PENTAQUARKS IN SU(3) QUARK MODEL

HUNGCHONG KIM
Department of Physics, Pohang University of Science and Technology
Pohang 790-784, Korea
E-mail: hungchon@postech.ac.kr

YONGSEOK OH
Department of Physics and Astronomy, University of Georgia
Athens, Georgia 30602, USA
E-mail: yoh@physast.uga.edu

Based on the flavor SU(3) symmetry, we classify all the possible pentaquark baryons made of four quarks and one antiquark. In particular, we present possible multiplets of pentaquarks, their interactions with mesons, and the mass relations within a multiplet. We also study the pentaquark decays in the generalized OZI rule.

1. Introduction

After the first report on the pentaquark $\Theta^+(1540)$\(^1\) and its subsequent confirmation\(^2\), there has been a huge amount of works studying pentaquark properties theoretically and experimentally. Experimentally the subsequent observation of $\Xi^{--}(1862)$ by NA49 Collaboration\(^3\) may suggest that $\Xi(1862)$ forms pentaquark antidecuplet with $\Theta^+(1540)$ as anticipated by the soliton model\(^4\). Later the H1 Collaboration reported on the existence of anti-charmed pentaquark state\(^5\), which revives the interests in the heavy pentaquark system\(^6,7,8\). However, the existence of pentaquark baryons is not fully confirmed yet as some experiments report null results for those states\(^9,10\). A summary for the experimental situation and perspectives can be found, e.g., in Refs. 11. Theoretically, many ideas have been put forward to study the exotic pentaquark states in various approaches and models\(^12,13,14\), but more detailed studies are required to understand the properties and formation of pentaquark states.

As the pentaquark baryons may be produced in photon-hadron or hadron-hadron reactions, it is important to understand their production
mechanisms and decay channels in order to confirm the existence of the pentaquark states and to study their properties. The present studies on the production reactions, however, are limited by the lack of experimental and phenomenological inputs on some couplings. In particular, those studies do not include the contributions from the intermediate pentaquark states in production mechanisms. Therefore it is desirable to classify the pentaquarks based on the flavor SU(3) symmetry albeit the experimental uncertainties for their existence. The general classification is useful not only for identifying possible pentaquarks but also for providing selection rules for their decays and the mass relations.

Of course, one can expect certain mixing among the possible multiplets. Indeed, many theoretical speculations suggest that the physical pentaquark states would be mixtures of various multiplets. Thus it is necessary to construct the wavefunctions of pentaquark baryons in terms of quark and antiquark for understanding the structure of pentaquark states. In this talk, we classify all the pentaquarks in SU(3) quark model and obtain their SU(3) symmetric interactions with other baryons. Then mass relations among the pentaquark baryons will be presented. In addition, we explore the special case when the antidecuplet-octet ideal mixing is imposed to the pentaquark baryons. The topics presented in this manuscript are discussed in more detail in Refs. 23, 24, 25.

2. General classification of pentaquarks

The SU(3) flavor symmetry is a nice platform to construct possible pentaquark multiplets. Having four-quark and one antiquark, the possible multiplets for the pentaquarks are

\[ 3 \otimes 3 \otimes 3 \otimes \bar{3} = 35 \oplus (3)27 \oplus (2)\bar{10} \oplus (4)10 \oplus (8)8 \oplus (3)1. \]  

Thus, we expect 91 different ground-state pentaquarks in total. Of course, possible multiplets can be reduced under model assumptions. We name all the pentaquarks based on hypercharge and isospin. We denote the first subscript as the multiplet that the resonance sits in and the second subscript as the isospin. For \( \Sigma \)-like resonance, for example, we have \( \Sigma_{27,2} \) belonging to the 27-plet with isospin 2. The superscript will be reserved for the charge. Obvious indices will be suppressed for simplicity.

It is straightforward to construct the highest multiplet from Eq. (1). The weight diagram for the 35-plet and our assignment for the resonances are shown in Fig. 1. The resonance \( X \), which has hypercharge \(-3\) and isospin 1/2, is interesting for future search. By eliminating the states at
Figure 1. The weight diagram for the 35-plet. Our assignment for the resonances are presented according to the specified hypercharge and isospin. In this diagram, the resonance $X$ is special by its hypercharge and isospin.

![Weight Diagram](image)

The corners in Fig. 1, one can generate the weight diagram for the 27-plet. Further successive elimination generates decuplet, antidecuplet, octet and singlet. All the resonances other than the 35-plet are listed in Table 1.

Table 1. Pentaquark baryons except the 35-plet. For the 35-plet, see Fig. 1.

| multiplet | hypercharge | isospin | particle |
|-----------|-------------|---------|----------|
| $1$       | $0$         | $0$     | $\Lambda^+$ |
| $8$       | $1$         | $1/2$   | $N^{0,+,+}$, $\Xi^{0,+,+}$ |
|           | $0$         | $1$     | $\Sigma^+,\Sigma^0,\Sigma^-$ |
|           | $0$         | $0$     | $\Delta^0$ |
|           | $-1$        | $1/2$   | $\Xi^+_1,\Xi^-_1$ |
| $10$      | $1$         | $3/2$   | $\Delta^{10,+,+},\Delta^{10,0,0},\Delta^{10,-}$ |
|           | $0$         | $1$     | $\Sigma^{10,+,+},\Sigma^{10,0,0},\Sigma^{10,-}$ |
|           | $-1$        | $1/2$   | $\Xi^{10,+,+},\Xi^{10,0,0},\Xi^{10,-}$ |
|           | $-2$        | $0$     | $\Omega^{10,+,+},\Omega^{10,0,0},\Omega^{10,-}$ |
| $27$      | $2$         | $1$     | $\Theta^{0,+,+},\Theta^{0,0,0}$ |
|           | $1$         | $3/2$   | $\Delta^{27,+,+},\Delta^{27,0,0},\Delta^{27,-}$ |
|           | $1$         | $1/2$   | $\Lambda^{27,+,+},\Lambda^{27,0,0},\Lambda^{27,-}$ |
|           | $0$         | $2$     | $\Sigma^{27,+,+},\Sigma^{27,0,0},\Sigma^{27,-}$ |
|           | $0$         | $1$     | $\Xi^{27,+,+},\Xi^{27,0,0},\Xi^{27,-}$ |
|           | $0$         | $0$     | $\Xi^{27,+,+}$ |
|           | $-1$        | $3/2$   | $\Xi^{27,+,+},\Xi^{27,0,0},\Xi^{27,-}$ |
|           | $-1$        | $1/2$   | $\Xi^{27,+,+},\Xi^{27,0,0},\Xi^{27,-}$ |
|           | $-2$        | $1$     | $\Omega^{27,+,+},\Omega^{27,0,0},\Omega^{27,-}$ |
3. Tensor notation and SU(3) Lagrangians

To get the SU(3) symmetric Lagrangian, it is useful to represent all the resonances in the tensor notation. In the tensor notation, the \((p, q)\) type of Young tableaux is represented by the tensor, \(T_{b_1 b_2 \ldots b_q}^{a_1 a_2 \ldots a_p}\), which is completely symmetric in upper and lower indices. Also it is traceless on every pair of upper and lower indices. In the tensor notation, all the pentaquark multiplets can be represented by

\[
1 : S, \quad 8 : D_{ij}^k, \quad 10 : T_{ijk}^k, \quad 27 : T_{ijkl}^k, \quad 35 : T_{ijklm}^k.
\]

(2)

Since we know how the quarks (and antiquarks) transform in SU(3), one can easily construct transformation rules for the upper and lower indices separately. Then one can assign each resonance with a specific tensor or linear combination of tensors within a multiplet. The SU(3) symmetric lagrangians can be constructed by collecting all the possible contractions of upper and lower indices. This is only way to form a SU(3) invariant under SU(3) transformation. These interactions give selection rules that can be used to search for specific pentaquarks.

For the interactions between pentaquark–baryon-octet–meson-octet, we obtain

\[
15 - 83 : g_{15-83} \bar{S} B_{i}^{k} M_{j}^{k} + (\text{H.c})
\]

\[
85 - 83 : (d + f) \bar{P}^d B_{i}^{k} M_{j}^{k} + (d - f) \bar{P}^d B_{i}^{k} M_{j}^{k} + (\text{H.c})
\]

\[
105 - 83 : g_{105-83} \epsilon_{ijk} \bar{T}_{ikm} B_{j}^{k} M_{m}^{k} + (\text{H.c})
\]

\[
\overline{105} - 83 : g_{\overline{105}-83} \epsilon_{ilm} \bar{T}_{ijk} B_{l}^{k} M_{m}^{k} + (\text{H.c})
\]

\[
275 - 83 : g_{275-83} \bar{T}_{ijkl} B_{i}^{k} M_{j}^{k} + (\text{H.c})
\]

(3)

Here we note that the 35-plet can not couple to the baryon octet and meson octet. For \(85 - 83\) case, there are two possible ways to form fully contracted terms, which lead to the famous \(f\)- and \(d\)-type interactions. It is somewhat painful to write down all the interactions in terms of the resonances that we have identified above but it can be done.

As a second set, we have pentaquark interactions with baryon decuplet...
and meson octet. They are

\[
\begin{align*}
8_5 - 10_3 & : g_8 10_3 \epsilon^{ijk} P_{ijkl} D_{jklm} M_k^m + (\text{H.c.}) \\
10_5 - 10_3 & : g_{10-10_3} D_{ijkl} D_{mkl}^3 M_j^m + (\text{H.c.}) \\
27_5 - 10_3 & : g_{27-10_3} \epsilon^{ilm} T_{ijkl}^3 D_{mkl}^3 M_j^m + (\text{H.c.}) \\
35_5 - 10_3 & : g_{35-10_3} T_{ijkl}^3 D_{ijkl}^a M_j^a + (\text{H.c.}) .
\end{align*}
\]

(4)

The interactions of pentaquark–pentaquark–meson-octet can be constructed similarly and they can be found in Ref. 25.

One remark is that the pentaquarks in the 35-plet can be measured in decuplet-octet decay. If \( X \) in the 35-plet exists, it can be measured in the unique decay mode

\[
X^-(X^-) \rightarrow K^0 \Omega^- (K^- \Omega^-) .
\]

(5)

This decay mode is not affected by the mixing among the multiplets.

4. Mass relations

To derive mass relations among pentaquarks, we note first that QCD mass terms can be written by

\[
M_{QCD} = (\bar{u} \hat{d} \bar{s}) \left( \begin{array}{ccc} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{array} \right) \left( \begin{array}{c} \bar{u} \\ \bar{d} \\ \bar{s} \end{array} \right) \quad \text{where} \quad Y = \frac{1}{3} \left( \begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{array} \right).
\]

(6)

This gives a simple recipe to construct mass terms to leading order in SU(3) breaking: the mass term can be constructed by making fully contracted terms including hypercharge matrix \( Y \). Within this prescription, we obtain the following mass formulas for each multiplet,

\[
\begin{align*}
8_5 & : a P_{ijkl}^j P_l^i + b P_{ijkl}^j Y_{ijkl}^l P_l^i + c T_{ijkl}^l Y_{ijkl}^l P_l^i \\
10_5 & : a D_{ijkl}^j D_{ijkl}^j + b D_{ijkl}^j Y_{ijkl}^l D_{ijkl}^l \\
27 & : a T_{ijkl}^j T_{ijkl}^j + b T_{ijkl}^j Y_{ijkl}^l T_{ijkl}^l + c T_{ijkl}^j Y_{ijkl}^l T_{ijkl}^l \\
35 & : a T_{ijkl}^j T_{ijkl}^j + b T_{ijkl}^j Y_{ijkl}^l T_{ijkl}^l + c T_{ijkl}^j Y_{ijkl}^l T_{ijkl}^l .
\end{align*}
\]

(7)
Note, the parameters $a, b, c$ in different multiplets should be different. Here, for the octet, we obtain the pentaquark analog of Gell-Mann–Okubo mass formula

$$2(N_8 + \Xi_8) = 3\Lambda_8 + \Sigma_8,$$

(8)
equal-spacing rule for the decuplet and antidecuplet

$$\Omega_{10} - \Xi_{10} = \Xi_{10} - \Sigma_{10} = \Sigma_{10} - \Delta_{10},$$
$$\Xi_{10},3/2 - \Sigma_{10} = \Sigma_{10} - N_{10} = N_{10} - \Theta .$$

(9)

We find additional mass relations for the 27-plet

$$3(\Sigma_{27} + \Theta_1) = 2(\Delta_{27} + 2N_{27}), \quad 3(\Xi_{27,3/2} + 2\Theta_1) = 4\Delta_{27} + 5N_{27},$$
$$3(\Xi_{27} + 2\Theta_1) = \Delta_{27} + 8N_{27}, \quad 3(\Omega_{27,1} + 3\Theta_1) = 2(\Delta_{27} + 5N_{27}) ,$$

(10)
from which we derive the GMO type relation

$$2(N_{27} + \Xi_{27}) = 3\Lambda_{27} + \Sigma_{27} ,$$

(11)
and two relations of equal-spacing-rule type

$$\Omega_{27,1} - \Xi_{27,3/2} = \Xi_{27,3/2} - \Sigma_{27,2},$$
$$\Sigma_{27,2} - \Delta_{27} = \Delta_{27} - \Theta_1.$$

(12)

For the 35-plet, we similarly obtain the followings

$$\Omega_{35} - \Xi_{35} = \Xi_{35} - \Sigma_{35} = \Sigma_{35} - \Delta_{35} = \Delta_{35} - \Theta_2 ,$$
$$X - \Omega_{35,1} = \Omega_{35,1} - \Xi_{35,3/2} = \Xi_{35,3/2} - \Sigma_{35,1} - \Sigma_{35,2} - \Delta_{5/2},$$
$$5(\Theta_2 + \Sigma_{35,2}) = 2(2\Delta_{5/2} + 3\Delta_{35}),$$
$$5(\Sigma_{35} - \Sigma_{35,2}) = -4(\Delta_{5/2} - \Delta_{35}) ,$$
$$5(\Xi_{35} - 2\Sigma_{35,2}) = -8\Delta_{5/2} + 3\Delta_{35} ,$$
$$5(\Omega_{35} - 3\Sigma_{35,2}) = -2(6\Delta_{5/2} - \Delta_{35}) .$$

(13)

5. Decay modes in the generalized OZI rule

In the diquark-diquark-antiquark model of pentaquarks, Jaffe and Wilczek advocated the ideal mixing of the antidecuplet with the octet. In this picture, the two diquarks form $\bar{f}_f$. By combining with the antiquark of $\bar{f}_f$, one can form pentaquarks belonging to the antidecuplet and octet, $\bar{f}_f \otimes \bar{f}_f = \bar{10} \oplus 8$. This multiplication in the tensor notation can be written as

$$S^{ij} \otimes q^k = T^{ijk} \oplus S^{[ij,k]} .$$

(14)
Obviously, the last part, being an octet representation, can be replaced by a two-index field $P^j_i$ as

$$S^{[ij,k]} = \epsilon^{ijk} P^j_i + \epsilon^{iik} P^j_i. \quad (15)$$

The separation into the two terms in the right-hand side is necessary to make it symmetric in $i$ and $j$. If one assumes that the pentaquark decay goes through the fall-apart mechanism, the index $k$ in Eq. (15), the index for the antiquark, should be contracted with the antiquark index of the meson field. This is in fact equivalent to the generalized OZI rule where the quark-connected diagram dominates over the quark-annihilated diagram in the pentaquark decay. In this approach, the interaction take the form

$$L_8 = g_8 \epsilon^{ilm} \overline{S}^{[ij,k]} B^j_i M^k_m + (\text{H.c.}). \quad (16)$$

Substituting Eq. (15) into Eq. (16), one has

$$L_8 = 2g_8 \overline{P}^m_i B^i_j M^k_m + g_8 \overline{P}^{im}_i M^i_j B^i_m + (\text{H.c.}). \quad (17)$$

Comparison with the standard expression for the octet baryon interactions leads to $f = 1/2$ and $d = 3/2$. Therefore, the OZI rule makes a special choice on the $f/d$ ratio as $f/d = 1/3$. \(^{21,24}\)

In Table 2, we present the decay modes of pentaquarks in the ideal mixing. The $\bar{s}s$ component has been separated in the quark wavefunctions for pentaquark baryons, normal baryons and normal mesons. The pentaquarks that do not suffer from the ideal mixing will have the same decay modes as presented in the earlier sections.

### 6. Summary

We have classified all the pentaquark baryons in the flavor SU(3). The tenor method has been facilitated in constructing their interactions with normal baryons and mesons. We have also presented the mass relations for the pentaquarks which take into account the SU(3) breaking to leading order. This will help to identify not only exotic baryons but also crypto-exotic states. Finally we have discussed the decay modes in the generalized OZI rule, which turns out be equivalent to the ideal mixing or fall-apart mechanism.

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Table 2. Couplings of the ideally mixed pentaquark baryon states. The subscripts represent states with either purely light quark-antiquark pairs or purely strange quark-antiquark pairs.

| $N^+_q$ | $N^+_{ss}$ | $N^0_q$ | $N^0_{ss}$ |
|---------|-------------|---------|-------------|
| $\pi^+ n$ | $-\sqrt{6}$ | $K^+ \Lambda$ | $-\frac{3\sqrt{2}}{2}$ | $\pi^0 n$ | $\sqrt{3}$ | $K^0 \Sigma^0$ | $-\frac{\sqrt{3}}{2}$ |
| $\pi^0 p$ | $-\sqrt{3}$ | $K^+ \Sigma^0$ | $\frac{\sqrt{2}}{2}$ | $\pi^- p$ | $-\sqrt{6}$ | $K^+ \Sigma^-$ | $\sqrt{3}$ |
| $\eta_{qq} p$ | $\sqrt{2}$ | $K^0 \Sigma^+$ | $\sqrt{3}$ | $\eta_{qq}$ | $\sqrt{3}$ | $K^0 \Lambda$ | $-\frac{3\sqrt{2}}{2}$ |
| $\eta_{ss} p$ | $-\sqrt{3}$ | $K^- n$ | $-\sqrt{3}$ |

| $\Sigma^+_q$ | $\Sigma^+_{ss}$ | $\Sigma^0_q$ | $\Sigma^0_{ss}$ |
|-------------|----------------|-------------|----------------|
| $\pi^+ \Sigma^0$ | $\sqrt{3}$ | $K^+ \Xi^0$ | $\sqrt{6}$ | $\pi^- \Sigma^0$ | $-\sqrt{3}$ | $K^0 \Xi^-$ | $-\sqrt{6}$ |
| $\pi^0 \Sigma^+$ | $-\sqrt{3}$ | $\eta_{ss} \Sigma^+$ | $-\sqrt{3}$ | $\eta_{ss} \Sigma^-$ | $\sqrt{3}$ | $\eta_{ss} \Sigma^-$ | $-\sqrt{3}$ |
| $\eta_{qq} \Sigma^+$ | $\sqrt{2}$ | $\eta_{qq} \Sigma^+$ | $\sqrt{3}$ | $\eta_{qq} \Sigma^-$ | $-\sqrt{3}$ | $\eta_{qq} \Sigma^+$ | $-\sqrt{3}$ |
| $\pi^+ \Lambda$ | $-\sqrt{3}$ | $\pi^- \Lambda$ | $\frac{3\sqrt{2}}{2}$ | $\eta_{qq} \Sigma^0$ | $-\sqrt{3}$ | $\eta_{qq} \Sigma^0$ | $-\sqrt{3}$ |
| $\eta_{qq} \Sigma^0$ | $\sqrt{3}$ | $\eta_{ss} \Sigma^0$ | $\sqrt{3}$ | $\eta_{ss} \Sigma^0$ | $-\sqrt{3}$ | $\eta_{ss} \Sigma^0$ | $-\sqrt{3}$ |
| $K_0^0 p$ | $-\sqrt{3}$ | $K^- n$ | $-\sqrt{3}$ |
| $\bar{K}^0 n$ | $\sqrt{3}$ | $K^+ n$ | $-\sqrt{3}$ |