

Recent Results for the Baryon Antidecuplet within the Chiral Quark-Soliton Model

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We review recent results of properties of the baryon antidecuplet within the $SU(3)$ chiral quark-soliton model, in particular, employing an model-independent approach. Considering isospin symmetry breakings from electromagnetic self-energies as well as hadronic contributions, we determine all model parameters based on the experimental data for the masses of the baryon octet together with the masses of the Θ^+ and $N^*(1685)$. The predicted masses of the baryon decuplet are in good agreement with the data. We also show the results for the transition magnetic moments of radiative decay $N^* \rightarrow \gamma N$. The results imply that the neutron channel is at least ten times more enhanced than the proton channel. The axial-vector constant for $\Theta^+ \rightarrow KN$ is predicted and turns out to be tiny, which leads to the small decay width for the Θ^+ decay: $\Gamma_{\Theta \rightarrow KN} = 0.80 \pm 0.12$ MeV.

§1. Introduction

Since the measurement of the LEPS collaboration,¹⁾ motivated by Diakonov et al.^{2),3)} in which the mass of the pentaquark Θ^+ was predicted with its small decay width, there has been a great deal of experimental and theoretical works on this five-quark baryon. However, after the null results of a series of the CLAS experiments,⁴⁾⁻⁷⁾ the existence of the Θ^+ was open to question. Nevertheless, several experimental groups continue to search for the Θ^+ . For example, the DIANA collaboration has reannounced the mass of the Θ^+ to be 1537 ± 2 MeV/ c^2 with the decay width $\Gamma = 0.36 \pm 0.11$ MeV.⁸⁾ The very recent measurement of the LEPS collaboration has yielded $M_{\Theta^+} = 1524 \pm 0.002 + 0.003$ MeV.⁹⁾ Though many people raise the question of the existence of the Θ^+ , we want to mention that the several important problems of the Θ^+ remain unanswered. Whether Θ^+ exists or not, we can summarize the present status of the pentaquark Θ^+ as follows: The pentaquark Θ^+ is elusive in almost all high-energy experiments, while it was seen by relatively low-energy experiments. Though it was not answered or explained whether these positive results were just statistical fluctuations or the real evidences for the Θ^+ ,^{***)} the finding of the Θ^+ seems to be reaction-dependent.

The decay width of the Θ^+ , if it exists, is very small ($\Gamma_{\Theta} < 1$ MeV) according to the DIANA results.^{8),10)} It indicates that the $KN\Theta$ coupling should be very small. This may provide an indirect and partial hint for the reason why the Θ^+ is hard to be found. Moreover, the total cross section of the Θ^+ photoproduction is small.^{4)-7),9)} It implies that the $K^*N\Theta$ coupling constant should be of the same order as the KN coupling. Thus, it is worthwhile to investigate the $KN\Theta$ and $K^*N\Theta$ coupling constants theoretically so that one may understand why it is so difficult to see the

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^{***)} A recent theoretical work¹¹⁾ put the LEPS measurement under question.

Θ^+ .

In the present talk, we will briefly review a very recent analysis about the mass of the Θ^+ and its decay within a chiral soliton model and will show the results that are much more improved, compared to the previous ones^{2),12)} in which experimental information on the masses of the $SU(3)$ baryons were only partially considered. In order to take into account the whole experimental data of the $SU(3)$ baryon masses, one has to incorporate effects of isospin symmetry breaking. Once we include these effects, we can unambiguously determine all theoretical parameters and proceed to determine the masses and couplings of the baryon antidecuplet. Thus, we summarize in this talk the results of a series of recent investigation on the properties of the baryon antidecuplet. The corresponding formalism and methods will be presented elsewhere in detail.

§2. Mass splittings of $SU(3)$ baryons in a chiral soliton model

The experimental data of baryon masses include all effects of isospin $SU(3)$ symmetry breakings. In order to employ them in the analysis of the mass splittings of $SU(3)$ baryons, we need to consider both isospin and $SU(3)$ symmetry breakings. In particular, the mass splittings of the $SU(3)$ baryons within an isospin multiplet can be cast into two different categories, i.e. the *hadronic* and *electromagnetic* parts

$$\Delta M_B = M_{B_1} - M_{B_2} = (\Delta M_B)_H + (\Delta M_B)_{EM}, \quad (2.1)$$

where the subscript B represents the baryon isospin multiplet and M_{B_1} and M_{B_2} denote the masses of two different baryons belonging to the same isospin multiplet. The $(\Delta M_B)_H$ and the $(\Delta M_B)_{EM}$ are the hadronic and the electromagnetic contributions to the mass splitting, respectively.

We first consider the electromagnetic contribution to the baryon mass splittings. The EM masses of the baryons are related to the two-point correlation functions of the electromagnetic current $M_B^{EM} \sim \langle B|T[J_\mu(\mathbf{x})J^\mu(\mathbf{y})]|B\rangle \sim \langle B|\mathcal{O}^{EM}|B\rangle$ with $J^\mu(x) = e\bar{\psi}(x)\gamma_\mu Q\psi(x)$, where e stands for the electric charge and Q the quark charge operator defined as the Gell-Mann-Nishijima relation $Q = T_3 + Y/2$. Since the EM current is taken as an octet operator, we can write in the chiral quark-soliton model \mathcal{O}_{EM} in terms of collective operators

$$\mathcal{O}^{EM} = \alpha_1 \sum_{i=1}^3 D_{Qi}^{(8)} D_{Qi}^{(8)} + \alpha_2 \sum_{p=4}^7 D_{Qp}^{(8)} D_{Qp}^{(8)} + \alpha_3 D_{Q8}^{(8)} D_{Q8}^{(8)} + \alpha_4 D_{Q3}^{(8)} D_{Q8}^{(8)}, \quad (2.2)$$

where $D_{Qa}^{(8)} = (D_{3a}^{(8)} + D_{8a}^{(8)}/\sqrt{3})/2$ with the $SU(3)$ Wigner functions $D_{ab}^{(8)}$. The parameters α_i contain specific dynamics of a chiral soliton model, which will be fitted to the empirical data of the EM mass differences.¹³⁾ The results for α_i are given as follows (see Ref. 14) for details):

$$\alpha_1 = -0.87 \pm 1.40, \quad \alpha_2 = -5.33 \pm 0.92, \quad \alpha_3 = 23.93 \pm 2.29, \quad \alpha_4 = -19.88 \pm 3.18. \quad (2.3)$$

Considering the hadronic part of isospin symmetry breaking, the symmetry breaking part of the collective Hamiltonian is given as

$$\begin{aligned}
H_{\text{sb}} = & (m_d - m_u) \left(\frac{\sqrt{3}}{2} \alpha D_{38}^{(8)} + \beta T_3 + \frac{1}{2} \gamma \sum_{i=1}^3 D_{3i}^{(8)} J_i \right) \\
& + (m_s - \bar{m}) \left(\alpha D_{88}^{(8)} + \beta Y + \frac{1}{\sqrt{3}} \gamma \sum_{i=1}^3 D_{8i}^{(8)} J_i \right) \\
& + (m_u + m_d + m_s) \sigma,
\end{aligned} \tag{2.4}$$

where m_u , m_d , and m_s are the current quark masses for the up, down and strange quarks, respectively. The \bar{m} is the average of the up and down quark masses. The coefficients α , β , and γ are expressed in terms of the πN sigma term and moments of inertia of the soliton. The σ is related to the πN sigma term,¹⁵⁾ defined as

$$\sigma = -(\alpha + \beta) = \frac{2}{3} \frac{\Sigma_{\pi N}}{m_u + m_d}. \tag{2.5}$$

Using the experimental data for the masses of the baryon octet together with the two known masses of the baryon antidecuplet, i.e. $M_{\Theta^+} = 1524 \pm 0.005$ MeV and $M_{n_{10}^*} = 1685 \pm 0.012$ MeV, we can straightforwardly fit the parameters in Eq. (2.4) and all other mixing parameters appearing in the baryon wave functions. Though we are not able to predict directly the masses of Θ^+ and n_{10}^* , we will show that the present framework produces the masses of the baryon decuplet extremely well. Moreover, it provides one great advantage, compared to previous works on the mass splittings of baryons, the magnetic moments, and the axial-vector constants, because we can produce all relevant results without any ambiguity. As a bonus, we are able to determine the sigma πN term as follows: $\Sigma_{\pi N} = 53.6 \pm 7.1$ MeV.

We now present the numerical results and discuss them. Within this formalism, we want to mention that the Gell-Mann-Okubo mass formulae, Coleman-Glashow relations, and Guadagnini formulae are correctly generalized with effects of the full isospin symmetry breakings.

In Table I, we list the input data for the parameters and reproduced results for the masses of the baryon octet. With the parameters obtained, we are able to predict the masses of the baryon decuplet, which are listed in Table II. As shown in

Table I. Reproduced masses of the baryon octet. The experimental data are taken from the Particle Data Group (PDG).¹⁶⁾

	T_3	Y	Exp. (input) [MeV]	Reproduced [MeV]
p	1/2	1	938.27203 \pm 0.00008	938.28 \pm 0.04
n	-1/2	1	939.56536 \pm 0.00008	939.51 \pm 0.19
Λ	0	0	1115.683 \pm 0.006	1106.73 \pm 0.11
Σ^+	1	0	1189.37 \pm 0.07	1189.38 \pm 0.08
Σ^0	0	0	1192.642 \pm 0.024	1192.65 \pm 0.07
Σ^-	-1	0	1197.449 \pm 0.030	1197.46 \pm 0.05
Ξ^0	1/2	-1	1314.83 \pm 0.20	1314.87 \pm 0.17
Ξ^-	-1/2	-1	1321.31 \pm 0.13	1321.72 \pm 0.09

Table II. Predictions of the masses of the baryon decuplet. The experimental data are taken from the Particle Data Group (PDG).¹⁶⁾

	T_3	Y	Exp. [MeV]	Predicted [MeV]
Δ^{++}	3/2	1	1231 – 1233	1234.8 ± 0.9
Δ^+	1/2	1	1231 – 1233	1235.4 ± 0.6
Δ^0	-1/2	1	1231 – 1233	1236.6 ± 0.3
Δ^-	-3/2	1	1231 – 1233	1238.5 ± 0.3
Σ^{*+}	1	0	1382.8 ± 0.4	1383.5 ± 0.6
Σ^{*0}	0	0	1383.7 ± 1.0 (input)	1384.7 ± 0.3
Σ^{*-}	-1	0	1387.2 ± 0.5	1386.6 ± 0.3
Ξ^{*0}	1/2	-1	1531.80 ± 0.32	1532.8 ± 0.3
Ξ^{*-}	-1/2	-1	1535.0 ± 0.6	1534.7 ± 0.3
Ω^-	0	-2	1672.45 ± 0.29	1682.8 ± 0.3

Table II, the present results are in very good agreement with the existing data. We predict the masses for the Δ multiplet.^{*)} As usual, M_{Δ^-} is the heaviest among the multiplet, while $M_{\Delta^{++}}$ is the lightest. Note that we have also employed the masses of the Θ^+ and $N^*(1685)$ as input in addition to those of the baryon octet. Considering the fact that these two masses of the antidecuplet members reproduce the decuplet masses, we can conclude conversely that these input masses are compatible with the present analysis.

§3. Transition magnetic moments, axial-vector constants and the decay width of Θ^+

The GRAAL experiment¹⁷⁾ has recently announced a resonant structure around 1.67 GeV in the neutron channel of η photoproduction, which was predicted as a member of the baryon antidecuplet by Refs. 18) and 19) but not in the proton channel. This isospin asymmetry has been already pointed out by Refs. 20) and 21). A new analysis of the free proton GRAAL data²²⁾ has shown the resonance structure in the beam asymmetry at around 1685 MeV with $\Gamma \leq 15$ MeV. This resonance structure has been confirmed by the LNS-GeV- γ collaboration^{23), 24)} and by the CB-ELSA collaboration.²⁵⁾ Thus, it is also of great interest to understand the properties of $N_{10}^*(1685)$. In this section, we first want to present the results for the magnetic transition $N^* \rightarrow N$.

Since we have fixed all parameters for the baryon wave functions, we can proceed to determine the magnetic moments and axial-vector constants of the baryon antidecuplet, as done in Refs. 21), 26) and 27). As a result, we can predict the decay width of the Θ^+ . The transition electromagnetic and axial-vector form factors are defined as the following baryonic matrix elements without the second-class currents:

$$\langle B'(p') | V_\mu^\chi | B(p) \rangle = \bar{u}_{B'}(p') \left[\gamma_\mu f_1(q^2) + \frac{i\sigma_{\mu\nu} q^\nu}{2M_N} f_2(q^2) \right] u_B(p),$$

^{*)} Since the Δ isobars have broad widths, it is rather difficult to analyze their masses experimentally.

$$\langle B'(p') | A_\mu^X | B(p) \rangle = \bar{u}_{B'}(p') \left[\gamma_\mu g_1(q^2) + \frac{i\sigma_{\mu\nu} q^\nu}{M_B} g_2(q^2) \right] \gamma_5 u_B(p) \quad (3.1)$$

with $V_\mu^X = \bar{\psi}(x)\gamma_\mu\frac{1}{2}\lambda^X\psi(x)$ and $A_\mu^X = \bar{\psi}(x)\gamma_\mu\gamma_5\frac{1}{2}\lambda^X\psi(x)$. Using the experimental data for the magnetic moments and semileptonic decay constants of the baryon octet, we can determine the transition magnetic moments and axial-vector constants of the baryon antidecuplet.

Having fixed all relevant parameters for the magnetic moments, we obtain the transition magnetic moments for $N^* \rightarrow N$ as follows:

$$\mu_{pp^*} = 0.102 \pm 0.020, \quad \mu_{nn^*} = 0.157 \pm 0.026 \quad (3.2)$$

in units of the nuclear magneton μ_N . Based on these results, we can calculate the decay widths for the radiative decays $N^* \rightarrow N$

$$\Gamma_{pp^*} = 8.55 \pm 0.84 \text{ keV}, \quad \Gamma_{nn^*} = 20.38 \pm 1.71 \text{ keV}, \quad (3.3)$$

which yields the ratio

$$\Gamma_{nn^*}/\Gamma_{pp^*} = 2.4 \pm 0.3. \quad (3.4)$$

It indicates that the neutron channel is at least two times larger than the proton channel, since the η strong coupling constants are isospin independent. This conclusion is in line with Refs. 20) and 21). However, the results given in Eq. (3.3) are more quantitative than those in Refs. 20) and 21).

Using the data for semileptonic decay constants, we are able to find the transition axial-vector constant for $\Theta^+ \rightarrow N$, which leads to the decay width for $\Theta^+ \rightarrow KN$. We obtain the transition axial-vector constant

$$g_1^{\Theta^+ \rightarrow n} = 0.13 \pm 0.01. \quad (3.5)$$

The decay width for $\Theta \rightarrow KN$ is

$$\Gamma_{\Theta \rightarrow KN} = 0.80 \pm 0.12 \text{ MeV}, \quad (3.6)$$

which is comparable to what the DIANA collaboration reported, i.e. $\Gamma = 0.36 \pm 0.11 \text{ MeV}$.⁸⁾

§4. Summary and conclusion

In the present talk, we have briefly reviewed the recent investigations the mass splittings of the $SU(3)$ baryons within the chiral quark-soliton model in a model-independent approach, with the effects of isospin symmetry breaking fully considered. We have employed the experimental data for the masses of the baryon octet and the Θ^+ and $N^*(1685)$ masses to fix the model parameters. We were able to fit all the parameters including mixing parameters in the baryon wave functions. By doing that, we have obtained more consistent and reliable results of the mass splittings of baryons, compared to previous works.

Using these fixed parameters, we calculated the transition magnetic moments for the radiative decay $N^* \rightarrow \gamma N$ and the axial-vector constant for $\Theta \rightarrow KN$. The

results of the transition magnetic moments are found to be consistent with recent experimental findings: The proton channel is shown to be suppressed, compared to the neutron channel. The axial-vector constant for $\Theta \rightarrow KN$ turns out to be very small, so that as a result the decay width $\Gamma_{\Theta \rightarrow KN}$ becomes tiny: $\Gamma_{\Theta \rightarrow KN} = 0.80 \pm 0.12 \text{ MeV}$ which is consistent with the DIANA data.

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