Article ID: 1007－4627(2009)Suppl.－0190－04

Charmed Baryon in Diquark Model*

WANG Qing-wu[1,3], ZHANG Peng-ming[1,2]
(1 *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou* 730000, *China*;
2 *Center of Theoretical Nuclear Physics, National Laboratory of*
Heavy Ion Research Facility in Lanzhou, Lanzhou 730000, *China*;
3 *Graduate School of Chinese Academy of Sciences, Beijing* 100049, *China*)

Abstract: A diquark model is used to investigate single-charmed baryons. In this model, baryon is composed of two diquarks and an antiquark. Masses of lowest lying states with $J^P=1/2^{\pm}$ are obtained. Baryons in our results are as heavy as other theoretic predictions and we suggest that the five-quark components should be considered in any three-quark model for studying the charmed baryons.

Key words: charm; diquark; pentaquark
CLC number: O572.33　　　**Document code**: A

1 Introduction

Recently many new excited charmed baryon states have been discovered by CLEO, BaBar, Belle and Fermilab. Heavy baryons have narrow widths and they are hard to produce. As products in the decays of heavy mesons or in hadron colliders, the cross sections to produce them are small. There are no resonant production mechanisms as in heavy mesons. So, heavy baryons always have been obtained by continuum production[1]. However, their quantum numbers, listed in the PDG book, are not really measured, but assignments based on quark model[2].

Heavy baryons provide a laboratory to study the dynamics of the light quarks in the environment of heavy quark, such as the chiral symmetry[3]. It really is an ideal place for studying the dynamics of diquark. In these baryons, a heavy quark can be used as a ‘ flavor tag’ to help us to go further in understanding the nonperturbative QCD than do the light baryons[1]. Theoretically, the study of heavy baryons has a long story[4－6]. But, up to now, simple and reliable estimations are still lack for the experimental quantities regarding to the baryon spectroscopy, the production and decay rates.

At present, masses of ground states as well as many of their excitations are known experimentally with rather good precision only for single-charmed baryons. The spectrum of the single-charmed baryons provides us a framework to study baryons with one bottom quark, which is also very helpful for us to understand the doubly or triply charmed baryons. In this paper, we extend the Jaffe-Wilczek[7] model to predict masses of single-charmed pentaquark states with $J^P=1/2^{\pm}$. In the following section we introduce the diquark and the Jaffe-Wilczek(J-W) model. In section 3 we give the mass

---

* **Received date**: 13 Nov. 2008; **Revised date**: 8 Apr. 2009
* **Foundation item**: Knowledge Innovation Project of Chinese Academy of Sciences(KJCX2-SW-No16, KJCX2-SW-No2); National Natural Science Foundation of China(10435080, 10575123); Western Light Talents Training Program of Chinese Academy of Sciences; Scientific Research Foundation for Returned Scholars, Ministry of Education of China
Biography: Wang Qing-wu(1979-), male(Han Nationality), Dazhu, Sichuan, China, working on the field of particle physics; E-mail: qw.wang@impcas.ac.cn

formula and our results. In the end, a short discussion will be given.

2 Diquark and J-W Model

The concept of diquark appeared soon after the original papers on quarks[8-10], which was used to consider the hadron properties. It helps us to understand hadron structure and high energy particle reactions [11]. In heavy quark effective theory, two light quarks are often referred as a diquark, which is treated as particle in parallel with quark itself. There are several phenomenal manifestations of diquark: the Σ-Λ mass difference, the isospin $\Delta I = 1/2$ rule, the structure function ratio of neutron to proton and so on[12, 13]. There are two kinds of diquarks, the good diquark and the bad diquark. The good diquark is more favorable energetically than the bad one, which is indicated by the one-gluon exchange and instanton calculations. In $SU_F(3)$, the good diquark has flavor-spin symmetry $\bar{3}_F\bar{3}_S$ while the bad diquark has 6_F6_S. To give a color singlet state, both kinds of diquark have the same color symmetry $\bar{3}_C$. Two diquarks obey Boson statistic while two quarks within a diquark obey Fermi statistic.

Jaffe and Wilczek's pentaquark is composed of two good diquarks and an antiquark. The two diquarks combine into a color anti-symmetric 3_C and flavor symmetric $\bar{6}_F$ with components: $[ud]^2$, $[us]^2$, $[ds]^2$, $[ud][us]_+$, $[ud][ds]_+$ and $[us][ds]_+$. In the following, we use [qq] to denote a good, scalar diquark and (qq) a bad, vector diquark. The spin wave function is symmetric because the diquark has spin zero. To give a totally symmetric wave function for the two diquarks subsystem, an orbital excitation between the two diquarks is needed which combines the spin of antiquark to give state $J^P = 1/2^+$ and $J^P = 3/2^+$.

Two diquarks can also combine into $SU_F(3)$ symmetric 3_F, with no orbital excitation[14]. Take the antiquark into account, we can obtain states with $J^P = 1/2^-$. In summary, we list the quantum numbers of these diquark systems in Table 1.

Table 1 Summary of diquark quantum numbers. The two quarks obey Fermi statistics while the diquarks do Boson. The subscripts a and s are anti-symmetric and symmetric for short

Quark combinations	Flavor	Color	Spin	Orbital
Gook diquark	$\bar{3}_a$	$\bar{3}_a$	$s=0_a$	$l=0_a$
Bad diquark	6_s	$\bar{3}_a$	$s=1_a$	$l=0_a$
2 diquarks	$\bar{6}_s$	$\bar{3}\times\bar{3}\rightarrow 3_a$	$s=0_a$	$l=1_a$
	$\bar{3}_s$	$\bar{3}\times\bar{3}\rightarrow 3_a$	$s=0_a$	$l=0_a$

The combination of two diquarks with an antiquark gives $SU_F(3)$ multiplets $8\oplus\overline{10}$ for flavor $\bar{6}_F$ and $8\oplus 1$ for 3_F. By replacing a strange quark with a charm quark, we get states of charmed or hidden charmed baryons. In this paper, we only consider baryons with one charm quark and with no charm antiquark.

3 Mass Formula and Spectrum

If we take the mass of baryon to be the sum of the masses of its components and other main contribution to its energy, a schematic mass formula of the pentaquark reads

$$M = m_{D1} + m_{D2} + m_q + E_L. \qquad (1)$$

Here, m_{Di} is the diquark mass, m_q the antiquark mass and E_L the orbital exciting energy.

Firstly, let's check the good diquark mass. Taking the $SU(2)$ isospin symmetry into account, we need to know the diquark masses of [ll], [ls] and [lc], with l and l′ being the up or down quark respectively. There is no [sc] diquark, since it is obtained by substituting one strange quark to one charm quark and the diquark is flavor antisymmetric. We can get the diquark mass by adding the two quark mass and their binding energy. The binding energy of [lc] can be obtained, with a coefficient 3/4 as in J-W's paper, from the mass difference of $\Sigma_c(2455)$ and $\Lambda_c(2285)$ which are composed of a diquark and an antiquark. We see in Table 1 that two quarks having a closer mass are more tightly bound which may be indicated by the spin-spin interaction. Then, we go to the bad diquark mass. From the spin-spin interaction a mass splitting

$$(ud)-[ud]>(us)-[us]>(uc)-[uc]\approx 0 \tag{2}$$

is expected.

Moreover, a generalized Chew-Frautschi formula relating baryon mass to orbital angular momentum is

$$E=\sqrt{\sigma L}+kL^{-1/4}(m_1^{3/2}+m_2^{3/2}), \tag{3}$$

with $k\approx 1.15\ \mathrm{GeV}^{-1/2}$ and $\sigma\approx 1.1\ \mathrm{GeV}^2$[12, 13]. Here, m_1 and m_2 are the diquark and quark mass respectively. In Ref. [12, 13], N(1 680) with good diquark [ud] and Δ(1950) with bad diquark (ud) are assigned to have orbital angular momentum $L=2$. By using the formula (3) they give the diquark mass splitting

$$(ud)^{3/2}-[ud]^{3/2}\simeq 0.28\ \mathrm{GeV}^{3/2}. \tag{4}$$

Similarly, the mass difference of Σ(2030) and Σ(1915) leads to

$$(us)^{3/2}-[us]^{3/2}\simeq 0.12\ \mathrm{GeV}^{3/2}. \tag{5}$$

From these diquark mass splitting relations we can get the bad diquark masses. In the end, all the parameters we will use are $m_c=1650$ MeV, $m_s=460$ MeV and $m_l=360$ MeV for quark masses and $m_{[ll']}=420$ MeV, $m_{[ls]}=580$ MeV, $m_{[ll']}=637$ MeV, $m_{(ls)}=680$ MeV, $m_{[lc]}=m_{(lc)}=1\,883$ MeV.

If we take the ideal mixing for $8\oplus\overline{10}$and $8\oplus 1$ respectively, the flavor assignments of charmed pentaquarks composed of good diquark are $[ll][lc]\bar{l}$ for Σ_c and Λ_c and $[ls][lc]\bar{l}$ for Ξ_c. Because the mass of [cs] is unknown, we will not consider Ω_c. Furthermore, in equation (1) we have not considered the splitting of the $J^P=1/2^+$ and $J^P=3/2^+$ states. The $J^P=1/2^+$ is generally lower in energy, so we take equation (1) as the mass formula for states $J^P=1/2^+$. The $J^P=1/2^-$ state with no orbital angular momentum is a little simple. With a substitution of bad diquark for good diquark, we can get more masses of single charmed baryons. Since the bad diquark is a spin triplet, we encounter the problem as before both for the pentaquark. We still only take states with $J=1/2$.

All the masses of single charmed baryons we have obtained are showed in Fig. 1. They are 2 663, 2 903, 2 916 and 3 156 MeV for Σ_c and Λ_c, 2 823, 3 063, 2 923 and 3 163 MeV for Ξ_c. For a comparison, the experimental data are also listed there. The Σ_c and Λ_c have the same predicted masses, because we can't distinguish them with the formula (1). The Λ_c(2663) $J^P=1/2^-$ is a little above the experimental doublet Λ_c(2595) $J^P=1/2^-$ and Λ_c(2628) $J^P=3/2^-$. And the Ξ_c(2823) is so close to the doublet Ξ_c(2790) and Ξ_c(2815). The predicted Λ_c(3065) and Σ_c(3165) is too heavy and there is no experimental date.

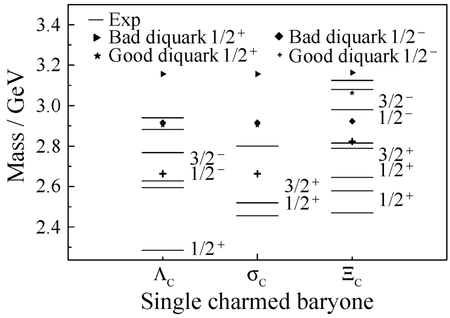

Fig. 1 The single-charmed baryon spectroscopy. The 'good diquark' labels baryons having two good diquarks, while 'bad diquark' labels baryons having one good diquark and one bad diquark.

Now, we compare our results for baryons of $J^P=1/2^-$ with some early theoretic predictions based on three-quark model. In Ref. [6], the constituent quarks interact via exchanges of pseudoscalar mesons of the $SU_F(3)$ octet in addition to the harmonic confinement potential. For charm quark, the hyperfine interaction is mediated by D or D_s. They have predicted Λ_c(2609, 2643, 2655), Σ_c(2654, 2693, 2747) and Ξ_c(2752, 2787, 2898, 2851, 2886, 2792) for the negative parity with $L=1$. Different values of the same baryon come from different spin-flavor symmetry. Compared with our results, we see that our results are almost in the range of their results except for the $\Lambda_c(2663)$ which is just a little above the heaviest one $\Lambda_c(2655)$. Roberts and Pervin[1] have used a non-relativistic quark model Hamiltonian, similar to that used by Isgur and Karl and considered the heavy quark approximation. Their results are $\Lambda_c(2625, 2816)$, $\Sigma_c(2748, 2768)$ and $\Xi_c(2763, 2773, 2859, 2855)$. The different values of the same baryon are of different $SU_F(4)$ multiplets and mixing of the multiplets. Still, our results are in the range of their results. One can find that the pentaquark states have comparable energies with the three-quark ones. So, we suggest including pentaquark components in addition to three quark ones in constitute quark model.

Lastly, we just simply discuss decays of these baryons. The binding energy of charmed diquark is relatively small. In the "fall-apart" mechanism, i. e. , the constituent quarks decay into the final baryon and meson without changing flavor, the dominant decay mode of these five quark objects is to decay into a three-quark charmed baryon and a π meson. For example, the $J^P=1/2^-$ $\Sigma_c(\Lambda_c)$ with mass 2 663 MeV can decay into the $J^P=1/2^+$ $\Lambda_c(2285)$ or $\Sigma_c(2455)$. We note that in the early paper of Copley[4] the decay of $\Lambda_c(2510, J^P=1/2^-)$ to $\Sigma_c(2455, J^P=1/2^-)$ and $\pi$is forbidden by the principle of energy conservation.

4 Summary and Discussion

In this paper, we have extended the Jaffe-Wilczek's diquark model for $J^P=1/2^+$ pentaquark to deal with charmed baryons. We have given a spectrum of $P=\pm1$ lowest lying charmed pentaqurank and compared them with experimental data and other theoretical results. In our model, the masses of pentaquark states have comparable energies with those of the three-quark states. So it is interesting to combine the three-quark and five-quark components in constituent quark model.

The mass formula we have used is just schematic. It is instructive to include mass contribution from the Pauli blocking and annihilation effects[16]. However, it is somewhat difficult to calculate them quantificationally. It is conjectured that energy contribution from Pauli blocking satisfies $E_{\mathrm{pb}}^{L=0} > E_{\mathrm{pb}}^{L=1}$, which means the two- diquark subsystem of flavor symmetry 3_F is heaver than the one of $\bar{6}_F$[13, 16]. If so, the mass of the states with $J^P=1/2^-$ will be a little heavier than that of our predictions.

Acknowledgments The author Wang thanks Dr. B. S. Zou for his helpful instruction and hospitality in doing this work and thanks J. J. Xie and C. S. An for their useful discussions.

References:

[1] Roberts W, Pervin M. Int J Mod Phys, 2008, A23: 2 817.

[2] Amsler C, Doser M, Antonelli M, *et al*. (Particle Data Group), Phys Lett, 2008, B667: 1.

[3] Cheng H Y. arXiv: hep-ph/07090958.

[4] Copley L A, Isgur N, Carl G. Phys Rev, 1979, D20: 768.

[5] Capstick S, Isgur N. Phys Rev, 1986, D34: 2 809.

[6] Glozman L Y, Riska D O. Nucl Phys, 1996, A603: 326; Glozman L Y, Riska D O. Nucl Phys, 1997, A620: 510.

[7] Jaffe R, Wilczek F. Phys Rev Lett, 2003, 91: 232 003.

[8] Gell-Mann M. Phys Lett, 1964, 8: 214.

[9] Ida M, Kobayashi R. Prog Theor Phys, 1966, 36: 846.

[10] Lichtenberg A, Tassie L. Phys Rev, 1967, 155: 1 601.

[11] Anselmino M, Predazzi E, Ekelin S, *et al*. Rev Mod Phys, 1993, 65: 1 199.

[12] Selem A, Wilczek F. arXiv: hep-ph/0602128.

[13] Wilczek F. arXiv: hep-ph/0409168.

[14] Zhang A, Liu Y R, Huang P Z, *et al*. High Energy Physics and Nuclear Physics, 2005, 29: 250.

[15] Artuso M, Ayad R, Boulahouache C, *et al*. Phys Rev Lett, 2001, 86: 4 479.

[16] Zhu S L. Phys Rev, 2004, C70: 045 201.