above that the parity of Θ^+ is positive as predicted by the chiral soliton model [6]. On the

FIG. 4. (Color online) Differential cross section for production of a positive parity Θ^+ from the reaction $\gamma p \rightarrow \pi^+ K^- \Theta^+$ at $E_\gamma=3, 4, 5$, and 6 GeV obtained with form factors and for the coupling constant $g_{K^*N\Theta}=1.8$ (dotted curves), 0 (solid curves), and -1.8 (dashed curves).

FIG. 5. (Color online) Total cross section for the production of negative parity Θ^+ from the reaction $\gamma p \rightarrow \pi^+ K^- \Theta^+$ as a function of photon energy for the coupling constant $g_{K^* N \Theta} = 0.25$ (dotted curve), 0 (solid curve), and -0.25 (dashed curve).

other hand, results from lattice QCD calculations have indicated that the mass of Θ^+ observed in experiments is consistent with that of a negative parity pentaquark baryon with spin 1/2 and isospin 0 [21,22]. In this case, the interaction Lagrangians involving Θ^+ are given by

$$\mathcal{L}_{KN\Theta} = g_{KN\Theta} \bar{N} \Theta K + \text{H.c.},$$

$$\mathcal{L}_{K^* N \Theta} = i g_{K^* N \Theta} \bar{N} \gamma_5 \gamma_\mu \Theta K^{*\mu} + \text{H.c.} \quad (9)$$

This changes the expression for the Θ^+ width shown in Eq. (2), i.e., the $-m_N$ is replaced by m_N . As a result, the coupling constant $g_{KN\Theta}$ is reduced by about a factor of 7, i.e., $g_{KN\Theta} = 0.42$ if the Θ^+ width is taken to be 9 MeV. Since $N(1710)$ is known to have positive parity, it could not be in the same multiplet as Θ^+ if the latter has negative parity. The SU(3) relation used previously for relating $g_{K^* N \Theta}$ to $g_{\rho N N(1710)}$ is then not applicable. Instead, we assume that the ratio $g_{K^* N \Theta}/g_{KN\Theta}$ remains the same whether Θ^+ has positive or negative parity. This leads to $g_{K^* N \Theta} = 0.25$ for negative parity Θ^+ .

The amplitudes for the three diagrams in Fig. 1 for producing a negative parity Θ^+ are similar to those in Eq. (4) for positive parity Θ^+ except that the factor $i\gamma_5$ should be inserted after $\bar{\Theta}(p_3)$ in all three amplitudes. The $i\gamma_5$ is also needed in the amplitude shown in Eq. (7) due to the contact interaction introduced for canceling the gauge violating terms after form factors are introduced at strong interaction vertices. The cross section formula for the reaction $\gamma p \rightarrow \pi^+ K^- \Theta^+$ with negative parity Θ^+ remains to be 2/3 of Eq. (8).

The total cross section for producing a negative parity Θ^+ from the reaction $\gamma p \rightarrow \pi^+ K^- \Theta^+$ is shown in Fig. 5 for the three values of 0.25 (dotted curve), 0 (solid curve), and -0.25 (dashed curve) for $g_{K^* N \Theta}$. Form factors at strong interaction vertices are taken to have the same form shown in Eq. (6) with cutoff parameter $\Lambda = 1.2$ GeV as in the case of positive parity Θ^+ . It is seen that these cross sections are insen-

FIG. 6. (Color online) Differential cross section for production of a negative parity Θ^+ from the reaction $\gamma p \rightarrow \pi^+ K^- \Theta^+$ at $E_\gamma = 3, 4, 5$, and 6 GeV obtained with form factors and for the coupling constant $g_{K^* N \Theta} = 0.25$ (dotted curves), 0 (solid curves), and -0.25 (dashed curves).

sitive to the value of $g_{K^* N \Theta}$ as the dominant contribution is from the t -channel diagram involving only $g_{KN\Theta}$. Their magnitude is more than an order of magnitude smaller than that for producing a positive parity Θ^+ . The peak value is now only about 8 nb at $E_\gamma \sim 3.2$ GeV.

In Fig. 6, the differential cross section for producing a negative parity Θ^+ as a function of negative four-momentum transfer $-t$ is shown for four photon energies of $E_\gamma = 3, 4, 5$, and 6 GeV with the coupling constant $g_{K^* N \Theta}$ having values of -0.25 (dashed curves), 0 (solid curves), and 0.25 (dotted curves). As in the production of positive parity Θ^+ , the differential cross section for producing a negative parity Θ^+ in the reaction $\gamma p \rightarrow \pi^+ K^- \Theta^+$ first decreases with increasing negative four-momentum transfer $-t$ then increases again at large $-t$ when the t -channel contribution diminishes and the u -channel contribution becomes important.

IV. DISCUSSION

The reaction $\gamma p \rightarrow \pi^+ K^- \Theta^+$ can also proceed via the exchange of K^{*-} as shown in Fig. 7 besides through the decay of $\bar{K}^{*0}$ shown in Fig. 1. This process involves an additional strong interaction vertex $K^* K \pi$ compared to those in Fig. 1. Although the coupling constant $g_{\pi K K^*} = 3.28$, determined from the decay width $\Gamma_{K^* \rightarrow K \pi} = 50.8$ MeV of K^* , is not small, the additional form factor would reduce its contribution significantly compared to that from the diagrams shown in Fig. 1. Similar considerations for the reactions $\gamma n \rightarrow \pi^0 K^- \Theta^+$ and $\gamma n \rightarrow \pi^- \bar{K}^0 \Theta^+$ have shown that the contribution from the K^* exchange is negligible (about a few percent) compared to that from the K^* decay [27]. It is thus safe to neglect its contribution.

The coupling constant $g_{KN\Theta}$ used in the present study is determined using SU(3) symmetry from the coupling constant $g_{\pi N N(1710)}$, which can be extracted from the empirical

FIG. 7. Diagram for Θ^+ production from the reaction $\gamma p \rightarrow \pi^+ K^- \Theta^+$ via K^{*-} exchange.

decay width of $N(1710)$ to $N\pi$. The resulting value leads to a Θ^+ decay width of about 9 MeV, which is between those seen in photonucleon experiments [1–4] and in kaon-nucleon reactions [5]. Such a large width seems, however, incompatible with the available empirical information on K^+N and K^+d scattering data [36,37]. Moreover, if Θ^+ width is less than 1 MeV as suggested in Ref. [38] based on analyses of K^+n scattering data, the cross sections shown above, which have a large contribution from the t -channel diagram involving the $KN\Theta$ coupling, would be reduced significantly as the latter is proportional to the square of the coupling constant $g_{KN\Theta}$, similar to the width of Θ^+ as shown in Eq. (2).

The calculated cross section is also sensitive to the value of cutoff parameter used in the form factors as shown by Figs. 2 and 3 for results without and with form factors. If we use a harder form factor with cutoff parameter $\Lambda=2.4$ GeV, which is twice the value used in the present study, the result-

ing cross sections would increase by about a factor of 5. To have a reliable prediction for the cross section for the reaction $\gamma p \rightarrow \pi^+ K^- \Theta^+$ as well as those for other Θ^+ production reactions thus requires a good knowledge of both the coupling constants $g_{KN\Theta}$ as well as the form factors.

V. SUMMARY

Using interaction Lagrangians that involve couplings of Θ^+ to both KN and K^*N , we have evaluated the cross section for its production in the reaction $\gamma p \rightarrow \pi^+ K^- \Theta^+$. The coupling constants $g_{KN\Theta}$ and $g_{K^*N\Theta}$ are determined via SU(3) relations from the empirical coupling constants $g_{\pi NN(1710)}$ and $g_{\rho NN(1710)}$ assuming that $N(1710)$ is an ideal mixture of antidecuplet and octet pentaquark baryon. With empirical cutoff parameter in the form factors, the cross section has been calculated for either positive or negative parity Θ^+ . We find that value of the cross section for producing a positive parity Θ^+ is about 50–110 nb at $E_\gamma \sim 3.2$ GeV depending on the value of the coupling constant $g_{K^*N\Theta}$. The cross section is reduced by an order of magnitude if Θ^+ has negative parity. In both cases, the differential cross section peaks at small negative four-momentum transfer $-t$. With nonzero $g_{K^*N\Theta}$, the differential cross first decreases with increasing $-t$ due to the t -channel contribution but increases again at large $-t$ when the u -channel becomes important.

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