Pentaquark baryon production from photon-neutron reactions

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(Dated: March 30, 2022)

Abstract

Extending the hadronic Lagrangians that we recently introduced for studying pentaquark $\Theta^+$ baryon production from meson-proton, proton-proton, and photon-proton reactions near threshold to include the anomalous interaction between $\gamma$ and $K^*K$, we evaluate the cross section for $\Theta^+$ production from photon-neutron reactions, in which the $\Theta^+$ was first detected in the SPring-8 experiment in Japan and the CLAS experiment at Thomas Jefferson National Laboratory. With empirical coupling constants and form factors, and assuming that the decay width of $\Theta^+$ is 20 MeV, the predicted cross section is found to have a peak value of about 280 nb, which is substantially larger than that for $\Theta^+$ production from photon-proton reactions.

PACS numbers: 13.75.Gx,13.75.Jz,12.39.Mk,14.20.-c
I. INTRODUCTION

Recently, a narrow baryon state was inferred from the invariant mass spectrum of $K^+n$ or $K^0p$ in nuclear reactions induced by photons \cite{1,2,3} or kaons \cite{4}. The extracted mass of about 1.54 GeV and width of less than 21-25 MeV are consistent with those of the pentaquark baryon $\Theta^+$ consisting of $uudd\bar{s}$ quarks and predicted in the chiral soliton model \cite{5}. Its existence has also been verified recently in the constituent quark model \cite{6,7} and the QCD sum rules \cite{8}. Although the spin and isospin of $\Theta^+$ are predicted to be 1/2 and 0, respectively, those of the one detected in experiments are not yet determined. Studies have therefore been carried out to predict its decay branching ratios based on different assignments of its spin and isospin \cite{9,10}. To evaluate the cross sections for $\Theta^+$ production from nucleons induced by mesons and protons, which are needed for studying $\Theta^+$ production in relativistic heavy ion collisions \cite{11}, we have used a hadronic model that is based on $SU(3)$ flavor symmetry with empirical hadron masses and form factors at interaction vertices \cite{12,13,14}. For the coupling constant between $\Theta^+$ and $KN$, it is determined from the width of $\Theta^+$. With the photon included as a $U_{em}(1)$ gauge boson, we have further generalized the hadronic model to calculate the cross sections for $\Theta^+$ production from photon-proton reactions. We find that the predicted cross sections have peak values about 1.5 mb in kaon-proton reactions, 0.1 mb in rho-nucleon reactions, 0.05 mb in pion-nucleon reactions, 20 $\mu$b in proton-proton reactions, and 40 nb in photon-proton reactions \cite{15}.

In the present paper, we extend this model to include the anomalous interaction between photon and $K^*K$ and to use it to evaluate the cross section for $\Theta^+$ production from photon-neutron reactions, in which the $\Theta^+$ baryon was first detected in the SPring-8 experiment in Japan and the CLAS experiment at Thomas Jefferson National Laboratory.

This paper is organized as follows. In Sect. \[\text{II}\] the cross section for $\Theta^+$ production from photon-neutron reactions with inclusion of final states up to four particles is evaluated. The process involving the coupling of $\Theta^+$ to $K^+N$ in the reaction $\gamma n \rightarrow K^-\Theta^+$ is discussed in Sect. \[\text{III}\]. Finally, a summary is given in Sect. \[\text{IV}\].
II. THETA PRODUCTION FROM PHOTON-NEUTRON REACTIONS

In photon-neutron interactions, the $\Theta^+$ baryon can be produced in various final states. In the present study, we consider reactions with final states up to four particles. For final states with two particles, the reaction is $\gamma n \rightarrow K^- \Theta^+$ and is described in Sect. II A. In Sect. II B, the reactions $\gamma n \rightarrow \pi^0 K^- \Theta^+$ and $\gamma n \rightarrow \pi^- K^0 \Theta^+$ with three particles in the final state are discussed. The reactions $\gamma n \rightarrow \pi^- K^* \Theta^+$, $\gamma n \rightarrow \pi^0 K^* \Theta^+$, $\gamma n \rightarrow \rho^- K^* \Theta^+$, and $\gamma n \rightarrow \rho^0 K^- \Theta^+$ with four particles in the final state, if we take into account decays of $K^*$ to $K\pi$ and $\rho$ to $\pi\pi$, are given in Sect. II C. Numerical results for the cross sections for these reactions are presented in Sect. II D.

A. $\gamma n \rightarrow K^- \Theta^+$

FIG. 1: Diagrams for $\Theta^+$ production from photon-neutron reactions with two-body final states.

For the reaction $\gamma n \rightarrow K^- \Theta^+$ with two-body final state, the two diagrams are shown in Fig. 1. To evaluate its cross section, we need the following interaction Lagrangians:

\begin{align}
\mathcal{L}_{KN\Theta} &= ig_{KN\Theta}(\bar{\Theta}\gamma_5 N\bar{K} + \bar{N}\gamma_5 \Theta K), \\
\mathcal{L}_{\gamma\Theta\Theta} &= ieA_\mu \bar{\Theta}\gamma_\mu \Theta, \\
\mathcal{L}_{\gamma KK} &= ieA_\mu [KQ\partial_\mu \bar{K} - \partial_\mu KQ\bar{K}],
\end{align}

(1)

In the above, $\Theta$ denotes the spin 1/2 and isospin 0 pentaquark baryon; $N$ and $K$ are, respectively, the isospin doublet kaon and nucleon fields; and $A_\mu$ is the photon field. The operator $Q$ is the diagonal charge operator with elements 0 and -1. The coupling constant $g_{KN\Theta}$ of $\Theta^+$ to $NK$ is determined from its decay width given by

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

(2)
where \( m_N \) and \( m_\Theta \) are masses of nucleon and \( \Theta^+ \), respectively, and \( k \) is the momentum of \( N \) or \( K \) in the rest frame of \( \Theta^+ \). Using \( m_\Theta = 1.54 \text{ GeV} \) and \( \Gamma_\Theta = 20 \text{ MeV} \), we find \( g_{K N \Theta} = 4.4 \), which is comparable to that given by the chiral soliton model \[5\].

The two amplitudes for the reaction \( \gamma n \rightarrow K^- \Theta^+ \) are then given by

\[
\mathcal{M}_{1a} = -e g_{K N \Theta} \frac{F(q^2)}{t-m_K^2} (p_2 - 2p_4) \mu \Theta(p_3) \gamma_5 n(p_1) \epsilon_\mu, \\
\mathcal{M}_{1b} = -e g_{K N \Theta} \frac{F(q^2)}{u-m_\Theta^2} \Theta(p_3) \gamma^\mu (\bar{\phi}_4 - \phi_4 + m_\Theta) \gamma_5 n(p_1) \epsilon_\mu, 
\]

(3)

with \( \epsilon_\mu \) denoting the photon polarization vector. In the above, \( p_1 \) and \( p_2 \) are momenta of \( n \) and \( \gamma \) while \( p_3 \) and \( p_4 \) are those of \( \Theta^+ \) and \( K^- \), respectively. The usual Mandelstam variables are given by \( s = (p_1 + p_2)^2, t = (p_1 - p_3)^2, \) and \( u = (p_1 - p_4)^2 \) with \( s \) needed later.

To take into account the final sizes of hadrons and also maintain the gauge invariance of the total amplitudes, we have included the same overall form factor \( F(q^2) \) in each amplitude as in our previous study of \( \Theta^+ \) production from photon-proton reactions. It is taken to have the following monopole form

\[
F(q^2) = \frac{\Lambda^2}{\Lambda^2 + q^2},
\]

(4)

with \( q \) being the photon three momentum in center-of-mass system. The cutoff parameter \( \Lambda \) is taken to be \( \Lambda = 0.75 \text{ GeV} \), which has been shown to reproduce the experimental data at center-of-mass energy of 6 GeV using similar Lagrangians based on the SU(4) flavor symmetry with empirical masses and coupling constants \[16\].

The cross section for the reaction \( \gamma p \rightarrow K^- \Theta^+ \) with two-body final state is then given by

\[
\frac{d\sigma}{dt} = \frac{1}{256\pi s q^2} \sum_{\text{spin}} |\mathcal{M}_{1a} + \mathcal{M}_{1b}|^2,
\]

(5)

with the summation over both initial neutron and final \( \Theta^+ \) spins.

**B. \( \gamma n \rightarrow \pi^0 K^- \Theta^+ \) and \( \gamma n \rightarrow \pi^- K^0 \Theta^+ \)**

For the reactions \( \gamma n \rightarrow \pi^0 K^- \Theta^+ \) and \( \gamma n \rightarrow \pi^- K^0 \Theta^+ \) with three-body final states, their diagrams are shown in Fig.2. These reactions are due to the the anomalous parity interaction between photon and \( KK^* \), i.e.,

\[
\mathcal{L}_{\gamma KK^{*0}} = g_{\gamma KK^{*0}} \epsilon_{\alpha \beta \mu \nu} \partial^\alpha A^\beta [\partial^\mu \bar{K}^{*\nu} K + \bar{K} \partial^\mu K^{*\nu}],
\]

(6)
where $\epsilon_{\alpha\beta\mu\nu}$ is the antisymmetric tensor with $\epsilon_{0123} = 1$. The coupling constant $g_{\gamma K K^*}$ has the dimension of inverse of energy and can be determined from the decay width of $K^{*0}$ or $K^{*\pm}$ to photons through the process $K^{*0} \to K^0\gamma$ or $K^{*\pm} \to K^{\pm}\gamma$, respectively, i.e.,

$$\Gamma_{K^*} = \frac{g_{\gamma K K^*}^2}{12\pi} k^3, \quad (7)$$

with $k$ being photon momentum in the rest frame of $K^*$. From the empirical values $\Gamma_{K^{*0} \to K^0\gamma} = 50.8 \times 2.3 \times 10^{-3} = 0.117$ MeV and $\Gamma_{K^{*\pm} \to K^{\pm}\gamma} = 50.8 \times 9.9 \times 10^{-4} = 0.05$ MeV, where the first factor 50.8 MeV is the $K^*$ total decay width while the second factor is the branching ratio for electromagnetic decay, we find that $g_{\gamma K^0 K^{*0}} = 0.0388\text{ GeV}^{-1}$ and $g_{\gamma K^\pm K^{*\pm}} = 0.0257\text{ GeV}^{-1}$.

Also needed is the interaction Lagrangian involving $\pi$, $K$, and $K^*$, which is given by

$$\mathcal{L}_{\pi KK^*} = ig_{\pi K K^*} K^{*\mu}(\bar{K}\partial_\mu \pi - \partial_\mu \bar{K} \pi) + \text{H.c.}, \quad (8)$$

with the coupling constant $g_{\pi K K^*} = 3.28$ determined from the decay width of $K^*$ to $K$ and $\pi$.

The amplitudes for the reactions $\gamma n \to \pi^0 K^- \Theta^+$ and $\gamma n \to \pi^- \bar{K}^0 \Theta^+$ are then given by

$$\mathcal{M}_i = ig_{\gamma K NE}\Theta(p_3)\gamma_5 n(p_1) \frac{F(q^2)}{t-m_K^2} \left[F((p_1-p_3)^2)\mathcal{M}_{ia}^{sub} + \mathcal{M}_{ib}^{sub}\right], \quad (9)$$

where

$$\mathcal{M}_{2a}^{sub} = \frac{g_{\gamma K^{*0} K^{*0} K^*} g_{\pi K K^*}}{(k_1-k_3)^2 - m_K^2} \epsilon_{\alpha\beta\mu\nu} p_2^\alpha \epsilon_2^\beta (k_3-k_1)^\mu(k_1+k_3)^\nu.$$
\[ \mathcal{M}_{2b}^{\text{sub}} = \frac{g_{\gamma KK^*} - g_{\pi KK^*}}{(k_1 + k_2)^2 - m_{K^*}^2 + i m_{K^*} \Gamma_{K^*}} \epsilon_{\alpha \beta \mu \nu} p_2^\alpha \epsilon_2^\beta (k_1 + k_2)^\mu (k_3 - k_4)^\nu, \]

\[ \mathcal{M}_{3a}^{\text{sub}} = \frac{\sqrt{2} g_{\gamma K^* K^*} - g_{\pi K K^*}}{(k_1 - k_3)^2 - m_{K^*}^2 + i m_{K^*} \Gamma_{K^*}} \epsilon_{\alpha \beta \mu \nu} p_2^\alpha \epsilon_2^\beta (k_3 - k_1)^\mu (k_1 + k_3)^\nu, \]

\[ \mathcal{M}_{3b}^{\text{sub}} = \frac{\sqrt{2} g_{\gamma K^* K^*} - g_{\pi K K^*}}{(k_1 + k_2)^2 - m_{K^*}^2 + i m_{K^*} \Gamma_{K^*}} \epsilon_{\alpha \beta \mu \nu} p_2^\alpha \epsilon_2^\beta (k_1 + k_2)^\mu (k_3 - k_4)^\nu, \]

are amplitudes for the subprocesses $\gamma K^* \rightarrow \pi^0 K^*$ and $\gamma K^* \rightarrow \pi^- K^0$. In the above, we have included the width of $K^*$ in its propagator to avoid possible singularity when it becomes on shell. Also, besides the overall monopole form factor $F(q^2)$, an additional monopole form factor $F((p_1 - p_3)^2)$ depending on the three momentum of $K^-$ and with cutoff parameter $\Lambda = 0.5 \text{ GeV}$, which is based on fitting the measured cross section for the reaction $\pi N \rightarrow K \Lambda$ using similar Lagrangians \[18\], has been included at the $KN\Theta$ vertex in diagrams (2a) and (3a). Since diagrams (2b) and (3b) of Fig.2 can also be viewed as the reaction $\gamma n \rightarrow K^{*-} \Theta^+$ with two-body final state, their cross sections thus involve only the overall form factor $F(q^2)$ as in reactions with two-body final state.

The cross sections for reactions with three-body final state can be expressed in terms of the off-shell cross sections for their two-body subprocesses \[18\], \[19\]. For the reaction $\gamma n \rightarrow \pi^0 K^- \Theta^+$, its cross section is thus

\[ \frac{d\sigma_{\gamma n \rightarrow \pi^0 K^- \Theta^+}}{dt ds_1} = \frac{g_{KN\Theta}^2}{32 \pi^2 s q^2} k \sqrt{s_1} [-t + (m_N - m_\Theta)^2] \frac{F^2(q^2)}{(t - m_K^2)^2} \frac{1}{s_1(s_1 - m_K^2)} \sigma_{\gamma K^- \rightarrow \pi^0 K^-}(s_1, t), \]

and similarly for the reaction $\gamma p \rightarrow \pi^0 K^+ \Theta^+$. In the above, $s_1$ and $k$ are the squared center-of-mass energy and three momentum of virtual $K^-$ in the subprocess $\gamma K^- \rightarrow \pi^0 K^-$. The cross section $\sigma_{\gamma K^- \rightarrow \pi^0 K^-}(s_1, t)$ for this off-shell subprocess is calculated with the amplitude $F((p_1 - p_3)^2) \mathcal{M}_{2a}^{\text{sub}} + \mathcal{M}_{2b}^{\text{sub}}$.

**C. $\gamma n \rightarrow \pi^- K^0 \Theta^+$, $\gamma n \rightarrow \pi^0 K^{*-} \Theta^+$, $\gamma n \rightarrow \rho^- K^0 \Theta^+$, and $\gamma n \rightarrow \rho^0 K^- \Theta^+$**

The reactions $\gamma n \rightarrow \pi^- K^0 \Theta^+$, $\gamma n \rightarrow \pi^0 K^{*-} \Theta^+$, $\gamma n \rightarrow \rho^- K^0 \Theta^+$, and $\gamma n \rightarrow \rho^0 K^- \Theta^+$ shown in Fig.3 involve four-body final states after taking into account the decay of rho meson to two pions and of $K^*$ to $K$ and $\pi$. In these reactions, the photon couples either to $K$ meson as in first three diagrams or to $\Theta^+$ as in the last diagram. Since the contribution from the latter diagram is expected to be much smaller than those from the former diagrams due to additional baryon propagator, as shown explicitly in charmed hadron production from
FIG. 3: Diagrams for $\Theta^+$ production from photon-neutron reactions with four-body final states after taking into account the decay of rho meson to two pions and of $K^*$ to $K$ and $\pi$.

photon-proton reactions with three-body final states [16], they are neglected in following calculations. As a result, results obtained in present study for $\Theta^+$ production with four-body final states violate slightly the gauge invariance.

To evaluate the diagrams in Fig. 3, we also need the following interaction Lagrangians:

\[
\mathcal{L}_{\gamma\pi\pi} = e A^\mu (\partial_\mu \vec{\pi} \times \vec{\pi})_3, \\
\mathcal{L}_{\gamma\rho\rho} = e \{A^\mu (\partial_\mu \vec{\rho} \times \vec{\rho})_3 + [(\partial_\mu A^\nu \vec{\rho}_\nu - A^\nu \partial_\mu \vec{\rho}_\nu) \times \vec{\rho}]_3 + [\vec{\rho} \times (A^\nu \partial_\mu \vec{\rho}_\nu - \partial_\mu A^\nu \vec{\rho}_\nu)]_3\}, \\
\mathcal{L}_{\gamma\pi KK^*} = -e g_{\pi KK^*} A^\mu (K_\mu^* (2\vec{\tau}Q - Q\vec{\tau})\vec{K} + K (2Q\vec{\tau} - \vec{\tau}Q)\vec{K}^*_\mu) \cdot \vec{\pi},
\]
\[ \mathcal{L}_{\gamma KK} = e g_{\rho KK} A^\mu K(\bar{\tau}Q + Q\bar{\tau})K \cdot \bar{p}_\mu, \]  

where the isospin triplet pion and rho meson fields are given by \( \pi = \bar{\tau} \cdot \bar{\tau} \) and \( \rho^\mu = \bar{\tau} \cdot \bar{\rho}^\mu \), respectively, with \( \bar{\tau} \) denoting the Pauli spin matrices. The coupling constant \( g_{\rho KK} = 3.25 \) is obtained from the empirical \( \rho NN \) coupling via \( SU(3) \) relations \[12].

As in reactions with three-body final state shown in Fig.2, the amplitudes for the four reactions shown in Fig.3 can be written as
\[
\mathcal{M}_i = i g_{\rho N\Theta}(p_3)\gamma_5 n(p_1) \frac{F(q^2) F((p_1 - p_3)^2)}{t - m_K^2} (\mathcal{M}_{ia}^{sub} + \mathcal{M}_{ib}^{sub} + \mathcal{M}_{ic}^{sub}).
\]

The amplitudes \( \mathcal{M}_{ia}^{sub} \), \( \mathcal{M}_{ib}^{sub} \), and \( \mathcal{M}_{ic}^{sub} \) are for the subprocesses, and they are given explicitly by

\[
\begin{align*}
\mathcal{M}_{ia}^{sub} &= \sqrt{2} e g_{\rho KK} ( -2 k_1 + k_3 )^\mu \frac{1}{(k_1 - k_3)^2 - m_\pi^2} (k_1 - k_3 + k_4)^\nu \varepsilon_{3\mu} \varepsilon_{2\nu}, \\
\mathcal{M}_{ib}^{sub} &= -\sqrt{2} e g_{\rho KK} (2 k_1 + k_2)^\nu \frac{1}{(k_1 + k_2)^2 - m_K^2} (k_1 + k_2 + k_4)^\mu \varepsilon_{3\mu} \varepsilon_{2\nu}, \\
\mathcal{M}_{ic}^{sub} &= 2 \sqrt{2} e g_{\rho KK} g^\mu \varepsilon_{3\mu} \varepsilon_{2\nu} \\
\mathcal{M}_{5a}^{sub} &= e g_{\rho KK} (k_1 + k_4)^\alpha (k_1 - k_4)^2 - m_K^2 \left[ g_{\alpha \beta} - \frac{(k_1 - k_4)_\alpha (k_1 - k_4)_\beta}{m_K^2} \right] \\
&\quad \times [- (k_2 + k_3)^\beta g^\mu + (k_1 + k_2 + k_4)^\nu g^\beta \mu + (k_1 + k_3 - k_4)^\mu g^\beta \nu] \varepsilon_{3\mu} \varepsilon_{2\nu}, \\
\mathcal{M}_{5b}^{sub} &= e g_{\rho KK} (2 k_1 + k_2)^\nu (k_1 + k_2 + k_4)^\mu \varepsilon_{3\mu} \varepsilon_{2\nu}, \\
\mathcal{M}_{5c}^{sub} &= -e g_{\rho KK} g^\mu \varepsilon_{3\mu} \varepsilon_{2\nu}, \\
\mathcal{M}_{6a}^{sub} &= -\sqrt{2} e g_{\rho KK} ( -2 k_1 - k_4 )^\mu (k_1 - k_4)^2 - m_\rho^2 \left[ g_{\alpha \beta} - \frac{(k_1 - k_4)_\alpha (k_1 - k_4)_\beta}{m_\rho^2} \right] \\
&\quad \times [- (k_2 + k_3)^\beta g^\mu + (k_1 + k_2 + k_4)^\nu g^\beta \mu + (k_1 + k_3 - k_4)^\mu g^\beta \nu] \varepsilon_{3\mu} \varepsilon_{2\nu}, \\
\mathcal{M}_{6b}^{sub} &= \sqrt{2} e g_{\rho KK} (2 k_1 + k_2)^\nu (k_1 + k_2 + k_4)^\mu \varepsilon_{3\mu} \varepsilon_{2\nu}, \\
\mathcal{M}_{6c}^{sub} &= -\sqrt{2} e g_{\rho KK} g^\mu \varepsilon_{3\mu} \varepsilon_{2\nu}, \\
\mathcal{M}_{7a}^{sub} &= e g_{\rho KK} ( -2 k_1 + k_3 )^\mu (k_1 - k_3 + k_4)^\nu \varepsilon_{3\mu} \varepsilon_{2\nu}, \\
\mathcal{M}_{7b}^{sub} &= -e g_{\rho KK} (2 k_1 + k_2)^\nu (k_1 + k_2 + k_4)^\mu \varepsilon_{3\mu} \varepsilon_{2\nu}, \\
\mathcal{M}_{7c}^{sub} &= 2 e g_{\rho KK} g^\mu \varepsilon_{3\mu} \varepsilon_{2\nu}.
\end{align*}
\]

As in our previous study of \( \Theta^+ \) production from photon-proton reactions with four-body (or three-body if not considering decays of the resonances in final state), we have introduced at the \( KN\Theta \) vertex another monopole form factor \( F((p_1 - p_3)^2) \) with cutoff parameter
\[ \Lambda = 0.5 \text{ GeV} \] and depending on the three momentum of \( K^- \) besides the overall monopole form factor \( F(q^2) \) with cutoff parameter \( \Lambda = 0.75 \text{ GeV} \). As in the case of three-body final states, the cross sections for these reactions can also be expressed in terms of those for their subprocesses, similar to that given in Eq.(11).

**D. results**

![Graph](attachment:graph.png)

**FIG. 4**: Cross sections for \( \Theta^+ \) production from photon-neutron reactions as functions of photon energy: total (solid curve), \( \gamma n \rightarrow K^- \Theta^+ \) (short dashed curve), \( \gamma n \rightarrow K^+ \Theta^- \) (long dashed curve), \( \gamma n \rightarrow \pi^0 K^+ (\pi^- \bar{K}^0) \Theta^+ \) (dotted curve), and \( \gamma n \rightarrow \rho^0 K^-(\rho^- \bar{K}^0) \Theta^+ \) (dash-dotted curve).

In Fig.4 we show the cross sections for \( \Theta^+ \) production from photon-neutron reactions as functions as photon energy. The reaction \( \gamma n \rightarrow K^- \Theta^+ \) (short dashed curve) with two-body final state has the largest cross section with a peak value of about 280 nb at \( E_\gamma \sim 2.2 \text{ GeV} \) with main contribution from the diagram involving \( t \)-channel \( K^- \) exchange. We note that this cross section is almost an order-of-magnitude larger than the corresponding reaction in photon-proton reactions, i.e., \( \gamma p \rightarrow \bar{K}^0 \Theta^+ \), due to the absence of a nucleon propagator. The reactions \( \gamma n \rightarrow \pi^0 K^0 \Theta^+ \) and \( \gamma n \rightarrow \pi^- \bar{K}^0 \Theta^+ \) with three-body final state, denoted combinedly as \( \gamma n \rightarrow K^* \Theta^+ \) (long dashed curve) in Fig.4 have values of about 50 nb above \( E_\gamma = 3 \text{ GeV} \). The contributions from reactions with four-body final state are smaller with
only a few nb for both $\gamma n \rightarrow \pi^0 K^*-(\pi^- K^0)\Theta^+$ (dotted curve), and $\gamma n \rightarrow \rho^0 K^-(\rho^- K^0)\Theta^+$ (dash-dotted curve). The total $\Theta^+$ production cross section from photon-neutron reactions is given by the solid curve.

III. DISCUSSIONS

The calculated cross sections are sensitive to the value of cutoff parameter used in form factors. If we increase the cutoff parameter in the overall form factor by a factor of 2, i.e., from $\Lambda = 0.75$ GeV, which is based on our previous study of charmed hadron production from photon-proton reactions \[16\], to $\Lambda = 1.5$ GeV, then all the cross sections evaluated here for photon energy near threshold will be increased by an order-of-magnitude.

\[\begin{align*}
\text{FIG. 5: Diagram for $\Theta^+$ production from photon-neutron reactions via $K^*$ exchange.}
\end{align*}\]

Also, if we allow the $\Theta^+$ to also couple to $NK^*$, then it can be produced from the reaction $\gamma n \rightarrow K^- \Theta^+$ via $K^{*-}$ exchange as shown by the diagram in Fig.5. In terms of the $K^* N \Theta$ interaction Lagrangian

\[L_{K^*N\Theta} = g_{K^*N\Theta}(\bar{N}\gamma_{\mu}\Theta \bar{K}^*_{\mu} + K^*_{\mu}\bar{\Theta}\gamma_{\mu}N),\]

the amplitude for this reaction is given by

\[M_{\gamma n \rightarrow K^- \Theta^+} = g_{\gamma K^- K^*} g_{K^* N \Theta} \frac{F(q^2)^2}{t - m_{K^*}^2} \epsilon_{\alpha \beta \mu \nu} P_2^\alpha P_2^\beta (p_3 - p_1)^\mu \Theta(p_3) \gamma^n n(p_1),\]

Its cross section can be written similarly as in Eq.(5).

The cross section for this reaction, using the same overall form factor with cutoff parameter $\Lambda = 0.75$ GeV as for other photon-neutron reactions with two-body final states, depends on the unknown coupling constant $g_{K^* N \Theta}$. If we take its value to be same as $g_{K N \Theta}$, i.e., $g_{K^* N \Theta} = 4.4$, then the cross section for the reaction $\gamma n \rightarrow K^- \Theta^+$ via $K^{*-}$ can reach
FIG. 6: Cross section for Θ⁺ production from photon-neutron reactions via $K^*$ exchange as functions of photon energy.

160 nb at $E_\gamma \geq 3$ GeV as shown in Fig. 6. We note that although the contribution from $K^{*-}$ exchange via the photon anomalous parity interaction to $\Theta^+$ production cross section is smaller than that due to $K^-$ exchange involving normal photon coupling in photon-neutron reactions, it is important in photon-proton reactions due to larger $g_{\gamma K^0 K^*0}$ coupling than $g_{\gamma K^- K^{*-}}$ coupling. The cross section due to this process in photon-proton reactions is more than 350 nb if $g_{K^* N \Theta} = 4.4$ is used [20], and this is comparable to that measured in the SAPHIR experiment at Bonn University’s ELSA accelerator.

IV. SUMMARY

The cross section for production of $\Theta^+$ baryon consisting of $uuud\bar{s}$ quarks from photon-neutron reactions is evaluated in a hadronic model that includes the $KN\Theta$ interaction with coupling constant determined from the decay width of $\Theta^+$. This model is based on a gauged SU(3) flavor symmetric Lagrangian with the photon introduced as a $U_{em}(1)$ gauged particle, which has been used previously in studying production of strange baryons and charmed hadrons, after extending to SU(4), in hadronic reactions. Symmetry breaking effects are taken into account by using empirical hadron masses and coupling constants. Form factors
of monopole type are introduced at interaction vertices to take into account finite hadron sizes, and values of the cutoff parameters are taken from fitting known cross sections of other reactions based on similar hadronic models. It has already been used to evaluate the cross sections for Θ\(^+\) production from meson-nucleon, proton-proton, and photon-proton reactions \([15]\). The model is used in the present study to evaluate the cross section for Θ\(^+\) production from photon-neutron reactions. Including also the anomalous parity coupling between photon and \(K^*K\), it is found that the dominant contribution is from the reaction \(\gamma n \rightarrow K^-\Theta^+\) with two-body final state, and its cross section reaches a value of 280 nb. The one with three-body final state has a value of about 50 nb, and those involving four-body final states have cross sections of only a few nb. The large Θ\(^+\) production cross section in the reaction \(\gamma n \rightarrow K^-\Theta^+\) than in the corresponding reaction \(\gamma p \rightarrow \bar{K}^0\Theta^+\) in photon-proton reactions, which has a peak value of only 40 nb \([15]\), is due to the coupling of photon to \(K^-\), which is absent in the photon-proton reactions.

We have also considered the process involving \(K^*\) exchange in the reaction \(\gamma n \rightarrow K^-\Theta^+\). Taking the unknown coupling constant \(g_{K^*N\Theta}\) to be the same as \(g_{KN\Theta}\), this process increases the cross section by about 50%. Because of the larger \(g_{\gamma K^0K}\) coupling, which appears in the reaction \(\gamma p \rightarrow \bar{K}^0\Theta^+\), than \(g_{\gamma K^-K^*}\) coupling, this process is more important in photon-proton reactions, and it may be responsible for the large cross section measured in the SAPHIR experiment.

Since cross sections for Θ\(^+\) production in hadronic reactions are proportional to the square of its coupling to \(KN\) as in its decay width to kaon and nucleon, it is then hard to understand the large cross section measured in the SAPHIR experiment if the width of Θ\(^+\) is less than 1 MeV as suggested in Ref.\([21]\) based on reanalysis of \(K^+n\) scattering data.

Acknowledgments

We thank Valeri Kubarovsky for communications. This paper was based on work supported in part by the US National Science Foundation under Grant No. PHY-0098805 and the Welch Foundation under Grant No. A-1358.

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