Magnetic and axial-vector transitions of the baryon antidecuplet

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We report the recent results of the magnetic transitions and axial-vector transitions of the baryon antidecuplet within the framework of the chiral quark-soliton model. The dynamical model parameters are fixed by experimental data for the magnetic moments of the baryon octet, for the hyperon semileptonic decay constants, and for the singlet axial-vector constant. The transition magnetic moments $\mu_{\Lambda \Sigma}$ and $\mu_{N \Delta}$ are well reproduced and other octet-decuplet and octet-antidecuplet transitions are predicted. In particular, the present calculation of $\mu_{\Sigma \Sigma^*}$ is found to be below the upper bound $0.82\mu_N$ that the SELEX collaboration measured very recently. The results explain consistently the recent findings of a new $N^*$ resonance from the GRAAL and Tohoku LNS group. We also obtain the transition axial-vector constants for the $\Theta^+ \to KN$ from which the decay width of the $\Theta^+$ pentaquark baryon is determined as a function of the pion-nucleon sigma term $\Sigma_{\pi N}$. We investigate the dependence of the decay width of the $\Theta^+$ on the $g_\Lambda^{(0)}$, with the $g_\Lambda^{(0)}$ varied within the range of the experimental uncertainty. We show that a small decay width of the $\Theta^+ \to KN$, i.e. $\Gamma_{\Theta KN} \leq 1$ MeV, is compatible with the values of all known semileptonic decays with the generally accepted value of $g_\Lambda^{(0)} \approx 0.3$ for the proton.

\textbf{§1. Introduction}

We would like to begin the present talk by mentioning about two Japanese physicists who were Yukawa's students and collaborators in 1940's. Shoichi Sakata and Mitsuo Taketani developed the three-stages theory based on a Marxist dialectical philosophy to explain how science is advanced.

"Suppose a researcher discovers a new, inexplicable phenomenon. First he or she learns the details and tries to discern regularities. Next the scientist comes up with a qualitative model to explain the patterns and finally develops a precise mathematical theory that subsumes the model. But another discovery soon forces the process to repeat. As a result, the history of science resembles a spiral, going round in circles yet always advancing."\textsuperscript{1)}

Since the first experimental observation of a signal of the pentaquark baryon $\Theta^+$ by the LEPS collaboration at SPring-8\textsuperscript{2)} which was triggered by the theoretical predictions from the chiral soliton model ($\chi$SM),\textsuperscript{3)} there has been a great amount of experimental and theoretical efforts to understand the nature of this new resonance $\Theta^+$. However, the null results of the recent CLAS experiment have cast doubt on

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its existence.\textsuperscript{4)} Meanwhile, the DIANA collaboration has continued to search for the $\Theta^+$ and announced very recently the formation of a narrow $pK^0\rightarrow n\pi$ peak with mass of $1537\pm 2\text{ MeV}/c^2$ and width of $\Gamma = 0.36\pm 0.11\text{ MeV}$ in the $K^+n \rightarrow K^0p$ reaction.\textsuperscript{5)} Moreover, several new experiments for the $\Theta^+$ are under way.\textsuperscript{6}–\textsuperscript{8)} In the present cloudy status for the $\Theta^+$, more efforts are required for understanding the $\Theta^+$ theoretically as well as experimentally. No matter whether the $\Theta^+$ exists or not, such efforts will surely not end up in vain, as Sakata and Taketani put forward.\textsuperscript{1)\textsuperscript{10}}

In addition to the $\Theta^+$, the GRAAL collaboration\textsuperscript{9),10} and the Tohoku LNS group\textsuperscript{11)} announced the evidence of a new nucleon-like resonance with a narrow decay width $\sim 10$ MeV and a mass $\sim 1675$ MeV in the $\eta$-photoproduction from the neutron target. This new nucleon-like resonance, $N^*(1675)$, may be regarded as a non-strange pentaquark because of its narrow decay width and dominant excitation on the neutron target which are known to be characteristic for typical pentaquark baryons.\textsuperscript{12)} Moreover, several theoretical calculations of the $\gamma N \rightarrow \eta N$ reaction\textsuperscript{14),15)} support the identification of the $N^*(1675)$ as a member of the baryon antidecuplet, based on the values of the transition magnetic moments in Refs.\textsuperscript{13),16)}

In the present talk, we would like to report recent investigations on the magnetic and axial-vector transitions of the baryon antidecuplet within the framework of the chiral quark-soliton model,\textsuperscript{13),17)} emphasizing in particular the $\Theta^+$ and $N^*_0$. We include the effects of flavor SU(3) symmetry breaking and employ the “\textit{model-independent approach}”\textsuperscript{18)} in which all dynamical parameters of the model are fixed by existing experimental data.

\section*{2. Formalism}

The electromagnetic and axial-vector transition form factors are defined by the following transition matrix elements of the vector and axial-vector currents:\textsuperscript{13)}

$$
\langle B|V^Q_\mu|B\rangle = \bar{u}_B(p_2) \left[ F_1(q^2) \gamma_\mu + \frac{iF_2(q^2)}{M_1} \sigma_{\mu\nu} q^\nu + \frac{F_3(q^2)}{M_1} q_\mu \right] u_B(p_1),
$$

$$
\langle B_2|A^X_\mu|B_1\rangle = \bar{u}_{B_2}(p_2) \left[ g_1(q^2) \gamma_\mu - \frac{i g_2(q^2)}{M_1} \sigma_{\mu\nu} q^\nu + \frac{g_3(q^2)}{M_1} q_\mu \right] \gamma_5 u_{B_1}(p_1),
$$

(2.1)

where the vector and axial-vector currents are defined as

$$
V^Q_\mu = \bar{\psi}(x) \gamma_\mu \lambda_Q \psi(x), \quad A^X_\mu = \bar{\psi}(x) \gamma_\mu \gamma_5 \lambda_X \psi(x)
$$

(2.2)

with $Q = \frac{1}{2}(3 + 8/\sqrt{3})$ for the electromagnetic currents and $X = \frac{1}{2}(1 \pm i2)$ for strangeness conserving $\Delta S = 0$ currents and $X = \frac{1}{2}(4 \pm i5)$ for $|\Delta S| = 1$. The $q^2 = -Q^2$ stands for the square of the momentum transfer $q = p_2 - p_1$. The form factors $F_i$ and $g_i$ are real quantities due to $CP$-invariance, depending only on the square of the momentum transfer, among which we are mostly interested in $F_2$ and $g_1$. Taking into account the $1/N_c$ rotational and $m_s$ corrections, we can write the resulting magnetic moments $\mu^{(B)}$ and axial-vector constants $g_1^{(B_1 \rightarrow B_2)}(0)$ as follows:

$$
\mu^{(B)} = w_1 \langle B|D^{(8)}_{Q3}|B\rangle + w_2 d_{pq3} \langle B|D^{(8)}_{Qp} \bar{J}_q|B\rangle + \frac{a_3}{\sqrt{3}} \langle B|D^{(8)}_{Q3} \bar{J}_3|B\rangle
$$

(2.3)
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\[ + m_4 \left[ \frac{w_4}{\sqrt{3}} d_{pq3}(B) D^{(8)}_{Q_3} \right. \left. D^{(8)}_{Q_8} |B\rangle + w_5 \langle B | \left( D^{(8)}_{Q_3} D^{(8)}_{Q_8} + D^{(8)}_{Q_8} D^{(8)}_{Q_3} \right) |B\rangle \right. \]
\[ + w_6 \langle B | \left( D^{(8)}_{Q_3} D^{(8)}_{Q_8} - D^{(8)}_{Q_8} D^{(8)}_{Q_3} \right) |B\rangle \right] , \]
\[ g_{1_{B \rightarrow B_2}}(0) = a_1 \langle B_2 | D^{(8)}_{X_3} |B_1\rangle + a_2 d_{pq3}(B_2) D^{(8)}_{X_3} \hat{J}_q |B_1\rangle + \frac{a_3}{\sqrt{3}} \langle B_2 | D^{(8)}_{X_3} \hat{J}_3 |B_1\rangle \]
\[ + m_4 \left[ \frac{a_4}{\sqrt{3}} d_{pq3}(B_2) D^{(8)}_{X_3} D^{(8)}_{P_q} |B_1\rangle + a_5 \langle B_2 | \left( D^{(8)}_{X_3} D^{(8)}_{Q_8} + D^{(8)}_{X_3} D^{(8)}_{Q_3} \right) |B_1\rangle \right. \]
\[ + a_6 \langle B_2 | \left( D^{(8)}_{X_3} D^{(8)}_{P_q} - D^{(8)}_{X_3} D^{(8)}_{Q_3} \right) |B_1\rangle \right] , \] (2.3)

where \( w_i \) and \( a_i \) denote parameters encoding the specific dynamics of the chiral quark-soliton model. \( \hat{J}_q \) (\( \hat{J}_3 \)) stand for the \( q \)-th (third) components of the collective spin operator of the baryons, respectively. The \( D^{(R)}_{ab} \) denote the SU(3) Wigner matrices in representation \( R \). The dynamical parameters \( w_i \) and \( a_i \) are fixed by the experimental data for the baryon magnetic moments, and hyperon semileptonic decay constants and singlet axial-vector constant of the proton, respectively. The magnetic moments of the baryon decuplet have been obtained in Ref.\textsuperscript{19} where those of the \( \Delta \) and \( \Omega \) baryons were well reproduced. Having obtained the numerical results of \( w_i \) and \( a_i \), we can immediately obtain the transition magnetic moments and axial-vector constants from the baryon octet to the antidecuplet.

\section*{§3. Results and discussion}

In Table \textsuperscript{[1] we list the numerical results for the transition magnetic moments of the nonexotic and exotic baryons for three different values of the \( \Sigma_{\pi N} \) in units of \( \mu_N \). Those for \( \mu_{N\Delta} \) and \( \mu_{\Lambda^0\Sigma^0} \) are in a very good agreement with the experimental and empirical data.\textsuperscript{13} The upper bound for \( |\mu_{\Sigma^+ - \Sigma^0}| \) extracted from the upper limit for the partial decay width of the SELEX experiment is around 0.82 \( \mu_N \).\textsuperscript{20} The present prediction for \( \mu_{\Sigma^+ - \Sigma^0} \) lies definitely in the allowed region for all reasonable values of \( \Sigma_{\pi N} \). The \( \mathcal{N}_{\mathcal{N}}^* \rightarrow N \) transition magnetic moments are rather sensitive to the \( \Sigma_{\pi N} \). It is very similar to the case of the magnetic moments of the baryon antidecuplet.\textsuperscript{19} The reason is due to the fact that \( \mu_{N\Sigma_{\mathcal{N}}} \) is proportional to \( w_1 + w_2 + \frac{1}{2} w_3 \), so that the terms with the \( \Sigma_{\pi N} \) in \( w_1 \) and \( w_2 \) interfere linearly. As a result, \( \mu_{N\Sigma_{\mathcal{N}}} \) decreases monotonically as \( \Sigma_{\pi N} \) increases, as shown in Fig. \textsuperscript{[1]}

Since the \( p^* \rightarrow p \) transition one is SU(3) forbidden, it is rather small. More

| \( \Sigma_{\pi N} \) [MeV] | \( \mu_{N\Delta} \) | \( \mu_{\Lambda^0\Sigma^0} \) | \( \mu_{\Sigma^+ - \Sigma^0} \) | \( \mu_{\Sigma^- - \Sigma^0} \) | \( \Gamma_{\pi N^*}^* \) | \( \Gamma_{\pi N^*} \) | \( \Gamma_{\pi N^*}^* / \Gamma_{\pi N^*} \) |
|----------------|---------|---------|---------|---------|----------------|----------------|----------------|
| 50             | -3.06   | 1.54    | -0.44   | 0.12    | 0.56          | 11.5           | 250            | 21.67          |
| 60             | -3.16   | 1.58    | -0.50   | 0.08    | 0.33          | 5.12           | 87.2           | 17.02          |
| 70             | -3.31   | 1.64    | -0.59   | 0.04    | 0.11          | 1.28           | 9.09           | 7.56           |
we obtain. When $g$ transition axial-vector constant as follows:

$$\Sigma$$ as a function of $\Gamma$ments.

Since the partial decay width $\Gamma$ turns out to be about eight to twenty times larger as shown in Eq. (3.2), it turns out to be about eight to twenty times larger than the proton one. The partial width of radiative decays from the baryon antidecuplet to the octet is expressed as

$$\Gamma(B_{\pi N} \rightarrow B_{\gamma N}) = 4\alpha_{\text{EM}} \frac{E^3_{\gamma}}{(M_N + M_{\pi N})^2} \left( \frac{\mu_{\pi N}}{\mu_N} \right)^2,$$

where $\alpha_{\text{EM}}$ denotes the fine structure constant and $E_{\gamma}$ is the energy of the produced photon:

$$E_{\gamma} = \frac{M^2_{\pi N} - M_N^2}{2M_{\pi N}}.$$

Since the partial decay width $\Gamma_{\pi NN}$ is proportional to the transition magnetic moment as shown in Eq. (3.2), it turns out to be about eight to twenty times larger than $\Gamma_{\pi NN}$. This result is consistent with those of the GRAAL and Tohoku experiments.

In Fig. 2, the transition axial-vector coupling constant for $\Theta^+ \rightarrow K^+N$ is drawn as a function of $\Sigma_{\pi N}$, three different values of the singlet axial-vector constant $g_A^{(0)}$ for the proton being varied from 0.2 to 0.4. The larger $g_A^{(0)}$ we use, the smaller $g_A^{(\Theta \rightarrow n)}$ we obtain. When $g_A^{(0)}$ is larger than 0.37, the $g_A^{(\Theta \rightarrow n)}$ becomes even negative.

Since the decay width of the $\Theta^+ \rightarrow KN$ is proportional to the square of the transition axial-vector constant as follows:

$$\Gamma_{\Theta KN} = 2\Gamma_{\Theta K^+N} = \frac{\left(g_A^{(\Theta \rightarrow n)} \right)^2 |\bar{p}|}{16\pi f_K^2 M_{\Theta}^2} \left[ (M_{\Theta} - M_N)^2 - m_K^2 \right] (M_{\Theta} + M_N)^2,$$

it is rather sensitive to the $g_A^{(\Theta \rightarrow n)}$. In Table II we list the numerical results of the the decay width of the $\Theta^+ \rightarrow KN$, $\Gamma_{\Theta KN}^{\text{total}}$ for four different values of the $g_A^{(0)}$ as a function of $\Sigma_{\pi N}$. The $\Gamma_{\Theta KN}^{\text{total}}$ turns out to be the smallest with $g_A^{(0)} = 0.36$ and $\Sigma_{\pi N}$. 

![Fig. 1. $p^* \rightarrow p$ transition magnetic moment as functions of $\Sigma_{\pi N}$ in the left panel and $n^* \rightarrow n$ one as functions of $\Sigma_{\pi N}$ in the right panel.](image-url)
Fig. 2. The transition axial-vector coupling constant for $\Theta^+ \rightarrow K^+ n$ as a function of $\Sigma_{\pi N}$. The solid curve denotes that with $g_A^{(0)} = 0.3$, while the dashed and dot-dashed ones represent that with $g_A^{(0)} = 0.2$, 0.4, respectively.

Table II. The decay width of $\Theta^+ \rightarrow K N$ determined with $g_A^{(0)}$ varied from 0.28 to 0.40. The $\Sigma_{\pi N}$ is varied from 45 to 75 MeV.

| $\Sigma_{\pi N}$ [MeV] | Input $g_A^{(0)}$ | $\Gamma_{\Theta K N}^{(\text{total})}$ |
|------------------------|-------------------|---------------------------------|
| 50                     | 0.28 0.32 0.36 0.40 | 22.25 7.82 0.76 1.10          |
| 60                     |                   | 10.45 3.82 0.46 0.36          |
| 70                     |                   | 4.54 1.50 0.10 0.35          |

Figure 3 shows the results of the total decay width of the $\Theta^+ \rightarrow K N$ as a function of $g_A^{(0)}$ and $\Sigma_{\pi N}$ in a three dimensional plot. As shown in Fig. 3, the minimum of the total decay width $\Gamma_{\Theta K N}$ is found to be around $g_A^{(0)} = 0.37$ with $\Sigma_{\pi N} = 65$ MeV. Thus, using this interrelation among $g_A^{(0)}$, $\Sigma_{\pi N}$, and $\Gamma_{\Theta K N}$, we can consider a certain window for their values within the present analysis.

Figure 4 shows the window for the total decay width of the $\Theta^+ \rightarrow K N$, given $g_A^{(0)}$ and $\Sigma_{\pi N}$. The shaded rectangle indicates the area where one has generally accepted experimental values of $g_A^{(0)}$ and $\Sigma_{\pi N}$, i.e. $0.3 - 0.4$ and $65 - 75$ MeV, respectively, and simultaneously a $\Gamma_{\Theta K N} \leq 1$ MeV. It is of great interest to see that the range of $g_A^{(0)}$ is compatible with a theoretical investigation, based on the $\chi$QSM, and on the COMPASS and HERMES measurements of the deuteron spin-dependent structure function. It is worthwhile to mention that the values of $g_A^{(0)}$ in the present analysis is almost the same as theoretical results within the $\chi$QSM. The range of $\Sigma_{\pi N}$ given above is consistent with a recent analysis. If one interprets the result of the DIANA collaboration as identification of the $\Theta^+$, namely the formation of a narrow $pK^0$ peak with mass of $1537 \pm 2$ MeV/c$^2$ and width of $\Gamma = 0.36 \pm 0.11$ MeV.
in the $K^+n \rightarrow K^0p$ transition, then that result is inside the shaded area of Fig. 4.
§4. Summary and Conclusions

In the present talk, we have reported the recent investigation on the magnetic transitions and axial-vector transitions from the baryon antidecuplet to the nucleons, emphasizing, in particular, the $\Theta^+$ baryon and the new $N^*(1675)$ resonance from the GRAAL and Tohoku LNS experiments. We used the the model-independent approach within the framework of the chiral quark-soliton model, thereby taking explicit SU(3)-symmetry breaking into account. The parameters in the model are all fixed by the known experimental data, i.e. octet magnetic moments, hyperon semileptonic decay constants, singlet axial-vector constant, octet masses, and the mass of the $\Theta^+$, where the residual freedom is parametrized by the pion-nucleon sigma term, $\Sigma_{\pi N}$. The results for $\mu_{N\Delta}$ and $\mu_{N^{\prime}\Sigma^0}$ are well reproduced, compared to the experimental and empirical data. The transition magnetic moment $\mu_{\Sigma^-\Sigma^*-}$, which has only a non-zero value due to explicit SU(3)-symmetry breaking, is found to be below its upper bound extracted from the SELEX data.$^{20}$

The transition magnetic moment $\mu_{n\pi n}$ turns out to be rather sensitive to the value of $\Sigma_{\pi N}$ due to the constructive interference of the parameters $w_1(\Sigma_{\pi N})$ and $w_1(\Sigma_{\pi N})$. The value of the $\mu_{pp\pi}$ is rather small in comparison with that of the $\mu_{nn\pi}$ due to the explicit SU(3)-symmetry breaking. As a result, the present predictions for the transition magnetic moments $\mu_{pp\pi}$ and $\mu_{nn\pi}$ are consistent with the recent GRAAL data on $\gamma p \rightarrow \eta p$ and $\gamma n \rightarrow \eta n$. This supports the view that the new resonance $N^*(1675)$ corresponds to a neutron-like member of the pentaquark baryon antidecuplet.

We also presented the recent results of the transition axial-vector coupling constant for the $\Theta^+ \rightarrow K^+n$, $g_A^{(\Theta^+\rightarrow n)}$ and the total decay width of the $\Theta^+ \rightarrow KN$. We showed that the $g_A^{(\Theta^+\rightarrow n)}$ decreases as $g_A^{(0)}$ increases. It also depends on the $\pi N$ sigma term in such a way that it is getting smaller as the $\Sigma_{\pi N}$ increases. It was also shown that the $g_A^{(\Theta^+\rightarrow n)}$ turns out to be negative around $g_A^{(0)} \approx 0.37$.

The total width $\Gamma_{\Theta KN}$ of the $\Theta^+ \rightarrow KN$ decay was finally investigated. Since it is proportional to the square of the transition axial-vector constant $g_A^{(\Theta^+\rightarrow n)}$, it is rather sensitive to the $g_A^{(\Theta^+\rightarrow n)}$. The $\Gamma_{\Theta KN}$ is getting suppressed as the singlet axial-vector constant $g_A^{(0)}$ increases. However, since the $g_A^{(\Theta^+\rightarrow n)}$ becomes negative around 0.37, the $\Gamma_{\Theta KN}$ starts to increase around 0.37. As a result, the total decay width $\Gamma_{\Theta KN}$ turns out to be smaller than 1 MeV for values of the $g_A^{(0)}$ and $\Sigma_{\pi N}$ larger than 0.31 and 65 MeV, respectively.

According to the analysis of the total width $\Gamma_{\Theta KN}$, we draw a conclusion as follows: The known data of semileptonic decays combined with $0.3 \leq g_A^{(0)} \leq 0.4$ and $\Sigma_{\pi N} \geq 65$ MeV is compatible with the existence of a $\Theta^+$ pentaquark having a small width of the total decay $\Theta^+ \rightarrow KN$, that is $\Gamma_{\Theta KN} \leq 1$ MeV.
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References

1) L. M. Brown and Y. Nambu, Scientific American, December 1998, 96 (1998).
2) T. Nakano et al. [LEPS Collaboration], Phys. Rev. Lett. 91, 012002 (2003).
3) D. Diakonov, V. Petrov and M. V. Polyakov, Z. Phys. A359 (1997) 305.
4) M. Battaglieri et al. [CLAS Collaboration], Phys. Rev. Lett. 96, 042001 (2006).
5) V. V. Barmin et al. [DIANA Collaboration], Phys. Atom. Nucl. 70, 35 (2007).
6) T. Hotta [LEPS Collaboration], Acta Phys. Polon. B 36, 2173 (2005).
7) K. Miwa et al. [KEK-PS E522 Collaboration], arXiv:nucl-ex/0601032
8) T. Nakano, a talk presented in the Workshop on Hadronic and Nuclear Physics 2007 (HNP 2007), [http://hadron.phys.pusan.ac.kr/~hnp07/].
9) V. Kuznetsov [GRAAL Collaboration], arXiv:hep-ex/0409032.
10) V. Kuznetsov [GRAAL Collaboration], arXiv:hep-ex/0606065.
11) J. Kasagi, “Observation of Narrow Resonance in the d(γ, η) Reaction at Eγ≈1000 MeV: A Candidate for the Anti-decuplet N* Produced in Photo-Neutron Excitation”, in this proceedings.
12) M. V. Polyakov and A. Rathke, Eur. Phys. J. A 18, 691 (2003).
13) H.-Ch. Kim, M. Polyakov, M. Praszalowicz, G. S. Yang and K. Goeke, Phys. Rev. D 71, 094023 (2005).
14) K. S. Choi, S. i. Nam, A. Hosaka and H.-Ch. Kim, Phys. Lett. B 636, 253 (2006).
15) A. Fix, L. Tiator and M. V. Polyakov, arXiv:nucl-th/0702034.
16) Y. Azimov, V. Kuznetsov, M. V. Polyakov and I. Strakovsky, Eur. Phys. J. A 25, 325 (2005).
17) G. S. Yang, H. C. Kim and K. Goeke, arXiv:hep-ph/0701168, accepted for publication in Phys Rev. D.
18) G. S. Adkins and C. R. Nappi, Nucl. Phys. B 249, 507 (1985).
19) G. S. Yang, H.-Ch. Kim, M. Praszalowicz and K. Goeke, Phys. Rev. D 70, 114002 (2004).
20) V. V. Molchanov et al. [SELEX Collaboration], Phys. Lett. B 590, 161 (2004).
21) M. Wakamatsu, Phys. Lett. B 646, 24 (2007).
22) E. S. Ageev et al. [COMPASS Collaboration], Phys. Lett. B 612, 154 (2005).
23) V. Y. Alexakhin et al. [COMPASS Collaboration], arXiv:hep-ex/0609038.
24) A. Airapetian et al. [HERMES Collaboration], arXiv:hep-ex/0609039.
25) M. Wakamatsu and T. Watabe, Phys. Rev. D 62, 054009 (2000).
26) A. Silva, H. C. Kim, D. Urbano and K. Goeke, Phys. Rev. D 72, 094011 (2005).
27) P. Schweitzer, Eur. Phys. J. A 22 (2004) 89.