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$J^P = \frac{1}{2}^-$ Pentaquarks in Jaffe and Wilczek's Diquark Model*

ZHANG Ao[1] LIU Yan-Rui[1] HUANG Peng-Zhi[1] DENG Wei-Zhen[1] CHEN Xiao-Lin[1] ZHU Shi-Lin[1,2;1)]

1(Department of Physics, Peking University, Beijing 100871)

2(Department of Physics, Taiwan University, Taipei 106)

Abstract If Jaffe and Wilczek's diquark picture for Θ_5^+ pentaquark is correct, there should also exist a $SU_F(3)$ pentaquark octet and singlet with no orbital excitation between the diquark pair, hence $J^P = \frac{1}{2}^-$. These states are lighter than the Θ_5^+ anti-decuplet and lie close to the orbitally excited ($L = 1$) three-quark states in the conventional quark model. We calculate their masses and magnetic moments and discuss their possible strong decays using the chiral Lagrangian formalism. Among them two pentaquarks with nucleon quantum numbers may be narrow. Selection rules of strong decays are derived. We propose the experimental search of these nine additional $J^P = \frac{1}{2}^-$ baryon states. Especially there are two additional $J^P = \frac{1}{2}^-$ Λ baryons around $\Lambda(1405)$. We also discuss the interesting possibility of interpreting $\Lambda(1405)$ as a pentaquark. The presence of these additional states will provide strong support of the diquark picture for the pentaquarks. If future experimental searches fail, one has to re-evaluate the relevance of this picture for the pentaquarks.

Key words pentaquark, diquark, magnetic moments

1 Introduction

Since LEPS announced the surprising discovery of the very narrow Θ_5^+ pentaquark (uudd$\bar{s}$) around 1540MeV last year[1], many other experimental groups have claimed the observation of evidence of its existence[2—9] while a few groups reported negative results[10,11]. Preliminary experimental data indicate that Θ_5^+ is an iso-scalar. Later, NA49 Collaboration[12] reported a second narrow pentaquark Ξ_5^{--} (ddss$\bar{u}$) at 1862MeV, to which serious challenge is raised in Ref. [13]. Very recently, H1 Collaboration reported the discovery of the anticharmed pentaquark[14].

One can use some textbook group theory to write down the wave functions in the framework of quark model. Because of its low mass, high orbital excitation with $L \geqslant 2$ is unlikely. Pauli principle requires the totally anti-symmetric wave functions for the four light quarks. Since the anti-quark is in the $[11]_C$ representation, the four quark color wave function is $[211]_C$.

With $L = 0$, hence $P = -$, the 4q spatial wave function is symmetric, i. e., $[4]_O$. Their $SU(6)_{FS}$ spin-flavor wave function must be $[31]_{FS}^{210}$ which contains $[22]_F^6 \times [31]_S^3$ after decomposition into $SU(3)_F \times SU(2)_S$[15—17]. Here 210, 6 etc is the dimension of the representation. When combined with anti-quark, we get $([33]_F^{10} + [21]_F^8) \times ([41]_S + [32]_S)$, which is nothing but $(\overline{10}_F + 8_F) \times ((\frac{3}{2})_S + (\frac{1}{2})_S)$ in terms of more common notation. The total angular momentum of the four quarks in one. The resulting exotic anti-decuplet is always accompanied by a nearly degenerate octet. Their argular momentum and parity is either $J^P = \frac{3}{2}^-$ or $\frac{1}{2}^-$.

With $L = 1$ and $P = +$, the four quark $SU(6)_{OFS}$ space-spin-flavor wave function must be $[31]_{OFS}$. Only this representation can combine with $[211]_C$ color wave function

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1) E-mail: zhusl@th.phy.pku.edu.cn

to ensure that the 4q total wave functions are anti-symmetric. The 4q orbital wave function is $[31]_O$. There are several $SU(6)_{FS}$ wave functions $[4]_{FS}$, $[31]_{FS}$, $[22]_{FS}$, $[211]_{FS}$ which allow the 4q total wave function to be anti-symmetric and lead to the octet and exotic anti-decuplet[16,17].

At present there are two outstanding pending issues: the Θ_5^+ parity and its narrow width. Two earlier lattice QCD simulation favored negative parity for Θ_5^+[18] while a recent one advocates positive parity[19]. Theoretical papers can be roughly classified into two categories according to Θ_5^+ parity.

The parity of the anti-decuplet is positive in the chiral soliton model[20—22]. But the foundation of this framework is questioned in Ref. [23,24]. Several clustered quark models were constructed to let the anti-decuplet carry positive parity[25—27]. There are other models favoring positive parity[28—30].

On the other hand, QCD sum rule approach favors negative parity for Θ_5^+[31,32]. Recently in the framework of the flux tube model Θ_5^+ pentaquark is proposed to have a extremely stable diamond structure with negative parity[33]. There are also many models supporting negative parity[34—36]. Many schemes have been proposed to determine the pentaquark parity experimentally[37].

All experiments indicate the Θ_5^+ pentaquark is very narrow. More stringent constraint on its decay width comes from the reanalysis of the previous kaon nucleon scattering data, which sets an upper bound of one or two MeV[38]. Otherwise, the Θ_5^+ pentaquark should not have escaped detection. The width of a conventional baryon 100MeV above the threshold is typically 100MeV or bigger. Therefore, the extremely narrow width is very puzzling.

Recently there appeared several interesting schemes for the narrow width. Within the chiral soliton model, the coupling constants in the leading order, next-leading order and next-next-leading order large N_c expansion cancel almost completely, which leads to a narrow width[22]. It is suggested that one of two nearly degenerate pentaquarks can be arranged to decouple from the decay modes after diagonalizing the mixing mass matrix via kaon nucleon loop[39]. After constructing a special pentaquark wave function with the color-orbital part being totally anti-symmetric, the overlap amplitude between the final state and pentaquark is suppressed significantly[35], which may also explain the narrow width. Such a scheme is based on the mismatch of initial and final state spin-flavor wave functions[40,41,17]. With the stable diamond structure the system undergoes a special structural phase transition when the Θ_5^+ pentaquark decays into the planar kaon and nucleon. The non-planar flux tubes were broken and new planar ones are formed. So the decay width of the Θ_5^+ pentaquark should be small[33].

In this paper we will study the phenomenology of Jaffe and Wilczek's diquark model for the pentaquarks. We note the problem with the identification of the ideally mixed positive parity pentaquarks with the N(1710) and N(1440) is discussed extensively in Ref. [42]. If the diquark model is correct, there should exist a $SU_F(3)$ pentaquark octet and singlet with no orbital excitation between the diquark pair and $J^P=\frac{1}{2}^-$. These states are lighter than the Θ_5^+ anti-decuplet and lie close to the orbitally excited ($L=1$) three-quark states in the conventional quark model.

Our paper is organized as follows: Section I is a brief review of the field. In Section 2 we use JW's model[25] to calculate the masses and magnetic moments of the pentaquark octet and singlet which arise from $\mathbf{3_F}\otimes\bar{\mathbf{3}}_\mathbf{F}$, where the diquark-diquark system is in the flavor $\mathbf{3_F}$ and the antiquark is in the flavor $\bar{\mathbf{3}}_\mathbf{F}$. Our present pentaquark octet is in the mixed anti-symmetric representation, which is different from the mixed symmetric pentaquark octet accompanying the anti-decuplet. In Section 3 we discuss strong decays of these states. In Section 4 we derive selection rules in the case of ideal mixing. The final section is a short summary.

2 Masses and magnetic moments of the pentaquark octet and singlet

Jaffe and Wilczek[25] proposed that pentaquark states are composed of two scalar diquarks and one antiquark. Diquarks obey Bose statistics. Each diquark is in the antisymmetric color $\bar{\mathbf{3}}$ state. The psin wave function of the two quarks within each scalar diquark is antisymmetric while the spatial part is symmetric. Pauli principle requires the total wave function of the two quarks in the diquark be anti-symmetric. Thus the flavor wave function of the two quarks in the diquark must be antisymmetric, i.e., the diquark is in the flavor $\bar{\mathbf{3}}_\mathbf{F}$ state. The diquark and antiquark flavor wave functions are listed in Table 1.

Table 1. Diquark and antiquark flavor wave functions. Y, I and I_3 are hypercharge, isospin and the third component of isospin respectively. $[q_1q_2]=\frac{1}{\sqrt{2}}(q_1q_2-q_2q_1)$.

(Y,I,I_3)	flavor wave functions
$(\frac{2}{3},0,0)$	$[ud],\bar{s}$
$(-\frac{1}{3},\frac{1}{2},\frac{1}{2})$	$[su],\bar{d}$
$(-\frac{1}{3},\frac{1}{2},-\frac{1}{2})$	$[ds],\bar{u}$

The color wave function of the two diquarks within the pentaquark must be antisymmetric $\mathbf{3_C}$. In order to get an exotic anti-decuplet, the two scalar diquarks combine into the symmetric $SU(3)$ $\bar{\mathbf{6}}_\mathbf{F}$: $[ud]^2$, $[ud][ds]_+$, $[su]^2$, $[su][ds]_+$, $[ds]^2$, 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 anti-decuplet and octet pentaquarks have $J^P=\frac{1}{2}^+,\frac{3}{2}^+$.

We note that lighter pentaquarks can be formed if the two scalar diquarks are in the antisymmetric $SU(3)_F\,\mathbf{3}$ representation: $[ud][su]_-$, $[ud][ds]_-$, 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 singlet pentaquark multiplet: $\bar{3}_F\otimes 3_F=\mathbf{8_F}\oplus\mathbf{1_F}$. The flavor wave functions of the pentaquarks are listed in Table 2. Similar mechanism has been proposed to study heavy pentaquarks with negative parity and lighter mass than $\Theta_{c,b}$ in[43,44].

Table 2. Flavor wave functions and masses of the $\frac{1}{2}^-$ pentaquark octet and singlet.

	(Y,I)	I_3	flavor wave functions	masses (MeV)
p_8	$(1,\frac{1}{2})$	$\frac{1}{2}$	$[su][ud]_-\bar{s}$	1460
n_8		$-\frac{1}{2}$	$[ds][ud]_-\bar{s}$	1460
Σ_8^+	$(0,1)$	1	$[su][ud]_-\bar{d}$	1360
Σ_8^0		0	$\frac{1}{\sqrt{2}}([su][ud]_-\bar{u}+[ds][ud]_-\bar{d})$	1360
Σ_8^-		-1	$[ds][ud]_-\bar{u}$	1360
Λ_8	$(0,0)$	0	$\frac{[ud][su]_-\bar{u}+[ds][ud]-\bar{d}-2[su][ds]_-\bar{s}}{\sqrt{6}}$	1533
Ξ_8^0	$(-1,\frac{1}{2})$	$\frac{1}{2}$	$[ds][su]_-\bar{d}$	1520
Ξ_8^-		$-\frac{1}{2}$	$[ds][su]_-\bar{u}$	1520
Λ_1	$(0,0)$	0	$\frac{[ud][su]_-\bar{u}+[ds][ud]_-d+[su][ds]_-\bar{s}}{\sqrt{3}}$	1447

According to JW's model[25], the strange quark mass explicitly breaks $SU(3)_F$ symmetry. The $[ud]$ diquark is more tightly bound than $[us]$ and $[ds]$. The energy difference can be related to the Σ-Λ mass splitting. Thus, every strange quark in the pentaquark contributes $\alpha\equiv\frac{3}{4}(M_\Sigma-M_\Lambda)\approx$ 60MeV arising from $[ud]$ and $[us]$, $[ds]$ binding energy difference. The Hamiltonian in JW's model reads

$$H_s=M_0+(n_s+n_{\bar{s}})m_s+n_s\alpha, \quad (1)$$

where M_0 is the pentaquark mass in the $SU(3)_F$ symmetry limit. The last two terms are from $SU(3)_F$ symmetry breaking with $m_s\approx 100$MeV. M_0 has the form

$$M_0=2m_{di}+m_{\bar{q}}+\delta M_l, \quad (2)$$

where m_{di} is the [ud] diquark mass, m_{q} is the antiquark mass and δM_l is the orbital excitation energy. We follow Ref. [25] to use $m_{\mathrm{di}} = 420\mathrm{MeV}$, $m_{\mathrm{q}} = 360\mathrm{MeV}$ and $\delta M_l = 0$ for $l = 0$ to get $M_0 = 1200\mathrm{MeV}$. Thus we can use Eq. (1) to compute masses of the pentaquark octet and singlet. The numerical results are collected in Table 2.

There are three mass relations among the nine pentaquarks. First we get the Gell-Mann-Okubo relation for the pentaquark octet

$$2M_{\mathrm{N}_8} + 2M_{\Xi_8} = 3M_{\Lambda_8} + M_{\Sigma_8}, \qquad (3)$$

which is similar to that for the ground state octet. We also have

$$M_{\Lambda_8} - M_{\Lambda_1} = M_{\Lambda_1} - M_{\Sigma_8}$$
$$M_{\Lambda_8} - M_{\mathrm{N}_8} = M_{\Xi_8} - M_{\Lambda_1} \qquad (4)$$

The pentaquark magnetic moment has the form[45]

$$\boldsymbol{\mu} = \sum_i \boldsymbol{\mu}_i = \sum_i (g_i \boldsymbol{s}_i + \boldsymbol{l}_i)\mu_i, \qquad (5)$$

where $\boldsymbol{s}_i$, $\boldsymbol{l}_i$ are the spin and orbital momentum of the i-th constituent respectively. g_i is the g-factor of the i-th constituent and μ_i is the magneton of the i-th constituent. The spin of the scalar diquark is zero. There is no orbital momentum. So the magnetic moment of $J^P = \frac{1}{2}^-$ pentaquark $\boldsymbol{\mu}$ simply reads

$$\boldsymbol{\mu} = (g_1\mathbf{0} + \mathbf{0})\mu_1 + (g_2\mathbf{0} + \mathbf{0})\mu_2 + (g_3\frac{\mathbf{1}}{\mathbf{2}} + \mathbf{0})\mu_3 = g_3\frac{\mathbf{1}}{\mathbf{2}}\mu_3, \qquad (6)$$

where 1, 2 denote the two scalar diquarks and 3 denotes the anti-quark. It is clear that the pentaquark magnetic moment arises from the anti-quark only. Finally we get

$$\mu = \mu_{\bar{\mathrm{q}}} = \frac{e_{\bar{\mathrm{q}}}}{2m_{\bar{\mathrm{q}}}} = -\frac{e_{\mathrm{q}}}{2m_{\mathrm{q}}}, \qquad (7)$$

where $e_{\bar{\mathrm{q}}}$ is the charge of the antiquark and $m_{\bar{\mathrm{q}}}$ is the mass of the antiquark. We present the expressions and numerical results of octet and singlet pentaquark magnetic moments in Table 3.

There exist several magnetic moment relations.

$$\mu_{\Lambda_8} - \mu_{\Sigma_8^0} = 2(\mu_{\mathrm{n}_8} - \mu_{\Lambda_8}) = 2(\mu_{\Lambda_8} - \mu_{\Lambda_1})$$
$$\mu_{\Sigma_8^+} - \mu_{\Sigma_8^0} = \mu_{\Sigma_8^0} - \mu_{\Sigma_8^-}$$
$$\mu_{\mathrm{n}_8} - \mu_{\Lambda_1} = 2(\mu_{\Lambda_1} - \mu_{\Sigma_8^0})$$
$$\mu_{\mathrm{p}_8} = \mu_{\mathrm{n}_8}$$
$$\mu_{\Xi_8^0} = \mu_{\Sigma_8^+}$$
$$\mu_{\Xi_8^-} = \mu_{\Sigma_8^-}. \qquad (8)$$

We note only the second one is similar to the Coleman-Glashow relations for nucleon octet[46].

Table 3. Expressions and numerical results of the magnetic moments of the pentaquark octet and singlet, where e_0 is the charge unit.

	(Y, I)	I_3	magnetic moments	numerical results (μ_{N})
p_8	$(1, \frac{1}{2})$	$\frac{1}{2}$	$\frac{e_0}{6m_{\mathrm{s}}}$	0.63
n_8		$-\frac{1}{2}$	$\frac{e_0}{6m_{\mathrm{s}}}$	0.63
Σ_8^+	$(0, 1)$	1	$\frac{e_0}{6m_{\mathrm{d}}}$	0.87
Σ_8^0		0	$\frac{1}{6}(-\frac{e_0}{m_{\mathrm{u}}} + \frac{e_0}{2m_{\mathrm{d}}})$	-0.43
Σ_8^-		-1	$-\frac{e_0}{3m_{\mathrm{u}}}$	-1.74
Λ_8	$(0, 0)$	0	$\frac{1}{18}(-\frac{e_0}{m_{\mathrm{u}}} + \frac{e_0}{2m_{\mathrm{d}}} + \frac{2e_0}{m_{\mathrm{s}}})$	0.27
Ξ_8^0	$(-1, \frac{1}{2})$	$\frac{1}{2}$	$\frac{e_0}{6m_{\mathrm{d}}}$	0.87
Ξ_8^-		$-\frac{1}{2}$	$-\frac{e_0}{3m_{\mathrm{u}}}$	-1.74
Λ_1	$(0, 0)$	0	$\frac{1}{9}(-\frac{e_0}{m_{\mathrm{u}}} + \frac{e_0}{2m_{\mathrm{d}}} + \frac{e_0}{2m_{\mathrm{s}}})$	-0.08

3 Pentaquark chiral Lagrangian, strong decays and selection rules

In the case of pentaquark decays, if symmetry and kinematics allow, the most efficient decay mechanism is for the four quarks and anti-quark to regroup with each other into a three-quark baryon and a meson. This is in contrast to the $^3\mathrm{P}_0$ decay models for the ordinary hadrons. This regrouping is coined as the "fall-apart" mechanism in Refs. [17, 35, 40, 41].

In the following we write down the interaction chiral Lagrangian using $SU(3)_{\mathrm{F}}$ symmetry. We denote a quark and anti-quark by q^i, $\bar{\mathrm{q}}_j$ where i, j are the $SU(3)_{\mathrm{F}}$ flavor indices. Note that the flavor wave function of the $J^P = \frac{1}{2}^-$ octet and singlet pentaquark arise from

$$A_{[ij]} \otimes \bar{q}_k = S_{ijk} \oplus O_{[ij,k]}, \qquad (9)$$

where the indices ij are antisymmetric, $A_{[ij]}$ is the $\mathbf{3}_{\mathbf{F}}$ diquark pair. S is the pentaquark singlet. $O_{[ij,k]}$ is the octet representation. The index k represents the antiquark which contracts with one of the meson index.

In Ref. [47] the chiral Lagrangian is built to discuss the decay modes of the anti-decuplet and octet with positive parity. The authors pointed out that keeping explicit track of the flavor indices of the two diquarks minimize the independent coupling constants and lead to some selection rules.

For the interaction of the $J^P = \frac{1}{2}^-$ pentaquark octet P, nucleon octet B and pseudoscalar meson octet M, we have

$$\mathscr{L}_8 = g_8 \epsilon_{ilm} O^{[ij,k]} B^l_j M^m_k + H.c., \tag{10}$$

where $O_{[ij,k]} = \epsilon_{ljk} P^l_i - \epsilon_{lik} P^l_j$. The explicit form of the matrix B^i_j, M^i_j and P^i_j is

$$(P^i_j) = \begin{pmatrix} \frac{\Sigma^0_8}{\sqrt{2}} + \frac{\Lambda_8}{\sqrt{6}} & \Sigma^+_8 & p_8 \\ \Sigma^-_8 & -\frac{\Sigma^0_8}{\sqrt{2}} + \frac{\Lambda_8}{\sqrt{6}} & n_8 \\ \Xi^-_8 & \Xi^0_8 & -\frac{2\Lambda_8}{\sqrt{6}} \end{pmatrix}, \tag{11}$$

$$(B^i_j) = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}, \tag{12}$$

$$(M^i_j) = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_0}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_0}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta_0}{\sqrt{6}} \end{pmatrix}. \tag{13}$$

We present the Clebsch-Gordan coefficient of each interaction term in Table 4.

The pentaquark octet can also couple with usual baryon octet and meson singlet η_1.

$$\mathscr{L}_1 = g_1 P^j_i B^i_j \eta_1 + H.c.$$
$$= g_1(\bar{N}_8 N + \bar{\Sigma}_8 \Sigma + \bar{\Xi}_8 \Xi + \bar{\Lambda}_8 \Lambda)\eta_1 + \text{H.c.}, \tag{14}$$

where

$$N = \begin{pmatrix} p \\ n \end{pmatrix}, \Xi = \begin{pmatrix} \Xi^0 \\ \Xi^- \end{pmatrix}, \Sigma = \begin{pmatrix} \Sigma^+ \\ \Sigma^0 \\ \Sigma^- \end{pmatrix}. \tag{15}$$

The interaction among pentaquark singlet Λ_1, normal baryon octet B and meson octet M is

$$\mathscr{L}_1' = G_1 \Lambda_1 B^i_j M^j_i + H.c. = G_1 \Lambda_1 (K_c N + \pi\Sigma + K\Xi + \eta_0 \Lambda) + \text{H.c.}, \tag{16}$$

where

$$\pi = (\pi^-, \pi^0, \pi^+), K = (K^0, K^+), K_c = (K^-, \bar{K}^0). \tag{17}$$

Table 4. Coupling of the $J^P = \frac{1}{2}^-$ pentaquark octet with the usual baryon octet and the pseudoscalar meson octet. The universal coupling constant g_8 is omitted.

Ξ^-_8		Ξ^0_8		p_8		n_8	
$\Xi^-\pi^0$	$\frac{1}{\sqrt{2}}$	$\Xi^-\pi^+$	1	$\Sigma^0 K^+$	$\frac{1}{\sqrt{2}}$	$\Sigma^- K^+$	1
$\Xi^0\pi^-$	1	$\Xi^0\pi^0$	$-\frac{1}{\sqrt{2}}$	$\Sigma^+ K^0$	1	$\Sigma^0 K^0$	$-\frac{1}{\sqrt{2}}$
$\Xi^-\eta_0$	$\frac{1}{\sqrt{6}}$	$\Xi^0\eta_0$	$\frac{1}{\sqrt{6}}$	$p\eta_0$	$-\frac{2}{\sqrt{6}}$	$n\eta_0$	$-\frac{2}{\sqrt{6}}$
ΛK^-	$-\frac{2}{\sqrt{6}}$	$\Lambda\bar{K}^0$	$-\frac{2}{\sqrt{6}}$	ΛK^+	$\frac{1}{\sqrt{6}}$	ΛK^+	$\frac{1}{\sqrt{6}}$
Σ^0_8		Σ^+_8		Σ^-_8		Λ_8	
$\Sigma^+\pi^-$	$\frac{1}{\sqrt{2}}$	$\Sigma^+\pi^0$	$-\frac{1}{\sqrt{2}}$	$\Sigma^-\pi^0$	$\frac{1}{\sqrt{2}}$	$\Sigma^+\pi^-$	$\frac{1}{\sqrt{6}}$
$\Sigma^-\pi^+$	$-\frac{1}{\sqrt{2}}$	$\Sigma^0\pi^+$	$\frac{1}{\sqrt{2}}$	$\Sigma^0\pi^-$	$-\frac{1}{\sqrt{2}}$	$\Sigma^-\pi^+$	$\frac{1}{\sqrt{6}}$
$\Sigma^0\eta_0$	$\frac{1}{\sqrt{6}}$	$\Sigma^+\eta_0$	$\frac{1}{\sqrt{6}}$	$\Sigma^-\eta_0$	$\frac{1}{\sqrt{6}}$	$\Sigma^0\pi^0$	$\frac{1}{\sqrt{6}}$
pK^-	$\frac{1}{\sqrt{2}}$	$p\bar{K}^0$	1	nK^-	1	pK^-	$\frac{1}{\sqrt{6}}$
$n\bar{K}^0$	$-\frac{1}{\sqrt{2}}$	$\Lambda\pi^+$	$\frac{1}{\sqrt{6}}$	$\Lambda\pi^-$	$\frac{1}{\sqrt{6}}$	$n\bar{K}^0$	$\frac{1}{\sqrt{6}}$
$\Lambda\pi^+$	$\frac{1}{\sqrt{6}}$					$\Xi^- K^+$	$-\frac{2}{\sqrt{6}}$
						$\Xi^0 K^0$	$-\frac{2}{\sqrt{6}}$
						$\Lambda\eta_0$	$-\frac{1}{\sqrt{6}}$

Since the parity of these pentaquarks is negative, they will decay via S-wave if kinematics allows. With the mass values in Table 2, it is easy to find out which decay process will occur.

According to our mass estimate, only p_8, n_8 are below the threshold of the listed decay modes in Table 4. At first sight, there is no strong decay modes for them. They should be stable particles.

However, there are multiple-pion decays modes which violate the "fall-apart" mechanism, such as S-wave $p_8 \to N\pi$, P-wave $p_8 \to N\pi\pi$ and S-wave $p_8 \to N\pi\pi\pi$ where N is either a proton or neutron.

Another possibility is the isospin violating strong decay mode $p_8 \to p\eta_0 \to p\pi$. The virtual intermediate state $p\eta_0$ helps this process happen. The first step satisfies the "fall-apart" mechanism. Then the virtual η_0 turns into a real pion through isospin violating effects. All these processes contribute to the decay width of p_8, n_8. However both p_8 and n_8 should still be narrow resonances.

4 Additional selection rules in the ideal mixing case for the $I=0$ sector

For the $I=0$ channel, physical states are the mixture of octet and singlet states. For example, the physical η, η' are the mixture of η_0 and η_1 where η_0 is the pure octet member and η_1 is the pure singlet. In the following we will let the mixing angle deviate from the physical value.

$$\eta = \eta_0\cos\theta - \eta_1\sin\theta$$
$$\eta' = \eta_0\sin\theta + \eta_1\cos\theta. \quad (18)$$

From the above we have

$$\eta_0 = \eta'\sin\theta + \eta\cos\theta$$
$$\eta_1 = \eta'\cos\theta - \eta\sin\theta. \quad (19)$$

The mixing of Λ_8 and Λ_1 is defined as

$$\Lambda_n = \Lambda_8\cos\varphi - \Lambda_1\sin\varphi$$
$$\Lambda_s = \Lambda_8\sin\varphi + \Lambda_1\cos\varphi. \quad (20)$$

Now the interaction terms involving $I=0$ states are

$$\begin{aligned}\mathscr{L}_{\rm mixing} = & g_8\{(\bar\Sigma_8\Sigma + \bar\Xi_8\Xi)\eta'(\frac{1}{\sqrt6}\sin\theta + a\cos\theta) + \\ & (\bar\Sigma_8\Sigma + \bar\Xi_8\Xi)\eta(\frac{1}{\sqrt6}\cos\theta - a\sin\theta) + \\ & N_8N\eta'(-\frac{2}{\sqrt6}\sin\theta + a\cos\theta) + \\ & N_8N\eta(-\frac{2}{\sqrt6}\cos\theta - a\sin\theta) + \\ & \Lambda_s(\pi\Sigma + K_cN)(\frac{1}{\sqrt6}\sin\varphi + b\cos\varphi) + \\ & \Lambda_n(\pi\Sigma + K_cN)(\frac{1}{\sqrt6}\cos\varphi - b\sin\varphi) + \\ & \Lambda_sK\Xi(-\frac{2}{\sqrt6}\sin\varphi + b\cos\varphi) + \\ & \Lambda_nK\Xi(-\frac{2}{\sqrt6}\cos\varphi - b\sin\varphi) + \\ & \bar\Lambda_s\Lambda\eta'(-\frac{1}{\sqrt6}\sin\varphi\sin\theta + a\sin\varphi\cos\theta + b\cos\varphi\sin\theta) + \\ & \bar\Lambda_s\Lambda\eta(-\frac{1}{\sqrt6}\sin\varphi\cos\theta - a\sin\varphi\sin\theta + b\cos\varphi\cos\theta) + \\ & \bar\Lambda_n\Lambda\eta'(-\frac{1}{\sqrt6}\cos\varphi\sin\theta + a\cos\varphi\cos\theta - b\sin\varphi\sin\theta) + \\ & \bar\Lambda_n\Lambda\eta(-\frac{1}{\sqrt6}\cos\varphi\cos\theta - a\cos\varphi\sin\theta - b\sin\varphi\cos\theta)\} + \\ & H.c. \end{aligned} \quad (21)$$

where $a = \frac{g_1}{g_8}$, $b = \frac{G_1}{g_8}$.

In the extreme case of ideal mixing, i.e., $\tan\theta = \tan\varphi = -\sqrt2$, we have

$$\Lambda_s = [su][ds]_-\bar s$$
$$\Lambda_n = \frac{1}{\sqrt2}([ud][su]_-\bar u + [ds][ud]_-\bar d)$$
$$\eta' = s\bar s$$
$$\eta = \frac{1}{\sqrt2}(u\bar u + d\bar d). \quad (22)$$

The so-called "fall-apart" mechanism requires that there is no annihilation or creation of quark pairs when pentaquarks decay. So the coefficient of the fourth and eighth terms must vanish in the limit of ideal mixing. In this way, we get

$$a = b = \frac{1}{\sqrt3}. \quad (23)$$

The three coupling constants g_1, G_1, g_8 are related to each other in this limit.

Now Eq.(21) has a simple form

$$\begin{aligned}\mathscr{L}_{\rm mixing} = & \frac{1}{\sqrt2}(\Sigma_8\Sigma + \Xi_8\Xi)\eta + N_8N\eta' + \\ & \frac{1}{\sqrt2}\Lambda_n(\pi\Sigma + K_cN) + \Lambda_sK\Xi - \\ & \frac{2}{\sqrt6}\Lambda_s\Lambda\eta' + \frac{1}{\sqrt6}\Lambda_n\Lambda\eta + (H.c.). \end{aligned} \quad (24)$$

The decay modes of Λ_s and Λ_n are

$$\Lambda_s \to K\Xi - \frac{2}{\sqrt6}\Lambda\eta'$$
$$\Lambda_n \to \frac{1}{\sqrt2}(\pi\Sigma + K_cN) + \frac{1}{\sqrt6}\Lambda\eta. \quad (25)$$

The above relation is the selection rule from the "fall-apart" mechanism in the ideal mixing limit.

It's very interesting to note that the only dynamically allowed two decay modes of Λ_s are kinematically forbidden since Λ_s is below the threshold. Therefore, Λ_s will not decay via strong interaction. It is a longlived stable particle in the ideal mixing case. For Λ_n the only both dynamically and kinematically allowed decay mode is $\pi\Sigma$. Unfortunately, the physical η and η' are not ideally mixed. So the results obtained in this section may be different from the realistic case, therefore not very useful.

5 Discussion

We have shown that there exist an octet and singlet pentaquark multiplet with $J^P = \frac{1}{2}^-$ in the framework of Jaffe and Wilczek's diquark model. We have calculated their masses and magnetic moments. Several interesting mass and magnetic moment relations are derived. We have also constructed the chiral Lagrangian for these pentaquarks. Possible strong decay modes are discussed. We have derived selection rules based on the "fall-apart" decay mechanism. In this limit there exists a long-lived stable $J^P=\frac{1}{2}^-$ Λ_s pentaquark which will not decay via strong interaction.

Because there is no orbital excitation within these nine pentaquarks, their masses are lower than the anti-decuplet and the accompanying octet with positive parity. Their masses range between 1360MeV and 1540MeV according to our calculation using the same mass formula in Ref. [25]. These states are close to the $L=1$ orbital excitations of the nucleon octet. The mixing between the pentaquark states and orbital excitations is expected to be small since their spatial wave functions are very different.

According to our calculation, two of the $J^P=\frac{1}{2}^-$ octet pentaquark members p_8, n_8 lie 22MeV below the $p\eta_0$ threshold and 228MeV below the ΣK threshold. The "fall-apart" decay mechanism forbids p_8 to decay into one nucleon and one pion. Although their interaction is of S-wave, lack of phase space forbids the strong decays $p_8\to p\eta_0$, ΣK to happen.

For p_8, the only kinematically strong decays are S-wave $p_8\to p\pi$, P-wave $p_8\to N\pi\pi$ and S-wave $p_8\to N\pi\pi\pi$ decays where N is either a proton or neutron. All these decay modes involve the anihilation of a strange quark pair and violate the "fall-apart" mechanism. Hence the width is expected to be small. Both p_8 and n_8 may be narrow resonances.

It is interesting to note there are three negativeparity Λ particles within the range between 1400MeV and 1540MeV if Jaffe and Wilczek's diquark model is correct. One of them is the well established $\Lambda(1405)$. $\Lambda(1405)$ is only 30MeV below kaon and nucleon threshold. Some people postulated it to be a kaon nucleon molecule[48]. We propose that there is another intriguing possibility of interpreting Λ (1405) as the candidate of $J^P=\frac{1}{2}^-$ pentaquark. The other $J^P=\frac{1}{2}^-$ pentaquark and the corresponding $L=1$ singlet Λ particle may have escaped detection so far.

The discovery of nine additional negative-parity baryons in this mass range will be strong evidence supporting the diquark model. On the other hand, if future experimental searches fail to find any evidence of these additional states with negative parity, one has to re-evaluate the relevance of the diquark picture for the pentaquarks.

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Jaffe与Wilczek双夸克模型中的负宇称五夸克态*

张翱[1] 刘言锐[1] 黄鹏志[1] 邓卫真[1] 陈晓林[1] 朱世琳[1,2;1)]
1(北京大学物理学院理论物理研究所 北京 100871)
2(台湾大学物理系 台北 106)

摘要 如果Jaffe与Wilczek关于Θ_5^+五夸克态的双夸克图像是正确的话,那就应该存在负宇称的五夸克$SU(3)$八重态与单态,其中两个双夸克间没有轨道激发.这些态比Θ_5^+质量低,与传统夸克模型中的由三夸克构成的重子的轨道激发质量接近.我们计算了这些负宇称态的质量与磁矩,用手征有效拉氏量讨论了他们可能的强衰变模式和选择定择,发现有两个态可能比较窄.我们建议实验上寻找这九个额外的负宇称态.如果将来的实验确实发现了这些态,那是对Jaffe与Wilczek双夸克模型的直接验证.否则,应该重新评估Jaffe与Wilczek的双夸克图像甚至抛弃这个模型.

关键词 五夸克态 双夸克 磁矩

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1) E-mail: zhusl@th.phy.pku.edu.cn