Diquarks, pentaquarks, and dibaryons

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We explore the connection between pentaquarks and dibaryons composed of three diquarks in the framework of the diquark model. With the available experimental data on H we estimate the Pauli blocking and annihilation effects and constrain the $P=-$pentaquark $SU(3)_F$ singlet mass. Using the Θ^+ pentaquark mass, we estimate $P=-$dibaryon mass

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I. INTRODUCTION

Baryons in the conventional quark model are color singlets composed of three quarks. So their color wave function is antisymmetric. The Pauli principle requires the total wave function of three quarks to be antisymmetric. For the $L=0$ ground state baryons, their orbital wave function is symmetric. Therefore, their spin-flavor wave function is totally symmetric, corresponding to the nucleon octet and delta decuplet with positive parity. The mass splitting between the members of the $SU(6)$ multiplet is caused by either the color-spin interaction from the gluon exchange or the flavor-spin interaction from the pseudoscalar meson exchange.

The quark model has been very successful in the classification of baryons [1]. However, quantum chromodynamics (QCD) as the underlying theory of strong interaction allows a much richer baryon spectrum. In particular, there may exist hybrid baryons (qqqG) and multiquark baryons such as pentaquarks ($qqqq\bar{q}$), dibaryons (qqqqqq), etc. Since Jaffe proposed the H dibaryon in 1977 [2], there has been extensive experimental search of this state. There also exist discussions of other possible dibaryons in the literature [3,4]. Up to now, none of these nonconventional baryon states has been established experimentally except pentaquarks.

The surprising discovery of the Θ^+ pentaquark [5,6] is one of the most important events in hadron physics in recent decades. There have appeared more than 200 pentaquark papers in the literature within one year. Its quantum number, internal structure, decay mechanism, and underlying dynamics are under heated debate [7–22].

Jaffe and Wilczek proposed the diquark picture for pentaquarks [8]. The diquark is very similar to an antiquark in many aspects. This feature leads to a deep connection between pentaquarks and dibaryons which are composed of three diquarks. In this paper, we will explore this connection.

II. $P=+$PENTAQUARKS VERSUS $P=-$DIBARYONS

Within the framework of the diquark model, we discuss the connection between $P=+$pentaquarks and those $P=-$dibaryons which are composed of three diquarks and contain one orbital excitation between diquarks.

Jaffe and Wilczek proposed that the Θ^+ pentaquark is composed of two diquarks and one strange antiquark [8]. They argued that the light quarks are strongly correlated. Two light quarks tend to form a scalar diquark in the $\bar{3}_c,\bar{3}_F$ representation whenever possible. The lighter the quark mass, the stronger the correlation. The one-gluon-exchange interaction and the instanton-induced interaction seem to support such an idea.

Since the pentaquark is a color singlet, the color wave function of the two diquarks within the pentaquark must be antisymmetric 3_C. In order to get an exotic antidecuplet, the two scalar diquarks combine into the symmetric SU(3) $\bar{6}_F$:$[ud]^2$, $[ud][ds]_+$, $[su]^2$, $[su][ds]_+$, $[ds]^2$, and $[ds][ud]_+$. Bose statistics demands symmetric total wave function of the diquark-diquark system, which leads to the antisymmetric spatial wave function with one orbital excitation. The resulting antidecuplet and octet pentaquarks have $J^P=\frac{1}{2}^+,\frac{3}{2}^+$. The resulting flavor wave functions can be found in Ref. [19].

Throughout our discussion, we assume exact isospin symmetry. We denote the up and strange quark mass by m_u, m_s and the $[ud],[us]$ diquark mass by $m_{[ud]}, m_{[us]}$. Since the same quark exists in the two diquarks, the Pauli blocking effect may raise the spectrum by $E_{pb}^{L=1}$. However, the centrifugal barrier from the orbital excitation causes the two diquarks to be far apart. One expects that the Pauli blocking effect is less significant for $P=+$pentaquarks than for $P=-$pentaquarks.

In contrast, the quark and antiquark annihilation effect tends to lower the spectrum. There are two kinds of possible annihilation mechanisms. For example, the $\bar{u}$ may annihilate with the up quark in either the $[ud]$ or $[us]$ diquark. Such a mechanism lowers the pentaquark mass by E_{ann}. The second possibility is that the $\bar{u}$ and down quark in the $[ud]$ diquark annihilates into a virtual K or K^*, which may also lower the pentaquark mass by E'_{ann}. E_{ann} is possibly greater than E'_{ann}. After taking into account the Pauli blocking and annihilation effects, Θ^+ and Ξ^{--} masses are

$$M_{\Theta^+} = 2m_{[ud]} + m_s + 2E_{pb}^{L=1} - 4E'_{ann} + E_L, \quad (1)$$

$$M_{\Xi^{--}} = 2m_{[us]} + m_u + 2E_{pb}^{L=1} - 4E'_{ann} + E_L. \quad (2)$$

We list $P=+$pentaquark masses in Table I.

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TABLE I. $P=+$pentaquark masses in unit of MeV with the correction from Pauli blocking and the annihilation effects. E_L is the orbital excitation energy. We have used $E_L=240$ MeV, $E_{pb}^{L=1}=40$ MeV, and $E_{ann}=E'_{ann}=20$ MeV for illustration.

(Y,I,I_3)	$\overline{10}$		(Y,I,I_3)	**8**	
(2,0,0)	$2m_{[ud]}+m_s+2E_{pb}^{L=1}-4E'_{ann}+E_L$	1540			
$(1,\frac{1}{2},\pm\frac{1}{2})$	$\frac{1}{3}(4m_{[ud]}+2m_{[us]}+2m_s+m_u+4E_{pb}^{L=1}-4E_{ann}-8E'_{ann})+E_L$	1587	$(1,\frac{1}{2},\pm\frac{1}{2})$	$\frac{1}{3}(5m_{[ud]}+m_{[us]}+m_s+2m_u+5E_{pb}^{L=1}-5E_{ann}-7E'_{ann})+E_L$	1513
$(0,1,\pm 1)$	$\frac{1}{3}(2m_{[ud]}+4m_{[us]}+m_s+2m_u+4E_{pb}^{L=1}-4E_{ann}-8E'_{ann})+E_L$	1660	$(0,1,\pm 1)$	$\frac{1}{3}(m_{[ud]}+5m_{[us]}+2m_s+m_u+4E_{pb}^{L=1}-5E_{ann}-7E'_{ann})+E_L$	1746
(0,1,0)	$\frac{1}{3}(2m_{[ud]}+4m_{[us]}+m_s+2m_u+3E_{pb}^{L=1}-6E_{ann}-6E'_{ann})+E_L$	1647	(0,1,0)	$\frac{1}{3}(m_{[ud]}+5m_{[us]}+2m_s+m_u+3E_{pb}^{L=1}-6E_{ann}-6E'_{ann})+E_L$	1733
$(-1,\frac{3}{2},\pm\frac{3}{2})$	$2m_{[us]}+m_u+2E_{pb}^{L=1}-4E'_{ann}+E_L$	1760			
$(-1,\frac{3}{2},\pm\frac{1}{2})$	$2m_{[us]}+m_u+\frac{1}{3}(4E_{pb}^{L=1}-4E_{ann}-8E'_{ann})+E_L$	1733	$(-1,\frac{1}{2},\pm\frac{1}{2})$	$2m_{[us]}+m_u+\frac{1}{3}(5E_{pb}^{L=1}-5E_{ann}-7E'_{ann})+E_L$	1747
			(0,0,0)	$m_{[ud]}+m_{[us]}+m_u+E_{pb}^{L=1}-2E_{ann}-2E'_{ann}+E_L$	1560

The Θ^+ pentaquark was interpreted as a bound state of two diquarks and one antiquark by Jaffe and Wilczek [8]. Its mass is as low as 1530 MeV even with one orbital excitation. One may wonder whether one can get a low-lying dibaryon with $L=1$ after replacing the antiquark in Θ^+ by a diquark.

Now let us discuss $P=-$dibaryons composed of three scalar diquarks with $L=1$. Its color wave function is antisymmetric. Its spin wave function is symmetric since diquarks are scalars. Bose statistics requires the total wave function to be symmetric. Hence the product of the flavor and orbital wave function is antisymmetric. Suppose there is one orbital excitation between two diquarks: A and B. The flavor wave function of the diquark pair A and B must be symmetric, which is the same as in the $P=+$pentaquarks. When the orbital wave function is mixed symmetric (or antisymmetric), the flavor wave function must be mixed antisymmetric (or symmetric). This situation is very similar to the $L=1$ baryon multiplet in the $SU(6)_{FS}$ 70_{FS} representation. The only difference is that the diquark is a scalar. Simple group theory tells us that the resulting $P=-$dibaryons are in the 8_F representation.

To some extent, one may correspond $[ud],[us],[ds]$ diquarks to $\bar{S},\bar{D},\bar{U}$, respectively. We classify the dibaryon type depending on its $\bar{S},\bar{D},\bar{U}$ content. For example, the quark content of the proton-type dibaryon is $\overline{UUD}$ or $[ds][ds][us]$. We use the lower index "6" to denote the dibaryon. For the Λ-type (or Σ^0-type) dibaryon Λ_6 (or Σ_6^0) with the quark content $[ud][us][ds]$, its mass can be estimated as

$$M_{\Lambda_6,\Sigma_6^0}=2m_{[us]}+m_{[ud]}+E_L+2E_{pb}^{L=0}+E_{pb}^{L=1}. \qquad (3)$$

For the Ξ-type dibaryon Ξ_6 with the quark content $[ud][ud][us]$,

$$M_{\Xi_6}=2m_{[ud]}+m_{[us]}+E_L+2E_{pb}^{L=0}+2E_{pb}^{L=1}. \qquad (4)$$

For the nucleon-type dibaryon N_6 with the quark content $[us][us][ds]$,

$$M_{N_6}=3m_{[us]}+E_L+2E_{pb}^{L=0}+2E_{pb}^{L=1}. \qquad (5)$$

For the $\Sigma^{\pm}$-type dibaryon $\Sigma_6^{\pm}$, its mass can be estimated as

$$M_{\Sigma_6^{\pm}}=2m_{[us]}+m_{[ud]}+E_L+2E_{pb}^{L=0}+2E_{pb}^{L=1}. \qquad (6)$$

III. $P=-$PENTAQUARKS VERSUS $P=+$DIBARYONS

Let us move on to those dibaryons which are composed of three diquarks and have no orbital excitation. Three $\bar{3}_c$ diquarks combine into a color singlet so their color wave function is antisymmetric. Diquarks are scalars. They obey Bose statistics. Their total wave function should be symmetric. Since there is no orbital excitation between scalar diquarks, their spin and spatial wave functions are symmetric. Hence their flavor wave function must be totally antisymmetric. That is, the resulting dibaryon is a $SU(3)_F$ singlet with positive parity, which is nothing but the H dibaryon proposed by Jaffe long ago [2]. Another $P=+$dibaryon with two P waves between the diquarks could also be low-lying [23].

Within the diquark framework, it was pointed out that lighter pentaquarks can be formed if the two scalar diquarks are in the antisymmetric $SU(3)_F 3$ representation [20,24]: $[ud][su]_-$, $[ud][ds]_-$, and $[su][ds]_-$, where $[q_1q_2][q_3q_4]_- =\sqrt{\frac{1}{2}}([q_1q_2][q_3q_4]-[q_3q_4][q_1q_2])$. No orbital excitation is needed to ensure the symmetric total wave function of two diquarks since the spin-flavor-color part is symmetric. The total angular momentum of these pentaquarks is $\frac{1}{2}$ and the parity is negative. There is no accompanying $J=\frac{3}{2}$ multiplet. The two diquarks combine with the antiquark to form a $SU(3)_F$ octet and a singlet pentaquark multiplet: $\bar{3}_F\otimes 3_F =8_{\boldsymbol{F}}\oplus 1_{\boldsymbol{F}}$.

We want to emphasize that the above pentaquark singlet with negative parity is very similar to the H dibaryon. Its flavor wave function reads

$$\frac{1}{\sqrt{3}}([ud][su]_-\bar{u}+[ds][ud]_-\bar{d}+[su][ds]_-\bar{s}). \qquad (7)$$

Since the same quark exists within two diquarks, the Pauli blocking effect may raise the spectrum by $E_{pb}^{L=0}$. In contrast, the quark and antiquark annihilation effect tends to lower the spectrum by E_{ann}. Since there is no orbital excitation, the diquarks are in an S wave. $E_{pb}^{L=0}$ can be quite significant and $E_{pb}^{L=0}\gg E_{pb}^{L=1}$.

The $P=-$pentaquark singlet mass may be estimated as

$$M_1 = \frac{1}{3}(2m_u + m_s + 2m_{[ud]} + 4m_{[us]}) + E_{pb}^{L=0} - 2E_{ann} - 2E'_{ann}. \tag{8}$$

Replacing the antiquark in Eq. (7) by the corresponding diquark, we arrive at the H dibaryon with the diquark content $[ud][us][ds]$. Its mass reads

$$M_H = m_{[ud]} + 2m_{[us]} + 3E_{pb}^{L=0}. \tag{9}$$

IV. DISCUSSION

We follow Ref. [8] and use $m_u = 360$ MeV, $m_s = 460$ MeV, $m_{[ud]} = 420$ MeV, and $m_{[us]} = 580$ MeV. If we naively ignore the Pauli blocking and annihilation effects, we get

$$M_{\Lambda_6} = M_{\Theta^+} + 2m_{[us]} - m_{[ud]} - m_s = 1710 \text{ MeV}, \tag{10}$$

where we have used $M_{\Theta^+} = 1530$ MeV [5]. Such a low-lying dibaryon with negative parity is clearly in conflict with the experimental data. In other words, the Pauli blocking and annihilation effects are important.

We may make a rough estimate of $E_{pb}^{L=0}$ from available experimental information on the H dibaryon. Using the MIT bag model and the color-magnetic interaction, the H dibaryon mass was predicted to be 2150 MeV, which is 81 MeV below the $\Lambda\Lambda$ threshold 2231 MeV [2]. The lower limit of H dibaryon mass can be inferred from the double-Λ hypernuclei experiments. The reason is simple. If M_H is less than the Λ masses in the nucleus, two Λ hyperons will form a H dibaryon. Then we get

$$M_H > 2M_\Lambda - B_{\Lambda\Lambda}, \tag{11}$$

where $B_{\Lambda\Lambda}$ is the binding energy of the two Λ hyperons. Experimentally there have been a series of double-Λ hypernuclei experiments [26–31]. For example, the lower limit of H dibaryon mass was found to be (2203.7 ± 0.7) MeV by the E176 experiment [29].

On the other hand, the upper limits of the production rate of H dibaryons were found to be significantly below theoretical calculation in the mass region below 2200 MeV by several counterexperiments [32–34], which cast doubt on the existence of a deeply bound H dibaryon. For example, the E836 Collaboration found that the H dibaryon production cross section was approximately one order of magnitude smaller than theoretical calculation in the mass range from 1851 MeV to 2181 MeV using the reaction $^3\text{He}(\text{K}^-, \text{K}^+)\text{Hn}$.

If the H particle really exists, it must be very loosely bound, which is close to the $\Lambda\Lambda$ threshold. Its binding energy must be less than a few MeV according to the recent doubly Λ hypernuclei experiments [35,36]. In fact, the lower bound of H dibaryon mass was pushed to be $M_H \geqslant 2224$ MeV. Assuming that the H dibaryon really exists as a loosely bound state, we get

$$E_{pb}^{L=0} \approx 215 \text{ MeV}. \tag{12}$$

It is important to note that $E_{pb}^{L=0}$ is correlated with the diquark mass. We may adjust the values of $m_{[ud]}, m_{[us]}$ within a reasonable range to get a smaller $E_{pb}^{L=0}$.

On the other hand, both E_{ann} [25] and E'_{ann} [17] may be important numerically. At present, a reliable dynamical calculation of E_{ann} and E'_{ann} is still lacking. For a rough estimate, we use $E_{ann} \approx 20$–40 MeV, $E'_{ann} \approx 10$–30 MeV. The orbital excitation energy E_L is typically around 240 MeV. From Eq. (1), we get

$$E_{pb}^{L=1} \approx 2E'_{ann} \approx 20\text{–}60 \text{ MeV}. \tag{13}$$

The presence of the orbital excitation in the Θ pentaquark contributes an additional energy $E_L \approx 240$ MeV to its mass. However, the centrifugal barrier from the orbital excitation reduces the Pauli blocking energy from $2E_{pb}^{L=0} \approx 430$ MeV to $2E_{pb}^{L=1} \approx 20$–60 MeV. This effect and the annihilation effect $-4E'_{ann}$ work together to make the Θ^+ pentaquark a low-lying baryon.

The singlet pentaquark mass reads

$$M_1 = 1662 - 2E_{ann} - 2E'_{ann} = 1522\text{–}1602 \text{ MeV}. \tag{14}$$

Clearly this $P=-$pentaquark singlet state is very probably low-lying in the framework of the diquark model. Possible decay channels were suggested for future experimental searches in [20].

Putting everything together, we get a rough estimate of the $P=-$dibaryon mass,

$$M_{\Lambda_6} = 2270\text{–}2310 \text{ MeV}. \tag{15}$$

This $P=-$isoscalar dibaryon state is probably 40–80 MeV above the $\Lambda\Lambda, \Xi N$ threshold. So it is unstable against P-wave $\Lambda\Lambda$ and ΞN strong decays. But it is possibly stable against $\Xi N\pi$ or $\Sigma\Lambda\pi$ S-wave strong decays. Its width is expected to be not very broad. This state could be searched at RHIC.

In short summary, we have discussed the deep connections between pentaquarks and dibaryons in the framework of the diquark model. It is understood that treating diquarks as a basic building block of hadrons as constituent quarks is a strong assumption, which is neither rigorously derivable from QCD nor verified by experiments. However, there does exist a broken dynamical supersymmetry between diquarks and antiquarks. In fact, after this paper was posted to the eprint archive, there appeared another interesting paper along these lines discussing the relation between conventional antibaryons and Θ pentaquarks through the replacement of two antiquarks in the antibaryon by two diquarks [37].

If diquarks do play a crucial role in the formation of low-lying narrow pentaquarks, they should also manifest themselves in all hadrons. An ideal approach is to include both diquarks and quarks and make a reanalysis of the conventional meson and baryon spectrum together with the multiquark spectrum such as tetraquarks, pentaquarks, dibaryons, etc. The comparison of the resulting hadron spectrum with experimental data may tell us whether diquarks are appropriate low-energy degrees of freedom. Such a project is beyond the scope of the present paper. Additional work along these lines will certainly prove very helpful in clarifying the effective degrees of freedom in the treatment of multiquark states.

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