Photo-production of the pentaquark $\Theta^+$ with positive and negative parities

Seung-Il Nam,1,2*, Atsushi Hosaka,1† and Hyun-Chul Kim2‡

1Research Center for Nuclear Physics (RCNP), Ibaraki, Osaka 567-0047, Japan
2Department of Physics and Nuclear physics & Radiation technology Institute (NuRI), Pusan National University, Busan 609-735, Korea

(Dated: February 16, 2004)

Abstract
We investigate the production of the pentaquark $\Theta^+$ baryon via the $\gamma n \rightarrow K^- \Theta^+$ and $\gamma p \rightarrow \bar{K}^0 \Theta^+$ processes, focusing on the parity of the $\Theta^+$. Using the effective Lagrangians, we calculate the total and differential cross sections with the spin of the $\Theta^+$ presumed to be 1/2. We employ the coupling constant of the $KN\Theta$ vertex determined by assuming its mass and the decay width to be 1540 MeV and 15 MeV. That of the $K^*N\Theta$ is taken to be about a half of the $KN\Theta$ coupling constant. We estimate the cutoff parameter by reproducing the total cross section of the $\gamma p \rightarrow K^+\Lambda$ reaction. It turns out that the total cross section for the $\gamma n \rightarrow K^-\Theta^+$ process is about four times larger than that of the $\gamma p \rightarrow \bar{K}^0\Theta^+$. We also find that the cross sections for the production of the positive-parity $\Theta$ are about ten times as large as those for the negative-parity ones.

PACS numbers: 13.60.Le, 13.75.Jz, 13.85.Fb
Keywords: Pentaquark baryon, Photo-production of the $\Theta^+$, Parity of the $\Theta^+$

*Electronic address: sinam@rcnp.osaka-u.ac.jp
†Electronic address: hosaka@rcnp.osaka-u.ac.jp
‡Electronic address: hchkim@pusan.ac.kr
I. INTRODUCTION

Since the discovery of the pentaquark $\Theta^+$ baryon by the LEPS collaboration \[1\], motivated by the theoretical work by Diakonov et al. \[2\], the physics of the pentaquark states has become a very hot issue in hadron physics. The subsequent experiments confirmed the existence of the $\Theta^+$ \[3,4,5,6,7\]. Its mass is around 1530 MeV with still about 20 MeV uncertainty, whereas only the upper bound is established for its width ($<25$ MeV). However, considering the fact that the DIANA collaboration has reported that its decay could be remarkably narrow ($<9$ MeV) \[3\], where the experimental energy resolution was significantly smaller than this number \[8\], the narrowness of the width is likely a characteristic of the pentaquark $\Theta^+$. The NA49 collaboration \[9\] has announced another exotic pentaquark baryon $\Xi_{3/2}$, the width of which is also very narrow. Praszalowicz \[10\] has pointed out that the smallness of the width can be explained in the large $N_c$ limit with SU(3) symmetry breaking. Karliner and Lipkin suggested an explanation based on a model with two diquarks and one antiquark \[11\].

It is also of great importance to determine the quantum numbers of the $\Theta^+$. Since the $\Theta^+$ decays into a neutron and a $K^+$, its strangeness is determined to be $S=+1$. Its isospin $T=0$ has been inferred from the SAPHIR \[6\] and HERMES collaborations \[7\] which have found no signal of the $\Theta^{++}$. On the other hand, the spin and parity of the $\Theta^+$ are still not known to date experimentally, which brought about a great deal of theoretical works to focus on determining its parity. However, there has been no agreement on its parity at all. While the chiral soliton model \[2\] prefers the positive parity, QCD sum rules \[12,13\] predict its parity to be negative. The lattice QCD \[14,15\] also supports the negative parity. In the chiral constituent quark model \[16,17\] with the spin-flavor interaction and in the chiral bag model \[18\], the positive-parity state turns out to be more stable than the negative-parity one due to the interaction inspired by chiral symmetry. However, Huang \textit{et al.} \[19\] argue that if $u$ (or $d$) - $\bar{s}$ interaction is considered, the negative-parity state produces the $\Theta^+$ mass closer to the experimental value.

A great amount of investigation on the production of the pentaquark baryons via various processes has been already performed. Its hadron-induced production also has been investigated in Refs. \[20,21,22,23\]. In particular, Refs. \[23,24\] have scrutinized the parity of the $\Theta^+$ in its production via the $NN$ interaction, motivated by a series of recent works \[25,26\]. It was found that the cross sections for the production of the positive-parity $\Theta^+$ are approximately ten times larger than those for the negative-parity ones. The photo-production of the $\Theta^+$ has been also studied in the Born approximation \[22,27,28,29,30,31,32,33\].

In the present work, we would like to extend our former study of the $\gamma n \rightarrow K^- \Theta^+$ and $\gamma p \rightarrow K^0 \Theta^+$ reactions \[28\]. We attempt to provide physical interpretation for the obtained results whenever possible and extract items which we can discuss in a model-independent manner. In the present work we investigate rather carefully the role of the vector meson $K^+(892)$ which was not included in the previous work \[28\]. Since the vector meson $K^*$ plays an important role in the $\gamma p \rightarrow K^0 \Lambda$, it is expected to be so also for the $\Theta^+$ production. While the coupling constants of $K$ exchange can be determined by using the width and mass of the $\Theta^+$, we do not have any information of that of $K^*$ exchange. Hence, we will follow Ref. \[27\] in which the value of the coupling constant for the $K^*N\Theta$ vertex is chosen to be about a half of that for the $KN\Theta$, reasoning that the empirical value of the $K \Lambda$ ($K \Sigma$) is approximately twice as large as that of the $K^*N\Lambda$ ($K^*N\Sigma$). In order to calculate the cross sections of the $\Theta^+$ photo-production, its magnetic moment also has to be considered. Due to the lack of
experimental information on the electro-magnetic structure of the pentaquark states, one has to rely on model calculations to determine its magnetic moment. The magnetic moment of the $\Theta^+$ has been already estimated in various models [28, 29, 31, 34, 35]. Its value varies in the range $0.1 \sim 0.3 \mu_N$, where $\mu_N$ is the nuclear magneton. Thus, we will use in this work the anomalous magnetic moment $\kappa_\Theta = -0.8$.

In order to take into account the extended size of hadrons, it is essential to introduce a form factor at each vertex. However, its presence violates the gauge invariance of the electromagnetic interaction. It is due to the fact that the form factors bring about the non-locality in the interaction [36]. Hence, we need to restore the gauge invariance. While there is no theoretical firm ground to remedy this gauge-invariance problem caused by form factors, various Refs. [36, 37, 38] put forward several prescriptions for the form factors to restore the gauge invariance. In this work, we closely follow the methods suggested by Ref. [38]. In addition, we estimate the cutoff parameters by reproducing the total cross sections for the photo-production of the $\Lambda$.

This paper is organized as follows: In Section II, we will describe a method to calculate the Feynman invariant amplitude for the processes $\gamma n \rightarrow \Theta^+ K^-$ and $\gamma p \rightarrow K^0 \Theta^+$. We will also discuss the gauge-invariant form factor and two different schemes of the pseudovector (PV) and pseudoscalar (PS) couplings. In the subsequent section, we will present the numerical results for the total and differential cross sections for the two different parities of the $\Theta^+$ and will discuss them in comparison with other models. In Section IV we will summarize the results and draw a conclusion.

II. GENERAL FORMALISM

Relevant diagrams for the photo-production of the $\Theta^+$ are drawn in Fig. 1. Concerning the $KN\Theta$ vertex, we utilize two different interactions, i.e., the pseudoscalar (PS) and pseudovector (PV) schemes. The effective Lagrangians for the reactions are given as follows:

$$\mathcal{L}_{N\Theta K} = ig\overline{\Theta}\Gamma_5 KN + (\text{h.c.}),$$
$$\mathcal{L}_{N\Theta K} = -\frac{g_A^*}{f_\pi}\overline{\Theta}\mu_5 \partial_\mu KN + (\text{h.c.}),$$
$$\mathcal{L}_{\gamma KK} = ie\left\{K(\partial^\mu K) - (\partial^\mu K)K\right\} A_\mu + (\text{h.c.}),$$
$$\mathcal{L}_{\gamma NN} = -eN\left(\gamma_\mu + i\frac{\kappa N}{2M_N}\sigma_{\mu\nu}k^\nu\right) N A_\mu + (\text{h.c.}),$$
$$\mathcal{L}_{\gamma \Theta} = -e\overline{\Theta}\left(\gamma_\mu + i\frac{\kappa_\Theta}{2M_\Theta}\sigma_{\mu\nu}k^\nu\right) \Theta A_\mu + (\text{h.c.}),$$

(1)

where $\Theta$, $N$, and $K$ stand for the pentaquark $\Theta^+$, the nucleon, and the kaon fields, respectively. Parameters $e$, $\kappa$, and $M$ designate the electric charge, the anomalous magnetic moment, and the mass of baryon, respectively. $\Gamma_5$ is generically $\gamma_5$ for the positive-parity $\Theta^+ (\Theta^\mp)$ and $1_{4\times4}$ for the negative-parity $\Theta^- (\Theta^\pm)$. In the case of the positive-parity $\Theta^+$, the coupling constants for $K$ exchange can be determined by using the decay width $\Gamma_{\Theta \rightarrow KN} = 15$ MeV and the mass $M_\Theta = 1540$ MeV, from which we obtain $g_A^* = 0.28$ for the PV interaction as well as $g = 3.8$ for the PS. Similarly, we find $g_A^* = 0.16$ and $g = 0.53$ for the negative-parity one.

$K^*$ exchange is also taken into account in this work as in Refs. [20, 22, 27, 30]. The
corresponding Lagrangians are given as follows:

\[ \mathcal{L}_{\gamma KK^*} = g_{\gamma KK^*} \epsilon_{\mu
u\rho} (\partial^\mu A^\nu)(\partial^\rho K^{*\mu}) + (\text{h.c.}), \]

\[ \mathcal{L}_{K^*N\Theta} = g_{K^*N\Theta} \gamma^\mu \Gamma_5 K^{*\mu} N + (\text{h.c.}). \]  

(2)

We neglect the tensor coupling of the \( K^*N\Theta \) vertex for the lack of information. In order to determine the coupling constant \( g_{\gamma KK^*} \), we use the experimental data for the radiative decay, which gives 0.388 GeV\(^{-1} \) for the neutral decay and 0.254 GeV\(^{-1} \) for the charged decay \[22, 27, 30\]. \( \Gamma_5 \) denotes \( 1_{4 \times 4} \) for the \( \Theta^+ \) and \( \gamma_5 \) for the \( \Theta^\pm \). Since we have no information on \( g_{K^*N\Theta} \) experimentally, we speculate its value as \( g_{K^*N\Theta}/g_{K\gamma\Theta} = \pm 0.5 \), assuming the ratio similar to \( g_{K^*N\Lambda}/g_{K\pi\Lambda} \). Note that in Refs. \[27, 30\] the ratio of the couplings was taken to be 0.6. In addition to \( K^* \) exchange, we also consider \( K_1(1270) \) axial-vector meson exchange. However, since we find that its contribution is tiny as in Ref. \[30\], we will not take into account it in this work. Since the anomalous magnetic moment of \( \Theta^+ \) has not been fixed experimentally, we need to rely on the model calculations \[28, 29, 31, 34, 35\]. Many of these calculations indicate small numbers for the \( \Theta^+ \) magnetic moment and hence negative values for the anomalous magnetic moment. As a typical value, we shall use for the anomalous magnetic moment \( \kappa_\Theta = -0.8 \mu_N \).

Now, we are in a position to calculate the invariant amplitudes for the photo-production of the \( \Theta^+ \). The amplitudes for \( \gamma n \to K^-\Theta^+ \) in the PS scheme can be obtained as follows:

\[ iM_s = eg\frac{\kappa_\Theta}{4M_n}\bar{\pi}(p')\Gamma_5 \frac{F_c(p' + k + M_\Theta)}{(p + k)^2 - M_\Theta^2} (\bar{\epsilon} k - \bar{\epsilon} k') u(p), \]

\[ iM_u = -eg\bar{u}(p') \left( \frac{F_c(p' + M_\Theta)}{(p' - k)^2 - M_\Theta^2} \Gamma_5 - \frac{\kappa_\Theta}{4M_\Theta}\bar{\pi}(\bar{\epsilon} \bar{\epsilon} - \bar{\epsilon} \bar{\epsilon}) \frac{F_u(p' - k + M_\Theta)}{(p' - k)^2 - M_\Theta^2} \Gamma_5 \right) u(p), \]

\[ iM_t = eg\bar{\pi}(p')\Gamma_5 \frac{F_c}{(k - k')^2 - m_{K^+}^2} u(p) (2k' \cdot \epsilon - k \cdot \epsilon), \]  

(3)

while that for the proton is derived as

\[ iM_s = -eg\bar{\pi}(p') \left( \Gamma_5 \frac{F_p(p + M_p)}{(p + k)^2 - M_p^2} \frac{\epsilon k}{(p + k)^2 - M_p^2} \frac{\epsilon k'}{(p + k)^2 - M_p^2} \frac{\epsilon k}{(p + k)^2 - M_p^2} \right) u(p), \]

\[ iM_u = -eg\bar{u}(p') \left( \frac{F_p(p + M_\Theta)}{(p' - k)^2 - M_\Theta^2} \Gamma_5 - \frac{\kappa_\Theta}{4M_\Theta}(\bar{\epsilon} \bar{\epsilon} - \bar{\epsilon} \bar{\epsilon}) \frac{F_u(p' - k + M_\Theta)}{(p' - k)^2 - M_\Theta^2} \Gamma_5 \right) u(p), \]

(4)

where \( \bar{\pi} \) and \( u \) are the Dirac spinors of \( \Theta^+ \) and the the nucleon. The four momenta \( p, p', k \) and \( k' \) are for the nucleon, \( \Theta^+ \), photon, and the kaon, respectively. Subscripts \( s, u \) and \( t \) stand for the Mandelstam variables. Note that in the case of the process \( \gamma p \to K^0\Theta^+ \), there is no contribution from the meson-exchange diagram in the \( t \)-channel. We have introduced
the form factors $F_{s,u,t}$ and $F_c^n$ in such a way that they satisfy the gauge invariance \[30, 37, 38\] in the form of

$$F_\xi = \frac{\Lambda^4}{\Lambda^4 + (\xi - M_\xi)^2},$$

(5)

where $\xi$ represents relevant kinematic channels, $s$, $t$, and $u$, generically. The common form factor $F_c^n$ is introduced according to the prescription suggested by Refs. [3 8]:

$$F_c^n = F_u + F_t - F_u F_t,$$
$$F_c^p = F_s + F_u - F_s F_u.$$

(6)

In the PV scheme, we need to consider an additional contribution, \textit{i.e.}, the contact term, also known as the Kroll-Rudermann (KR) term corresponding to diagram (d) in Fig. 1. The term can be written as follows:

$$i M_{KR} = -e g^* A_2 f_\pi u(p') \Gamma^5 / \epsilon u(p).$$

(7)

While Yu \textit{et al.} [30] introduced the form factors into the KR term in such a way that they satisfy the gauge invariance, we make use of the following relation:

$$i \Delta M^0 = i M_{PV}^0 - i M_{PS}^0 = e g_{MN} (\frac{K_T}{2M} + \frac{C_{K\Theta}}{2M_N}) \pi(p') \Gamma^5 \epsilon u(p).$$

(8)

Here, the superscript 0 denotes the bare amplitudes without the form factor. Since $i \Delta M^0$ is gauge-invariant due to its tensor structure, we can easily insert the form factors, keeping the gauge invariance. Thus, we arrive at the gauge-invariant amplitudes in the PV scheme as follows:

$$i M_{PV} = i M_{PS} + i \Delta M$$
$$= i M_{PS} + e g_{MN} (\frac{F_u K_T}{2M} + \frac{F_s C_{K\Theta}}{2M_N}) \pi(p') \Gamma^5 \epsilon u(p).$$

(9)

Finally, the $K^*$-exchange amplitude is derived as follows:

$$M_{K^*} = i \frac{F_3 g_{K^* K^*} g_{K^* N \Theta}}{(k - k')^2 - M_{K^*}^2} \pi(p') \epsilon_{\mu \nu \sigma \rho} k^\mu k'^\nu k^\sigma k'^\rho \Gamma^5 u(p),$$

(10)

which is clearly gauge-invariant.

**III. NUMERICAL RESULTS**

Before we calculate the photoproduction of the $\Theta^+$ numerically, we need to fix the cutoff parameters in the form factors. In doing so, we will try to estimate the value of the cutoff parameters by considering the process $\gamma p \rightarrow K^+ \Lambda$, which is known experimentally \[42\] and the comparison of the theoretical prediction with the corresponding data is possible. We have calculated the Born diagrams as shown in Fig. 1 for the $K^+ \Lambda$ production. In Fig. 2 we present the total cross sections of the $\gamma p \rightarrow K^+ \Lambda$ reaction without the form factors. Here, we have employed the coupling constants $g_{K^* N \Lambda} = -13.3$ and $g_{K^* N \Lambda} = -6.65$. While the
results without form factors are monotonically increased unphysically as shown in the left panel of Fig. 2 those with the form factors defined in Eq. (5) describe relatively well the experimental data as in the right panel of Fig. 2. We find that $\Lambda = 0.85 \sim 0.9$ GeV give reasonable results qualitatively. Note that the peaks at around 1.0 GeV and 1.5 GeV in the experimental data are believed to be related to higher nucleon resonances such as $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$ and $D_{13}(1895)$, which in our calculations are not included.

FIG. 2: The total cross sections of $\gamma p \rightarrow K^+ \Lambda$ without (the left) and with (the right) the form factors written in Eq. (5). The experimental data was taken from Ref. [42].

FIG. 3: The total cross sections for the reactions of $\gamma n \rightarrow K^- \Theta^+$ (a) and $\gamma p \rightarrow \overline{K}\Theta^+$ (b). PV and PS indicate the coupling schemes. 0, + and - indicate $g_{KN\Theta} = 0$, $g_{KN\Theta} = g_{KN\Theta}/2$ and $g_{KN\Theta} = -g_{KN\Theta}/2$, respectively.

Based on these results, we assume that the cutoff parameter for the $KN\Theta$ vertex is the same as for the $KN\Lambda$ one and use $\Lambda = 0.85$ GeV. Figure 3 draws the total cross sections with the form factors and $g_{KN\Theta}$ being varied between $-g_{KN\Theta}/2$ and $g_{KN\Theta}/2$. We see that the differences between the PV and PS schemes turn out to be small, as compared to the results of Ref. [30]. The reason lies in the fact that Ref. [30] introduced the form factor in the KR term directly, while we employ the relation between the PV and PS schemes as given in Eq.(9). It is very natural that in the low-energy limit the difference between the PV and PS schemes should disappear. In this sense, the present results is consistent with the low-energy relation for the photo-production.

Coming to the photo-production of the $\Theta^+$ in the $\gamma p \rightarrow \overline{K}\Theta^+$ reaction, we notice that the total cross section is smaller than the case of $\gamma n$ and rather sensitive to the contribution
of $K^*$ exchange. It can be understood by the fact that the contribution of $K$ exchange is absent and the $s$– and $u$–channels are suppressed by the form factors. The average values of the total cross sections are estimated as follows: $\sigma_{\gamma n \rightarrow K^- \Theta^+} \sim 44$ nb and $\sigma_{\gamma p \rightarrow K^0 \Theta^+} \sim 13$ nb in the range of the photon energy $1.73 \text{ GeV} < E_\gamma < 2.6 \text{ GeV}$. Note that these values are smaller than those of Ref. [28], where $\Lambda = 1.0 \text{ GeV}$ is employed.

![FIG. 4:](image)

FIG. 4: The differential cross sections for the reactions of $\gamma n \rightarrow K^- \Theta^+$ (a) and $\gamma p \rightarrow K^0 \Theta^+$ (b) at $\sqrt{s} = 2.1 \text{ GeV}$.

In Fig. 4 we draw the differential cross sections. In the case of the $\gamma n \rightarrow K^- \Theta^+$, the peak around $60^\circ$ is clearly seen as shown in the left panel of Fig. 4. This peak is caused by the $t$–channel dominance which brings about the combination of the factor $|\epsilon \cdot k'|^2 \sim \sin^2 \theta$ and the form factor. In the multipole basis, an $M1$ amplitude is responsible for it. In contrast, for the production from the proton, $K$ exchange is absent, and the role of $K^*$ exchange and its interference with the $s$– and $u$–channel diagrams become more important. Therefore, the differential cross section of the $\gamma p \rightarrow K^0 \Theta^+$ process is quite different from that of the $\gamma n \rightarrow K^- \Theta^+$. The present results look rather different from those of Ref. [22], where the relation $g_{K^*N\Theta} = \pm g_{KN\Theta}$ was employed. It is so since the amplitude of $K^*$ exchange is twice as large as that in the present work, and has an even more important contribution to the amplitudes. We need more experimental information in order to settle the uncertainty in the reaction mechanism.

![FIG. 5:](image)

FIG. 5: The total cross sections for the reactions of $\gamma n \rightarrow K^- \Theta^+$ (a) and $\gamma p \rightarrow K^0 \Theta^+$ (b).

We now present the total cross sections for the negative parity $\Theta^+$ in Fig. 5. The contri-
bution of $K^*$ exchange is almost negligible in the case of the $\gamma n \to K^-\Theta^+$ process, whereas it plays a main role in $\gamma p \to K^0\Theta^+$. The total cross sections for the negative-parity $\Theta^+$ turn out to be approximately ten times smaller than those for the positive-parity one. This fact pervades rather universally various reactions for the $\Theta^+$ production. The reason is that the momentum-dependent $p$-wave coupling $\vec{\sigma} \cdot \vec{q}$ for the positive parity $\Theta^+$ enhances the coupling strength effectively at the momentum transfer $|\vec{q}| \sim 1$ GeV, a typical value for the $\Theta^+$ production using non-strange particles. The enhancement factor is about $1$ GeV$/0.26$ GeV, where $0.26$ GeV is the kaon momentum in the $\Theta^+$ decay. Therefore, the cross sections become larger for the positive parity case than for the negative parity case by a factor $(1/0.26)^2 \sim 10$.

![FIG. 6: The differential cross sections for the reactions of $\gamma n \to K^-\Theta^+$ (a) and $\gamma p \to K^0\Theta^+$ (b) at $\sqrt{s} = 2.1$ GeV.](image)

The differential cross sections for the $\Theta^+$ photo-production are drawn in Fig. 6. The peak around $60^\circ$ appears in the $\gamma n$ interaction as in the case of the $\Theta^+$. That for the production via the $\gamma p$ interaction shows quite different from the case of the $\Theta^+$.

### IV. SUMMARY AND DISCUSSIONS

We investigated $\gamma N \to \overline{K}\Theta^+$ reactions with the Born approximation including $t$–channel $K^*$ exchange. In order to make our discussions quantitative, we employed the phenomenological strong form factor with the cutoff, $\Lambda$, which was determined by $p(\gamma, K^+)\Lambda$ reaction without $K_1$ and the nucleon resonances. Then we obtained $\Lambda = 0.85 \sim 0.9$ GeV with about $30\%$ tolerance and took $\Lambda = 0.85$ GeV for the numerical calculations. We also treated them in the pseudoscalar (PS) and pseudovector (PV) coupling schemes. Then we constructed the gauge-invariant amplitudes in the PS and PV using the relation, $iM_{PV} = iM_{PS} + i\Delta M$. In this method, the result in the PV becomes rather similar to that of the PS as expected from the low-energy limit. This behaviour is deeply related to the prescription of the form factor which we employed. As shown in Fig. 3 our form factor suppressed the $u$– and $s$–channels more than that of the $t$–channel. However, this situation is not accidental but explains the physics about the amplitude, which extracts the most dominant one from the Born amplitudes in the kinematical channels: The intermediate states in the $s$– and $u$–channels ($N$ and $\Theta^+$) are further off-shell than that in the $t$–channel ($K$). Reminding of that $\kappa_\Theta$ is only contained in $s$– and $u$–channel amplitudes, it is natural for us to have the cross sections which
are not dependent much on $\kappa_\Theta$. Consequently in this method, we were able to diminish the model and parameter dependences. We note that these results are rather different from those of Ref. [30] in which the authors modified Kroll-Ruderman term with the form factors directly in order to keep the gauge invariance. However, as for the PS scheme only, their results are essentially equivalent to ours.

For the total cross sections, we found that $\sigma_{\gamma n \to K^- \Theta^+} (44 \text{ nb}) > \sigma_{\gamma p \to K^0 \Theta^+} (13 \text{ nb})$ for the positive parity $\Theta^+$. This was a similar result as obtained in Refs. [20, 27], in which they used one overall form factor and ignored the anomalous magnetic moments ($\kappa_\Theta = \kappa_N = 0$). Once again in our calculations the form factor played an important role here. In Ref. [22], they obtained the cross sections for $\gamma n$ and $\gamma p$ processes similar by employing a larger value of the $K^*N\Theta$ coupling than ours ($g_{K^*N\Theta} = g_{K^*N\Theta}$). This value produced the total cross sections consistent with the data from SAPHIR. However, more experimental analyses should be necessary in order to confirm the absolute value of the total cross section. In Ref. [30], they also obtained similar total cross sections both for $\gamma n$ and $\gamma p$ reactions by employing a large cutoff parameter $\Lambda = 1.8 \text{ GeV}$.

So far, we have variable theoretical predictions based on different reaction mechanisms and model parameters. More experimental information will be necessary in order to pin down such uncertain situation. However, it is a universal feature that the total cross section for the positive parity $\Theta^+$ production is about factor ten larger than that of the negative parity one. This might be useful when proceeding step by step to obtain more information about the nature of the pentaquark baryon $\Theta^+$.

**Acknowledgment**

We thank Hiroshi Toki and Takashi Nakano for discussions and comments. The work of H.-Ch.Kim is supported by the Korean Research Foundation (KRF–2003–070–C00015) and in part by the 21st COE Program “Towards A New Basic Science: Depth and Synthesis” (Osaka university). The work of S.I.Nam has been supported by the scholarship endowed from the Ministry of Education, Science, Sports and Culture of Japan. A.H. would like to thank the hospitality of the members of the NuRI at Pusan National University.

[1] T. Nakano et al. [LEPS Collaboration], Phys. Rev. Lett. 91, 012002 (2003)
[2] D. Diakonov, V. Petrov and M. V. Polyakov, Z. Phys. A 359, 305 (1997)
[3] V. V. Barmin et al. [DIANA Collaboration], Phys. Atom. Nucl. 66, 1715 (2003) [Yad. Fiz. 66, 1763 (2003)]
[4] S. Stepanyan et al. [CLAS Collaboration], Phys. Rev. Lett. 91, 252001 (2003)
[5] V. Kubarovsky et al. [CLAS Collaboration], Erratum-ibid. 92, 049902 (2004) [Phys. Rev. Lett. 92, 032001 (2004)]
[6] J. Barth et al. [SAPHIR Collaboration], hep-ex/0307083
[7] A. Airapetian et al. [HERMES Collaboration], hep-ex/0312044
[8] Private conversation with T.Nakano
[9] C. Alt et al. [NA49 Collaboration], Phys. Rev. Lett. 92, 042003 (2004)
[10] M. Praszalowicz, Phys. Lett. B 583, 96 (2004)
[11] M. Karliner and H. J. Lipkin, arXiv:hep-ph/0401072
10