

Photoproduction and radiative decay of spin 1/2 and 3/2 pentaquarks

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We study photoproduction and radiative decays of pentaquarks paying particular attention to the differences between spin-1/2 and spin-3/2, positive and negative parities of pentaquarks. Detailed study of these processes can not only give crucial information about the spin, but also the parity of pentaquarks.

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I. INTRODUCTION

Recently several experiments have reported evidences of pentaquarks Θ and other states [1–3]. The first observed pentaquark state was the $\Theta(1540)$ with strangeness $S = +1$ and was identified as a state with quark content $udud\bar{s}$. This particle is an isosinglet and belongs to the antidecuplet multiplet in flavor $SU(3)_f$ symmetry [4]. Consequently NA49 has reported evidence of isoquartet $\Xi_{3/2}$ in the antidecuplet [2]. At present there is very limited information on the detailed properties such as the spin, the parity, and the magnetic dipole moment. Several other experiments have also carried out searches for these particles. Some of them reported positive and while others reported negative results [3]. One has to wait future experiments to decide whether these pentaquark states are real. On the theoretical front, there are also many studies trying to understand the properties of these possible pentaquark states.

In this paper we explore possibilities of studying the properties of pentaquark Θ and its partners in the $SU(3)$ antidecuplet multiplet, using radiative processes involving a pentaquark P , an ordinary baryon N and a pseudoscalar Π . We consider two classes of processes, the photoproduction $\gamma + N \rightarrow \Pi P$ and radiative decay $P \rightarrow N\Pi\gamma$.

In the above N and Π indicate a member in the ordinary baryon octet and pseudoscalar octet of $SU(3)_f$, respectively. They are given by

$$N = (N_i^j) = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}, \quad (1)$$

$$\Pi = (\Pi_i^j) = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta}{\sqrt{6}} \end{pmatrix}.$$

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P is a member of the antidecuplet ($\bar{10}$) pentaquark multiplet. This multiplet has ten members which can be described by a totally symmetric tensor P^{ijk} in $SU(3)$. The ten members are

$$\begin{aligned} P^{111} &= \Xi_{3/2}^{--}, & P^{112} &= \Xi_{3/2}^-/\sqrt{3}, \\ P^{122} &= \Xi_{3/2}^0/\sqrt{3}, & P^{222} &= \Xi_{3/2}^+, \\ P^{113} &= \Sigma_a^-/\sqrt{3}, & P^{123} &= \Sigma_a^0/\sqrt{6}, \\ P^{223} &= \Sigma_a^+/\sqrt{3}, & P^{133} &= N_a^0/\sqrt{3}, \\ P^{233} &= N_a^+/\sqrt{3}, & P^{333} &= \Theta^+. \end{aligned} \quad (2)$$

Without $SU(3)_f$ symmetry breaking, members in a $SU(3)_f$ multiplet all have the same mass. The degeneracy of mass is lifted by the light quark mass differences, m_u , m_d , and m_s . Using information on the masses of Θ and $\Xi_{3/2}$ including the leading $SU(3)_f$ breaking effects, the masses of the antidecuplet members are given by [5] $m_\Theta = 1542$ MeV, $m_{\Xi_{3/2}} = 1862$ MeV, $m_{\Sigma_a} = 1755$ MeV, and $m_{N_a} = 1648$ MeV.

Discussions for radiative processes involving a P , a N , a Π , and a γ with spin-1/2 pentaquarks have been carried out in several papers [5,6]. There are also some studies for spin-3/2 pentaquarks [7], but no detailed studies of radiative processes. In this work we will consider both spin-1/2 and spin-3/2 cases. We will first repeat the calculation in Ref. [5] for spin-1/2 photoproduction for the purpose of notation set up and also for easy comparison of our calculations for the spin-3/2 case. Our aims are to use these processes to extract information about properties of pentaquarks, such as parity, magnetic dipole moment, and also spin which can only be done by comparing data with calculations for different spins. Since the processes considered involve pseudoscalar goldstone bosons π and K , we will use chiral perturbation theory to carry out the analysis.

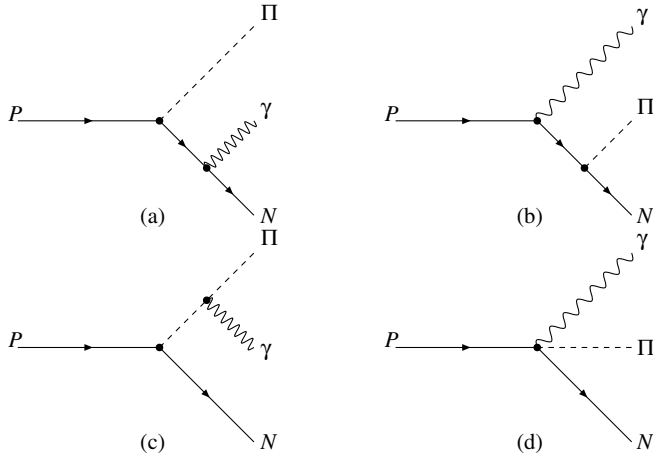


FIG. 1. Radiative processes involving a pentaquark, an octet baryon, and an octet meson.

II. THE MATRIX ELEMENTS FOR RADIATIVE PROCESSES

The leading order diagrams for the radiative processes involving a P , a N , a Π , and a γ are shown in Fig. 1. The electromagnetic coupling of a photon with Π and N are known. To evaluate these diagrams, we need to know the various couplings involving pentaquarks.

The spin-1/2 case

There are two types of electromagnetic couplings, the electric charge and magnetic dipole interactions. The leading chiral electric charge and magnetic dipole couplings are given by

$$\begin{aligned}
 L_e &= \bar{P}i\gamma^\mu D_\mu P \\
 &= \bar{P}_{ijk}i\gamma^\mu(\partial_\mu P^{ijk} - V_{\mu,l}^i P^{ljk} - V_{\mu,l}^j P^{ilk} \\
 &\quad - V_{\mu,l}^k P^{ijl}), \\
 L_m &= \frac{\mu_P}{4} \bar{P}_{ijk}\sigma^{\mu\nu}(f_{\mu\nu,l}^i P^{ljk} + f_{\mu\nu,l}^j P^{ilk} + f_{\mu\nu,l}^k P^{ijl}),
 \end{aligned} \tag{3}$$

TABLE I. P - N - Π couplings in unit $g_{PN\Pi}/\sqrt{2}f_\pi$. The couplings in the Table are understood to be in the form $-a_{PN\Pi}\bar{P}\Gamma_P\gamma^\mu N\partial_\mu\Pi$. The coefficient in front of $N\Pi$ in the second column is $-a_{PN\Pi}$.

Θ^+	$-nK^+ + pK^0$
N_a^0	$\frac{1}{6}(-3\sqrt{2}n\eta + 3\sqrt{2}\Lambda K^0 + \sqrt{6}\Sigma^0 K^0 - \sqrt{6}n\pi^0 + 2\sqrt{3}p\pi^- - 2\sqrt{3}\Sigma_a^- K^+)$
N_a^+	$\frac{1}{6}(3\sqrt{2}p\eta - 3\sqrt{2}\Lambda K^+ + \sqrt{6}\Sigma^0 K^+ - \sqrt{6}p\pi^0 - 2\sqrt{3}n\pi^+ + 2\sqrt{3}\Sigma^+ K^0)$
Σ_a^-	$\frac{1}{6}(2\sqrt{3}nK^- + 3\sqrt{2}\Lambda\pi^- + \sqrt{6}\Sigma^0\pi^- - 3\sqrt{2}\Sigma^-\eta - \sqrt{6}\Sigma^-\pi^0 - 2\sqrt{3}\Xi^- K^0)$
Σ_a^0	$\frac{1}{6}(\sqrt{6}n\bar{K}^0 - \sqrt{6}pK^- - 3\sqrt{2}\Lambda\pi^0 + 3\sqrt{2}\Sigma^0\eta - \sqrt{6}\Sigma^-\pi^+ + \sqrt{6}\Sigma^+\pi^- - \sqrt{6}\Xi^0 K^0 + \sqrt{6}\Xi^- K^+)$
Σ_a^+	$\frac{1}{6}(-2\sqrt{3}p\bar{K}^0 - 3\sqrt{2}\Lambda\pi^+ + \sqrt{6}\Sigma^0\pi^+ + 3\sqrt{2}\Sigma^+\eta - \sqrt{6}\Sigma^+\pi^0 + 2\sqrt{3}\Xi^0 K^+)$
$\Pi_{3/2}^-$	$\Sigma^- K^- - \Xi^- \pi^-$
$\Pi_{3/2}^0$	$\frac{1}{6}(-2\sqrt{6}\Sigma^0 K^- + 2\sqrt{3}\Sigma^- \bar{K}^0 - 2\sqrt{3}\Xi^0\pi^- + 2\sqrt{6}\Xi^- \pi^0)$
$\Pi_{3/2}^+$	$\frac{1}{6}(-2\sqrt{6}\Sigma^0 \bar{K}^0 - 2\sqrt{3}\Sigma^+ K^- + 2\sqrt{3}\Xi^0\pi^0 + 2\sqrt{6}\Xi^- \pi^+)$
$\Pi_{3/2}^+$	$-\Sigma^+ \bar{K}^0 + \Xi^0 \pi^+$

where $V_\mu = (1/2)(\xi^\dagger\partial_\mu\xi + \xi\partial_\mu\xi^\dagger) + i(e/2)A_\mu(\xi^\dagger Q\xi + \xi Q\xi^\dagger)$. Here $\xi = \exp[i\Pi/\sqrt{2}f_\pi]$ and $Q = \text{Diag}(2/3, -1/3, -1/3)$ is the quark charge matrix and A_μ is the photon field. $f_{\mu\nu,i}^j = F_{\mu\nu}(\xi^\dagger Q\xi + \xi Q\xi^\dagger)_i^j$ with $F_{\mu\nu}$ being the photon field strength. Expanding to the leading order, we have for each individual pentaquark

$$\begin{aligned}
 L_e &= -eQ_i\bar{P}_i\gamma^\mu A_\mu P_i, \\
 L_m &= -\frac{e\mu_P Q_i}{2} \bar{P}_i\sigma^{\mu\nu} F_{\mu\nu} P_i.
 \end{aligned} \tag{4}$$

We note that for neutral pentaquarks, to the leading order the anomalous dipole moments are zero. The kappa parameter $\kappa_P = 2m_P\mu_P$ has been estimated to be of order 1 [8]. In our analysis we will treat it as a free parameter to see if experimental data can provide some information.

We also need to know the strong interaction coupling of a pentaquark with an ordinary baryon and a pseudoscalar. It can be parametrized as

$$L_{PN\Pi} = g_{PN\Pi}\bar{P}_{ilm}\Gamma_P\gamma^\mu(\tilde{A}_\mu)_j^i N_k^m \epsilon^{ijk} + \text{H.C.} \tag{5}$$

In the above, Γ_P takes “+1” and “ γ_5 ” if P has negative and positive parities, respectively. $\tilde{A}_\mu = (i/2) \times (\xi^\dagger\partial_\mu\xi - \xi\partial_\mu\xi^\dagger) - (e/2)A_\mu(\xi^\dagger Q\xi - \xi Q\xi^\dagger)$.

Expanding the above effective Lagrangian to the leading order we obtain P - N - Π type of couplings. The results are given in Table I.

The contact γ - P - N - Π coupling in Fig. 1(d) is obtained from a term $ieg_{PN\Pi}A_\mu\bar{P}_{ilm}\Gamma_P\gamma^\mu[\Pi, Q]_j^i N_k^m \epsilon^{ijk}$ obtained by expanding $L_{PN\Pi}$.

In the following we display the matrix element for $P \rightarrow N\Pi\gamma$. The matrix element for $\gamma N \rightarrow P\Pi$ can be obtained by making appropriate changes of signs for the relevant particle momenta. We have

$$\begin{aligned}
M(P \rightarrow N\Pi\gamma) = & \frac{e g_{PN\Pi}}{\sqrt{2}f} a_{PN\Pi} \epsilon_{\mu}^* \bar{N} \left[Q_{\Pi} \Gamma_P \gamma^{\mu} - \left(Q_N \gamma^{\mu} + \frac{\mu_N}{2} [\gamma^{\mu}, \gamma \cdot P_{\gamma}] \right) \frac{1}{\gamma \cdot P_{\gamma} + \gamma \cdot P_N - m_N} \Gamma_P \gamma \cdot P_{\pi} \right. \\
& - \Gamma_P \gamma \cdot P_{\Pi} \frac{1}{\gamma \cdot P_N + \gamma \cdot P_{\Pi} - m_P} (Q_P \gamma^{\mu} + \frac{\mu_P}{2} [\gamma^{\mu}, \gamma \cdot P_{\gamma}]) - Q_{\Pi} \frac{(2P_{\Pi} + P_{\gamma})^{\mu}}{(P_{\Pi} + P_{\gamma})^2 - m_{\Pi}^2} \\
& \left. \times \Gamma_P (\gamma \cdot P_{\Pi} + \gamma \cdot P_{\gamma}) \right] P. \quad (6)
\end{aligned}$$

For $\Theta^+ \rightarrow nK^+ \gamma$, $a_{PN\Pi} = a_{\Theta nK} = 1$, $Q_P = Q_{\Theta} = 1$, $Q_N = Q_n = 0$, $Q_{\Pi} = Q_{K^+} = 1$. For $\Theta^+ \rightarrow pK^0 \gamma$, $a_{PN\Pi} = a_{\Theta pK} = -1$, $Q_N = Q_p = 1$, and $Q_{K^0} = 0$. For $\Xi_{3/2}^- \rightarrow \Sigma^- K^- \gamma$, $a_{PN\Pi} = a_{\Xi_{3/2}^- \Sigma^- K^-} = -1$, $Q_P = Q_{\Xi_{3/2}^-} = -2$, $Q_N = Q_{\Sigma^-} = -1$, $Q_{\Pi} = Q_{K^-} = -1$. And for $\Xi_{3/2}^- \rightarrow \Xi^- \pi^- \gamma$, $a_{PN\Pi} = a_{\Xi_{3/2}^- \Xi^- \pi^-} = 1$, $Q_P = Q_{\Xi_{3/2}^-} = -2$, $Q_N = Q_{\Xi^-} = -1$, $Q_{\Pi} = Q_{\pi^-} = -1$.

The parameter $g_{PN\Pi}$ can be determined from when a pentaquark P decays into a baryon and a meson. For example

$$\frac{g_{PN\Pi}^2}{2f_{\pi}^2} = \frac{\Gamma(\Theta^+ \rightarrow nK^+) 16\pi m_{\Theta}}{(m_n + \hat{P}m_{\Theta})^2 ((m_n - \hat{P}m_{\Theta})^2 - m_K^2) \text{Phase}}, \quad (7)$$

$$\text{Phase} = \sqrt{(1 - (m_K + m_n)^2/m_{\Theta}^2)(1 - (m_K - m_n)^2/m_{\Theta}^2)}.$$

In the above “ \hat{P} ” is the eigenvalue of the parity, it takes “+” for positive parity and “-” for negative parity pentaquark, respectively.

From Table I we see that Θ^+ only has two strong decay channels, pK^0 and nK^+ . The total width of Θ^+ is therefore $\Gamma_{\Theta} = \Gamma(\Theta^+ \rightarrow pK^0) + \Gamma(\Theta^+ \rightarrow nK^+)$. If the Γ_{Θ} is determined, one can determine $g_{PN\pi}^2$ from Eq. (7).

B. The spin-3/2 case

In this case one needs to use the Rarita-Schwinger field for pentaquarks P_{ilm}^{μ} . The electromagnetic couplings needed are modified compared with spin-1/2 particles,

$$\begin{aligned}
M(P \rightarrow N\Pi\gamma) = & \frac{e g_{PN\Pi}}{\sqrt{2}f} a_{PN\Pi} \epsilon_{\mu}^* \bar{N} \left[Q_{\Pi} \gamma_5 \Gamma_P g^{\mu\nu} - \left(Q_N \gamma^{\mu} + \frac{\mu_N}{2} [\gamma^{\mu}, \gamma \cdot P_{\gamma}] \right) \frac{1}{\gamma \cdot P_{\gamma} + \gamma \cdot P_N - m_N} \gamma_5 \Gamma_P P_{\nu}^{\mu} \right. \\
& \left. + \gamma_5 \Gamma_P P_{\Pi}^{\alpha} G_{\alpha}^{\nu} \left(Q_P \gamma^{\mu} + \frac{\mu_P}{2} [\gamma^{\mu}, \gamma \cdot P_{\gamma}] \right) - Q_{\Pi} \frac{(2P_{\Pi} + P_{\gamma})^{\mu}}{(P_{\Pi} + P_{\gamma})^2 - m_{\Pi}^2} \gamma_5 \Gamma_P (P_{\Pi} + P_{\gamma})^{\nu} \right] P_{\nu}. \quad (12)
\end{aligned}$$

In the above $G^{\mu\nu}$ is the spin-3/2 propagator resulting from the following most general Lagrangian [10]

$$\begin{aligned}
L = & \bar{P}_{\mu} \Lambda^{\mu\nu} P_{\nu}, \\
\Lambda^{\mu\nu} = & (\gamma \cdot P_P - m_P) g^{\mu\nu} + A(\gamma^{\mu} P_P^{\nu} + P_P^{\mu} \gamma^{\nu}) \\
& + \frac{1}{2}(3A^2 + 2A + 1) \gamma^{\mu} \gamma \cdot P_P \gamma^{\nu} \\
& + m_P(3A^2 + 3A + 1) \gamma^{\mu} \gamma^{\nu}. \quad (13)
\end{aligned}$$

and they are given by

$$\begin{aligned}
L_e = & \bar{P}^{\alpha} i \gamma^{\mu} D_{\mu} P_{\alpha} \\
= & \bar{P}^{\alpha} i \gamma^{\mu} (\partial_{\mu} P_{\alpha}^{ijk} - V_{\mu,l}^i P_{\alpha}^{ljk} - V_{\mu,l}^j P_{\alpha}^{ilk} \\
& - V_{\mu,l}^k P_{\alpha}^{ijl}), \\
L_m = & \frac{\mu_P}{4} \bar{P}_{ijk}^{\alpha} \sigma^{\mu\nu} (f_{\mu\nu,l}^i P_{\alpha}^{ljk} + f_{\mu\nu,l}^j P_{\alpha}^{ilk} + f_{\mu\nu,l}^k P_{\alpha}^{ijl}). \quad (8)
\end{aligned}$$

Since a spin-3/2 particle can have dipole and quadrupole moments, if both are not zero, one should add another term to the electromagnetic couplings,

$$L_q = \tau_P \bar{P}_{\nu} F^{\mu\nu} P_{\mu}, \quad (9)$$

We will take it to be zero in our later discussions.

The chiral Lagrangian for strong coupling involving a pentaquark, a baryon, and a pseudoscalar is given by

$$L_{PN\Pi} = g_{PN\Pi} \bar{P}_{ilm}^{\mu} \gamma_5 \Gamma_P (A_{\mu})_j^l N_k^m \epsilon^{ijk} + H.C. \quad (10)$$

From the above we have

$$\begin{aligned}
\Gamma(P \rightarrow N\Pi) = & \frac{g_{PN\Pi}^2}{2f^2} \frac{\text{Phase}}{16\pi m_P} \frac{1}{3} ((\hat{P}m_P + m_N)^2 - m_{\Pi}^2) \\
& \times \left(\frac{1}{4m_P^2} (m_P^2 + m_{\Pi}^2 - m_N^2)^2 - m_{\Pi}^2 \right). \quad (11)
\end{aligned}$$

Combining the above information we obtain the matrix element for $P \rightarrow N\Pi\gamma$

The propagator is given by [10]

$$\begin{aligned}
G^{\mu\nu} = & \frac{1}{\gamma \cdot P_P - m_P} \left(-g^{\mu\nu} + \frac{1}{3} \gamma^{\mu} \gamma^{\nu} \right. \\
& \left. + \frac{1}{3m_P} (\gamma^{\mu} P_P^{\nu} - P_P^{\mu} \gamma^{\nu}) + \frac{2}{3m_P^2} P_P^{\mu} P_P^{\nu} \right) \\
& - \frac{1}{3m_P^2} \frac{A+1}{(2A+1)^2} \left((2A+1) (\gamma^{\mu} P_P^{\nu} + P_P^{\mu} \gamma^{\nu}) \right. \\
& \left. - \frac{A+1}{2} \gamma^{\mu} (\gamma \cdot P_P + 2m_P) \gamma^{\nu} + m \gamma^{\mu} \gamma^{\nu} \right). \quad (14)
\end{aligned}$$

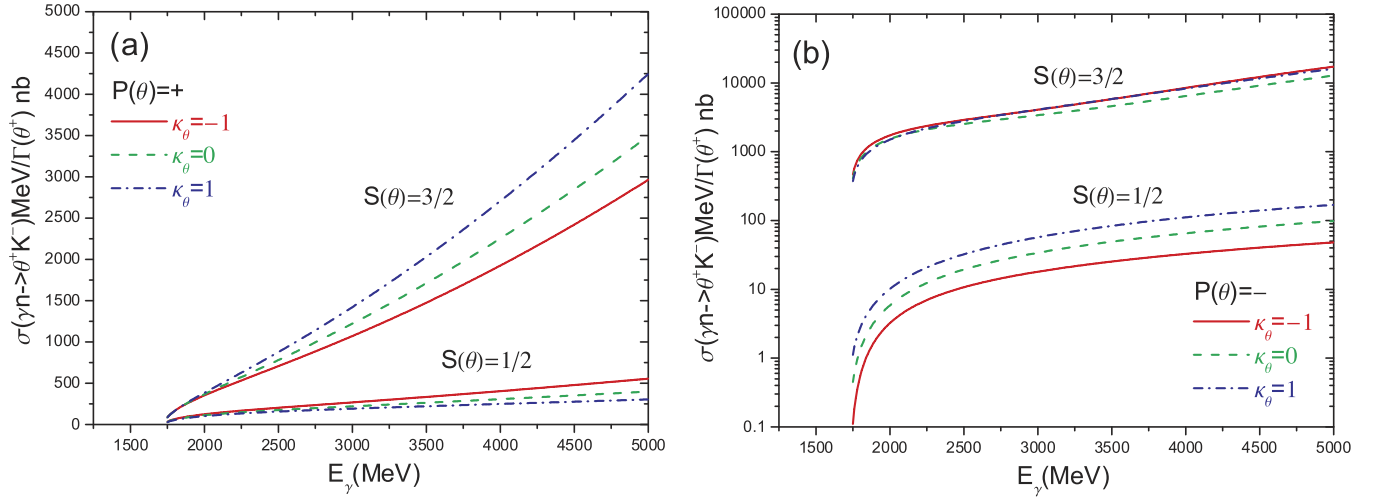


FIG. 2 (color online). Cross sections for $\gamma n \rightarrow \Theta^+ K^-$ in the laboratory frame with spin 1/2 and 3/2. Figures a and b are for positive and negative parities, respectively.

To include interaction with the photon, one uses the minimal substitution which guarantees gauge invariance to obtain the couplings. The lowest order interaction vertex $Q_P \bar{P}_\alpha \Gamma_\mu^{\alpha\beta} P_\beta$, which is different than spin-1/2 interaction vertex $Q_P \bar{P} \gamma_\mu P$. $\Gamma_\mu^{\alpha\beta}$, is given by

$$\gamma^\mu g_{\alpha\beta} + A(\gamma_\alpha g_\beta^\mu + g_\alpha^\mu \gamma_\beta) + \frac{1}{2}(3A^2 + 2A + 1)\gamma^\alpha \gamma_\mu \gamma^\beta. \quad (15)$$

The final result is A independent. In Eq. (12) we have chosen a particular case of $A = 0$ for simplicity. Therefore, one should also use G_α^ν with $A = 0$ in Eq. (14).

III. NUMERICAL RESULTS

In our numerical studies, we will concentrate on processes involving pentaquarks with exotic quantum numbers, the Θ and $\Xi_{3/2}^-$. Processes involving other pentaquarks can be similarly carried out. We now display our numerical results for both spin-1/2 and spin-3/2, and different parities cases. For the pentaquark masses, we use $m_\Theta = 1542$ MeV and $m_{\Xi_{3/2}^-} = 1862$ MeV. We will treat the magnetic dipole moments as free parameters and let $\kappa_P = 2m_P \mu_P$ vary between -1 to 1 . The parameter $g_{P\Pi}$ is determined by the decay width of the pentaquark. In our calculations we will express it as a function of Γ_θ .

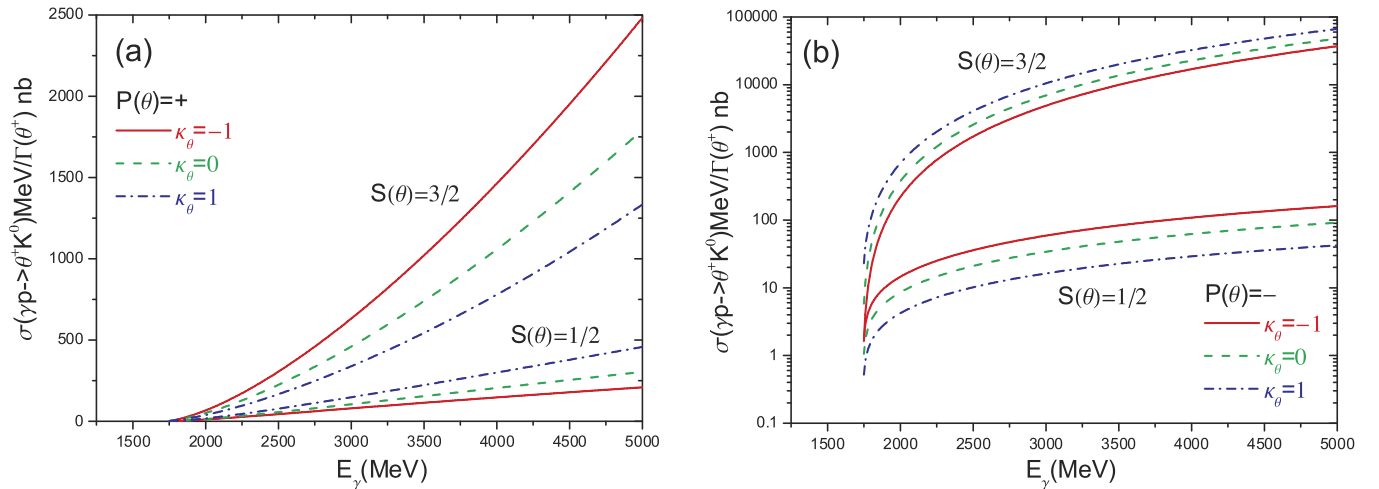


FIG. 3 (color online). Cross sections for $\gamma p \rightarrow \Theta^+ \bar{K}^0$ in the laboratory frame with spin-1/2 and spin-3/2. Figures a and b are for positive and negative parities, respectively.

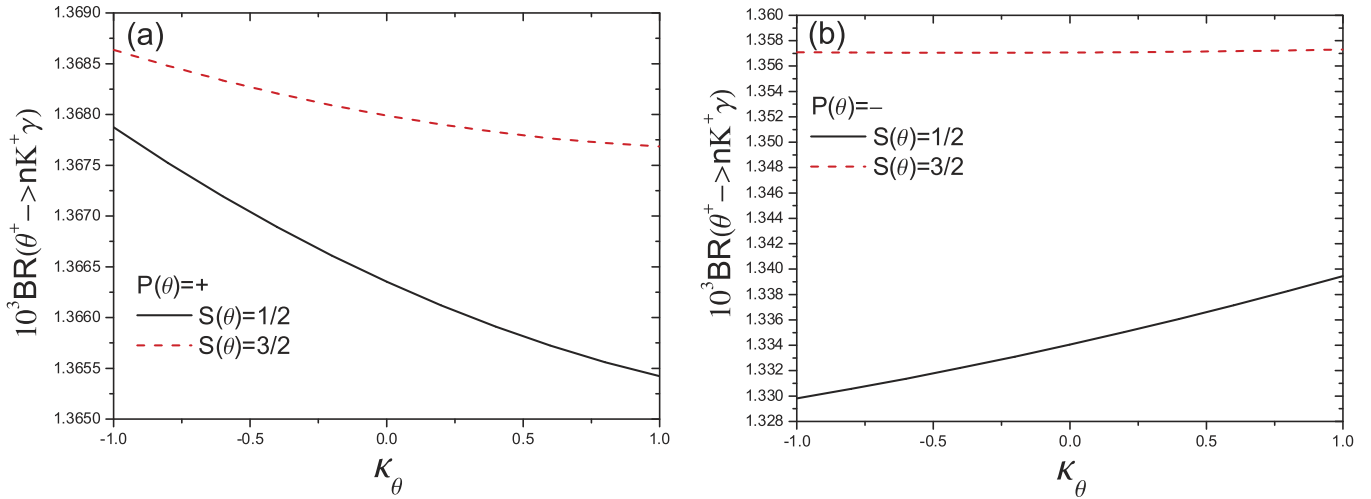


FIG. 4 (color online). Radiative $\Theta^+ \rightarrow \gamma n K^+$ decay for spin-1/2 and spin-3/2. Figures a and b are for positive and negative parities, respectively.

A. Photoproduction

Photoproduction of pentaquarks can provide useful information about the pentaquark properties [6]. An easy way of photoproduction of pentaquarks is through a photon beam colliding with a fixed target containing protons and neutrons. In this case, only production of Θ is possible via $\gamma n \rightarrow \Theta^+ K^-$, and $\gamma p \rightarrow \Theta^+ \bar{K}^0$. The results for the cross sections in the laboratory frame (fixed n and p) as functions of photon energies for both spin-1/2 and spin-3/2 are shown in Figs. 2 and 3.

From Figs. 2 and 3, it can be seen that for the spin-1/2 case, the cross section for $\gamma n \rightarrow \Theta^+ K^-$ with positive

parity has a larger cross section than the negative parity case. For example for $\kappa_\Theta = 0$ and $E_\gamma = 2.4$ GeV, the cross sections for these two cases are $155\Gamma(\Theta^+) \text{ nb} \cdot \text{MeV}^{-1}$ and $17\Gamma(\Theta^+) \text{ nb} \cdot \text{MeV}^{-1}$, respectively. The cross section for $\gamma p \rightarrow \Theta^+ K^0$ with positive parity has a larger cross section than the negative parity case, the cross sections for these two cases are $47\Gamma(\Theta^+) \text{ nb} \cdot \text{MeV}^{-1}$ and $18\Gamma(\Theta^+) \text{ nb} \cdot \text{MeV}^{-1}$, respectively.

For spin-3/2, the negative parity case has a larger cross section compared with the positive parity case. For example with $\kappa_\Theta = 0$ and $E_\gamma = 2.4$ GeV, the cross sections for $\gamma n \rightarrow \Theta^+ K^-$ are $2350\Gamma(\Theta^+) \text{ nb} \cdot \text{MeV}^{-1}$ and

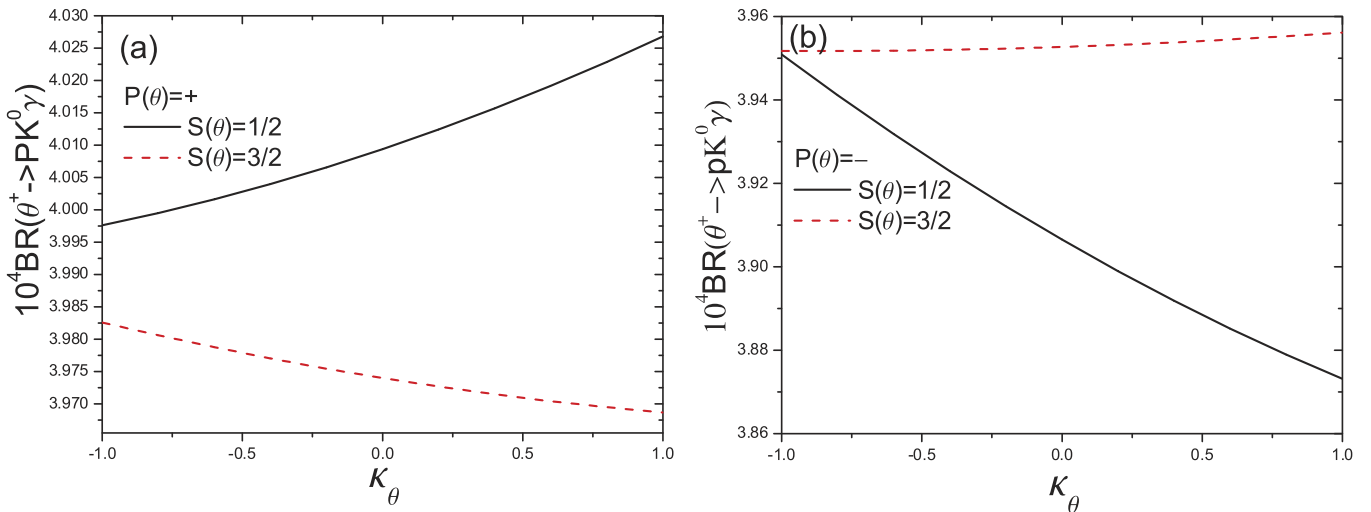


FIG. 5 (color online). Radiative $\Theta^+ \rightarrow \gamma p \bar{K}^0$ decay for spin-1/2 and spin-3/2. Figures a and b are for positive and negative parities, respectively.

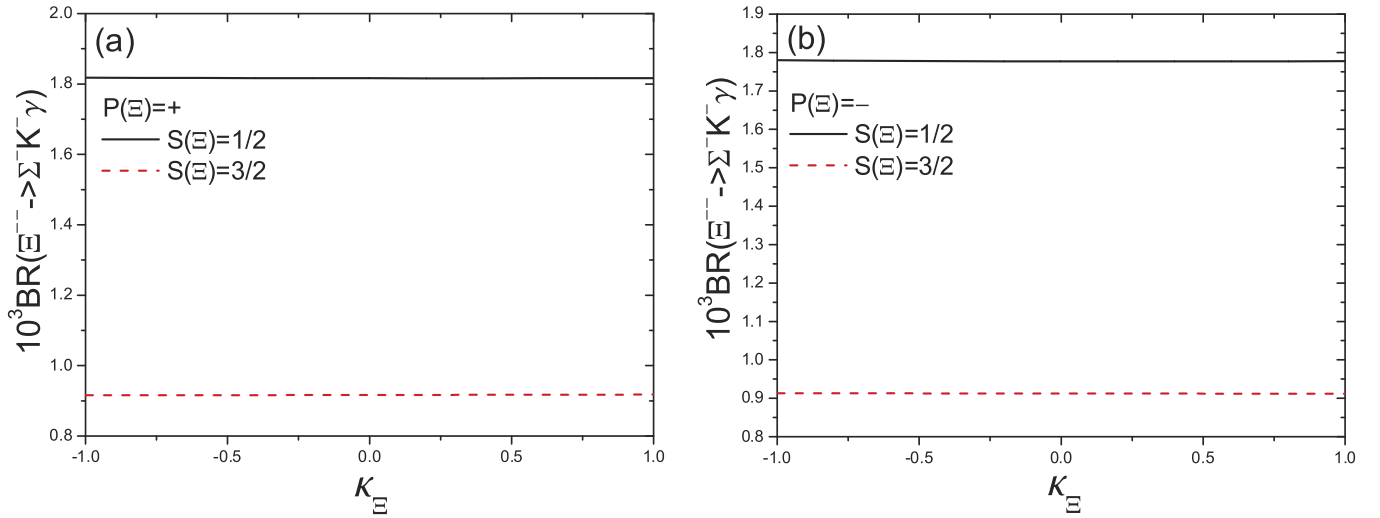


FIG. 6 (color online). Radiative $\Xi_{3/2}^- \rightarrow \gamma \Sigma^- K^-$ decay for spin-1/2 and spin-3/2. Figures a and b are for positive and negative parities, respectively.

$691\Gamma(\Theta^+) \text{ nb} \cdot \text{MeV}^{-1}$ for negative parity and positive parity. The cross sections for $\gamma p \rightarrow \Theta^+ K^0$ are $1953\Gamma(\Theta^+) \text{ nb} \cdot \text{MeV}^{-1}$ and $184\Gamma(\Theta^+) \text{ nb} \cdot \text{MeV}^{-1}$ respectively.

One can clearly see from Figs. 2 and 3 that regardless of the parity, the spin-3/2 pentaquark has cross section larger than the spin-1/2. This can provide important information about the spin. The separation between the cross sections with positive and negative parities is large which can be used to obtain information about the parity of the pentaquark too.

The cross sections also depend on magnetic dipole moment of pentaquarks. From the figures we see that the

changes in the cross section can vary several times when κ changes from -1 to 1 .

The case for Θ with spin-1/2 has been discussed in Refs. [5,6]. Our approach is the same as that used in Ref. [5] and we agree with their results which are shown in Fig. 2. Our approach is dramatically different than that used in Ref. [6]. This leads to the different behavior of photon energy E_γ dependence. Each method has limitations. In our calculations since chiral Lagrangian is used which is believed to provide reliable results only for low energy pseudoscalars (not larger than a few hundred MeV), one should not extrapolate the photon energy to too large a value. The cut is, however, not clear. If one requires that the

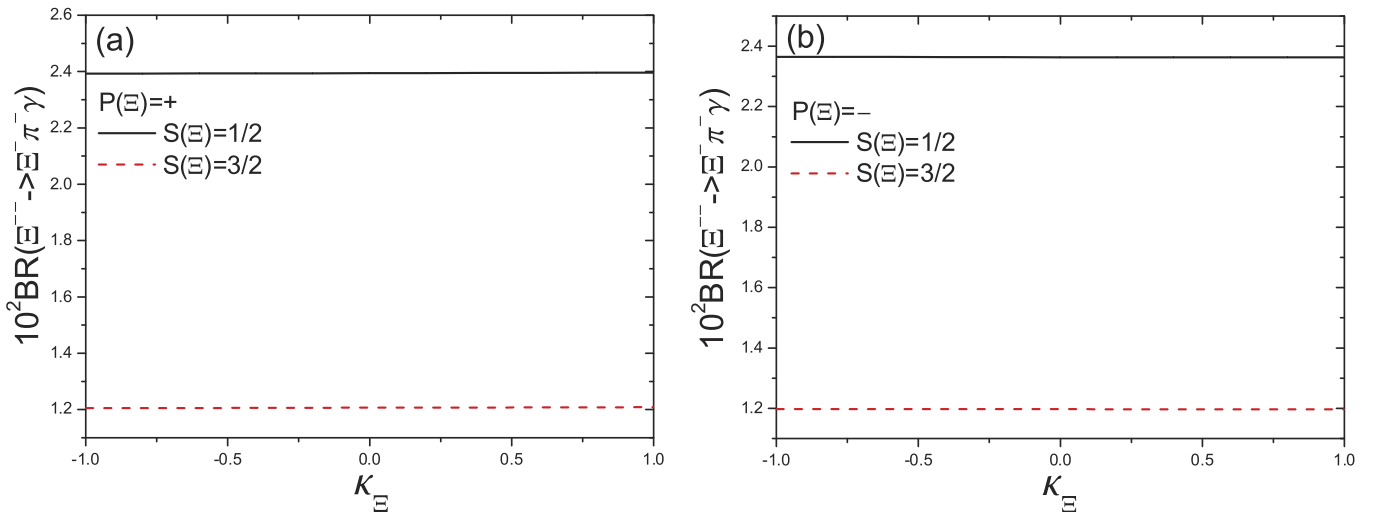


FIG. 7 (color online). Radiative $\Xi_{3/2}^- \rightarrow \gamma \Xi^- \pi^-$ decay for spin-1/2 and spin-3/2. Figures a and b are for positive and negative parities, respectively.

kaon energy to be less than a GeV or so in the center of mass frame for $\gamma N \rightarrow \Theta^+ K$, the photon energy should not exceed about 3.5 GeV in the laboratory frame. In the low energy ranges, one should use experimental data to decide which method better represents the underlying theory for photoproduction of pentaquarks. We note that in radiative decays of the pentaquark to be discussed in the following, the energies for the pseudoscalars are all low. The applicability of the chiral Lagrangian is in a better situation. In our estimate we have neglected other possible intermediate states, such as K^* which can change the cross section. But model calculations show that the K^* contribution does not change the general features [6]. We expect that the results obtained here provide a reasonable estimate.

B. Radiative Decays

Once pentaquarks are produced, they can decay radiatively through $\Theta^+ \rightarrow \gamma K^+ n$, $\Theta^+ \rightarrow \gamma K^0 p$, and $\Xi_{3/2}^{--} \rightarrow \gamma K^- \Sigma^-$, $\Xi_{3/2}^{--} \rightarrow \gamma \pi^- \Xi^-$, respectively.

It is well known that there are divergencies when photon energies approach zero in radiative decays of the types discussed here. To remedy these divergencies, we require that the photon energies be larger than 0.05 MeV. The results for radiative Θ decays are shown in Figs. 4 and 5. The results for radiative $\Xi_{3/2}^{--}$ decays are shown in Figs. 6 and 7.

For Θ^+ radiative decays, the branching ratios for spin-1/2 and spin-3/2 cases are approximately 1.3×10^{-3} and 4×10^{-4} for $\Theta^+ \rightarrow \gamma n K^+$ and $\Theta^+ \rightarrow \gamma p K^0$, respectively. These can be used to check the consistency of the model. However, the branching ratios for these decays are not sensitive to the spin, parity, or anomalous magnetic dipole moment of the pentaquarks.

The situation changes when we consider radiative decays of Ξ^{--} . From Figs. 6 and 7, one can see that the branching ratios for spin-1/2 cases are about 2 times larger than the branching ratios for spin-3/2 cases. It is also interesting to note that the branching ratio for $\Xi^{--} \rightarrow \gamma \Xi^- \pi^-$ is at the level of a few percent which may be easily studied experimentally.

In conclusion we have studied several radiative processes of pentaquarks using chiral perturbation theory. We find that the photoproduction cross sections of Θ^+ are sensitive to the spin, parity, and anomalous magnetic dipole moment of the pentaquark. Radiative decays of Θ^+ can also provide a consistent check of the theory, although these decays are not very sensitive to the spin, parity, or anomalous magnetic dipole moment. Radiative decays of Ξ^{--} are sensitive to the spin of the pentaquark. Near future experiments on pentaquark radiative processes can provide important information about pentaquark properties.

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