International Journal of Scientific & Engineering Research Volume 4, Issue 1, January-2013
ISSN 2229-5518

# Heavy Quark – Light Diquark Approach to a Heavy Baryon in the Heavy Quark Symmetry Limit

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**Abstract**— The masses and distance configurations of the ground and excited states of heavy – charmed and bottom baryons $J^P = 1/2^{+-}, 3/2^{+-}$,containing a single heavy quark and a light diquark are studied within HQS limit of the HQLD sector of NRQCD framework. We find how the average distances between the heavy quark and the center of mass of the light diquark are smaller than the size of the light diquark which is in agreement with expectations from QCD sum rules and lattice QCD calculations.

**Keywords –** Baryon , Diquark , Heavy Baryon , Lattice QCD , Quark Mass , Quark Symmetry , Sum Rule .

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## 1 INTRODUCTION

THEORETICALLY, the study of heavy baryons has always been interesting [1] and these baryons play an important role in our understanding of QCD at the hadronic scale [2]. There is many theoretical treatments of heavy baryons, including quark models [3] - QCD sum rules [4] - Lattice QCD [5] – Relativistic quark diquark approximation [6] and Non relativistic QCD ( NRQCD ) which has been able to explain the mass spectrum of light baryons and is an effective field theory which is obtained from QCD by integrating out modes of energy of the order of the heavy quark masses [8] for describing baryons made of one or more heavy quarks. The heavy quark light diquark ( HQLD) sector of NRQCD lagrangian is a heavy quark effective theory ( HQET ) . In this effective field theory framework ( EFT ) of heavy baryons where the typical gluon momenta are small compared with the heavy quark mass $m_Q$ , QCD dynamics of light diquark is independent of the flavor and spin of heavy quark [9] . For the heavy flavors , this new symmetry called heavy quark symmetry [ HQS ][10] . In fact in this limit of heavy quark mass, low energy QCD dynamics remains non-perturbative but using HQS one can separate the light quark and gluon dynamics from that of heavy one by systematically expanding the QCD lagrangian in powers of $1/m_Q$ and imposing HQS effects [11] . According to these effects in heavy baryons the light degrees of freedom quantum numbers are well defined up to corrections in the inverse of the $m_Q$ . Consequently the heavy quark momentum is close to the kinetic momentum resulting from the hadron motion. Thus the kinetic energy of the internal motion of the heavy baryon system is close to the kinetic energy of the relative motion of the heavy quark and light diquark up to corrections of the $m_L / m_Q$ where L , denotes a light quark.This is one of the basis for treating the light quark subsystem as a diquark in our calculations . The quark-diquark picture of a baryon is the nice approximation used to describe the baryon properties [12] . In this picture we reduce the task of treating a three body system to a two body system which is a successful task specially where we approximate the heavy quark mass to be infinity with respect to mass scale in process [13], and hence enormously reduces the complexity of theoretical analysis .The paper is organized as follows . In section 2 we ntroduce HQS effects for heavy baryons and calculate their mass spectrum using this symmetry limit . Finally section 3 devoted to conclusions and results.

## 2 HQS LIMIT

Theoretically, the full QCD Lagrangian for a heavy quark ( c , b or t ) is given by

$$L_Q = Q\,(i\gamma_\mu D^\mu - m_Q)\,Q, \qquad (1)$$

where $D^\mu \equiv \partial^\mu - i g_s T^a A^{a\mu}$ with $T^a = \lambda^a/2$ .Thus the heavy quark interacts with the light degrees of freedom by exchanging gluons with the momenta of order $\Lambda_{QCD}$ which is much smaller than its mass $m_Q$ . In the HQS limit with low energy situations, where the typical gluon momenta is small compared with the heavy quark mass $(m_Q)$ , QCD dynamics becomes independent of the heavy degrees of freedom, especially for the flavor and spin of the heavy quark.This means that the hyperfine interaction that involves the heavy quark is suppressed by the mass of the heavy quark. As a consequence, one-gluon exchange HF interaction should depend on the interacting light diquark pair, independently of the baryon the pair belongs to. In fact the

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QCD hyperfine interaction and the QED electromagnetic hyperfine interaction between i and j quarks are proportional to $1/m_i m_j$ , where $m_i$, $m_j$ are their masses. These interactions contribute to systematic uncertainty of the experimental results and can be ignored in HQS limit, where one of the quarks is heavy [14] . Indeed we characterize the heavy baryon mass by two widely separated scales: the large heavy quark mass,($m_Q$), and the low momentum transfer between the heavy and the light quarks of the diquark, which is of order $\Lambda_{QCD}$. In this system the light diquark circle around the nearly static heavy quark and the system behaves as the the QCD analogue of the familiar hydrogen bounded by electromagnetic force . In HQS limit, where $m_Q \rightarrow \infty$ a good quantum number is the angular momentum of the light degrees of freedom. Thus, heavy quark baryons belong to either SU(3) antisymmetric $3_F$ or symmetric $6_F$ representations fig.1. The spin of the light diquark is 0 for $3_F$, while it is 1 for $6_F$ For the spin of the ground state heavy baryons we have 1/2 for $3_F$ , representing the $\Lambda_h$ and $\Xi_h$ heavy baryons , while it can be both 1/2 or 3/2 for $6_F$, representing $\Sigma_h$, $\Sigma^h$, $\Xi^h$, $\Xi^h$, $\Omega_h$ and $\Omega^h$, where the star and *h* indicates spin 3/2 c b quarks respectively. The mass difference between states belonging to different representations $3_F$ and $6_F$, do contain the dynamics of the light scalar and vector diquark subsystem respectively. But the mass splitting between states belonging to same representation is caused by the chromomagnetic interaction at the order $1/m_Q$ and can be ignored in HQS limit. Thus baryons containing a single heavy quark should fall into almost degenerate multiplets .For example the $\Sigma_b$ and $\Sigma^b$ doublet will be degenerate in heavy quark limit approximation. Generally these states have the same parity as the light component Table 1 .

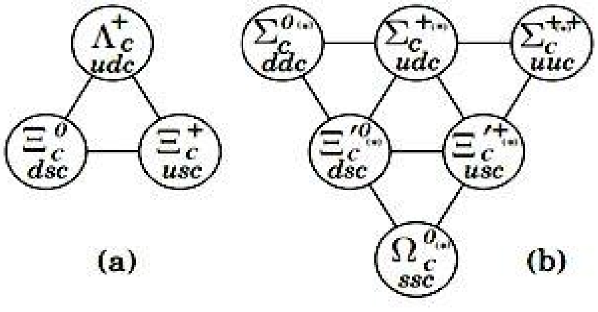

Fig. 1.SU(3) multiplets of charmed baryons , (a) $3_F$ antisymmetric and (b) $6_F$ symmetric representations.

The members of the two multiplets of singly charmed baryons have flavor wave functions

$$\Sigma^{c++} = uuc, \quad \Sigma^{c+} = 1/\sqrt{2}\,(ud + du)\,c\,, \quad \Sigma^{c0} = ddc \tag{2}$$

$$\Xi^{c+} = 1/\sqrt{2}\,(us + su)\,c \quad \Xi^{c0} = 1/\sqrt{2}\,(ds + sd)\,c$$

$$\Omega^{c} = ssc,$$

for the sextet and

$$\Lambda^{c+} = 1/\sqrt{2}\,(ud - du)\,c\,, \quad \Xi^{c+} = 1/\sqrt{2}\,(us - su)\,c \tag{3}$$

$$\Xi^{c0} = 1/\sqrt{2}\,(ds - sd)\,c$$

For the antitriplet which are similar to the set of flavor wave functions for baryons containing b quark

TABLE 1

The s-wave heavy baryons and their quantum numbers.

| state | $\Lambda_Q$ | $\Sigma_Q$ | $\Sigma^{*Q}$ | $\Xi_Q$ | $\Xi^{\prime Q}$ | $\Xi^{*Q}$ | $\Omega_Q$ | $\Omega^{*Q}$ |
|---|---|---|---|---|---|---|---|---|
| $J^P$ | 1/2 + | 1/2+ | 3/2+ | 1/2 + | 1/2+ | 3/2+ | 1/2 + | 3/2+ |
| Jl | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |

Table 2. shows the experimental masses of the Ground-state charmed and bpttom baryons [15].

TABLE 2

Ground - state charmed baryons and their SU(3)multiplets
Lattice estimates (†) have been taken from ( Ref [19] ).

| Heavy baryon | | Mass(GeV) | SU(3)multiplet |
|---|---|---|---|
| Λc+ | Λb+ | 2.285 -5.624 | 3bar |
| $\Sigma_{c++,+0}$ | $\Sigma_{b++,+0}$ | 2.455-5.808 | 6 |
| Ωc0 | Ωb0 | 2.698-5.990† | 6 |
| Ξc+ | Ξb+ | 2.468-5.793 | 3bar |
| Ξc0 | Ξb0 | 2.471-5.760† | 3bar |
| Ξ’c+ | Ξ’b+ | 2.576-5.900† | 6 |
| Ξ’c0 | Ξ’b0 | 2.578-5.900† | 6 |

In the limit of HQS, where the heavy quark mass $m_Q \rightarrow \infty$, all states in the $6_F$ representation would be degenerate and this is true for all states in the $3_F$ representation . In this limit without the $m_Q \rightarrow \infty$ approximation there is a mass splitting between states belonging to each representation due to differences between the masses of the light diquark sectors of the heavy baryons.we calculated the light diquark masses by adding the two quarks mass and their binding hyperfine HF energy .Table .3.

TABLE 3

Quark and diquark masses and quantum numbers.

| Quark mass (MeV) | $m_c$ | $m_s$ | $m_l$ | $m_b$ |
|---|---|---|---|---|
| | 1650 | 460 | 360 | 4275 |
| Diquark mass (MeV) | $ll'$ | ls | lc | |
| Scalar | 420 | 580 | 1840 | |
| Vector | 673 | 680 | 1840 | |
| Quantum numbers | Flavor | Color | Spin | Orbital |
| Scalar | 3bar | 3bar | 0 | 0 |
| Vector | 6 | 3bar | 1 | 0 |

Now we evaluate the masses of the ground state heavy baryons in the framework of the HQS limit. Thus we can use the mass formula

$$M = m_D + m_Q + E_L + Er \qquad (4)$$

Here, $m_D$ is the light diquark mass, $m_Q$ the heavy baryon mass, $E_L$ the orbital and $Er$ the radial exciting energies between heavy quark and light diquark respectively. According to table 3 two quarks having a closer mass have more tightly bound which is indicated by the spin-spin interaction, Thus the mass splitting

$$(ud) - [ud] > (us) - [us] > (uc) - [uc] \simeq 0 \qquad (5)$$

is spected where [ ] ,( ) , denotes scalar and vector diquarks respectively.We have accommodated the ground state ,$J^P = 1/2^+$ heavy charmed and bottom baryons . These states have no orbital angular momentum,EL = 0 and the mass splitting between them is indicated by radial exciting energy, $E_r$ of each ground state heavy baryon .By using this exciting energy we have evaluated the average distance between heavy quark and the center of mass of the light diquark for each heavy baryon state. We set the Jacobi coordinates for a heavy quark -light diquark description.fig.2.

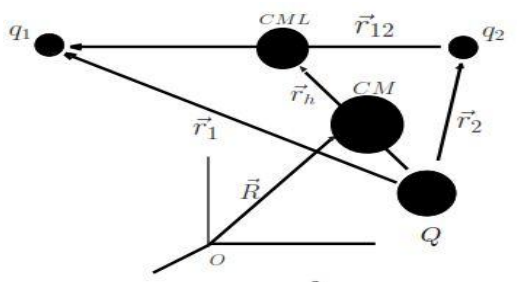

FIG.2 : q2Q rest frame.

For the coordinates we consider the following relations

$$\begin{aligned} R &= m_{q1}x_{q1} + m_{q2}x_{q2} + m_Q x_h \;/\; m_{q1} + m_{q2} + m \\ r_{12} &= x_q \qquad (6) \\ r_h &= (m_{q1}x_{q1} + m_{q2}x_{q2} \;/\; m_{q1} + m_{q2}) - x_h \end{aligned}$$

where $x_{q1}$ , $x_{q2}$ and $x_h$ represent the positions with respect to a certain reference frame and $r_{12}$ and $r_h$ are the Jacobian coordinates. Thus we would have for the heavy baryon Kinetic energy

$$T(q^2Q) \simeq \nabla^2{}_{rh} / 2\mu \qquad (7)$$

Where $\nabla^2$ denotes the Laplacian and $\mu$ is the heavy quark-light diquark reduced mass. By using of the Baryon wave function

$$\psi_B = N[Y_{00}(rh)\exp(-a^2 r_h^2 / 2)] \qquad (8)$$

we would have for the Kinetic energy

$$Er = \langle T \rangle_\psi \simeq 3a^2 / 4\mu \qquad (9)$$

and for the relative distance between havey quark and light diquark we have

$$r_0 = \langle r_h \rangle = \sqrt{5} / 2a^2 \qquad (10)$$

We have calculated the radial kinetic energy, Er of each ground state heavy baryon listed in table 2 ,using their parameters, $m_D$ $m_Q$ and $Er = 0$ . Also by using of Eq8-9 we obtained the average distance , $r_0$ between the heavy quark and the center of mass of light diquark. Table 4 .

The results with QCD sum rule[ 16 ]and lattice QCD calculation [ 17 ] have suggested a clear dominance of the collinear-type configurations ( the heavy quark is close to the center of mass of the light diquark).This results seems to support our calculations based on HQS limit of HQLD picture of heavy baryons. In Ref.[ 18 ],the authors studied the baryon properties using Isgur-Wise function and found the heavy quark is far from the light diquark which is against the HQS approximation of HQLD.

TABLE 4

Ground - state charmed and bottom baryons and their radial kinetic energy and relative distance between heavy quark and light diquark center of mass,Experimental masses have been taken from ( Ref [18] ) and Lattice estimates († ) have been taken from ( Ref [19] ) .

| Heavy baryon | Mass(GeV) | Er(MeV) | $r_0$(MeV $)^{-1}$ |
|---|---|---|---|
| $\Lambda$c+ $\Lambda$b+ | 2.285-5.624 | 215-929 | 0.00509-0.00229 |
| $\Sigma$c++,+0 $\Sigma$b++,+0 | 2.455-5.808 | 132-860 | 0.00535-0.00192 |
| $\Omega$c0 $\Omega$b0 | 2.698-5.990 | 368-103 | 0.00320-0.00174 |
| $\Xi$c+ $\Xi$b+ | 2.468-5.793 | 238-938 | 0.00425-0.00179 |
| $\Xi$c0 $\Xi$b0 | 2.471-5.760 | 241-905 | 0.00423-0.00200 |
| $\Xi$'c+ $\Xi$'b+ | 2.576-5.900 | 246-945 | 0.00392-0.00183 |
| $\Xi$'c0 $\Xi$'b0 | 2.578-5.900 | 248-945 | 0.00391-0.00183 |

The average size of a scalar and a vector diquark is 0.0045 MeV $^{-1}$ and 0.0205 ( 0.0235 ) MeV $^{-1}$ respectively. According to Table 4 one sees that the average distance of the heavy quark to the center of mass of the light diquark , $r^0$is smaller than the average size of the light diquark.The picture that emerges from this analysis is the one depicted in Fig.3, where the heavy quark is too close to the center of mass of the light diquark, which is in agreement with the findings of Ref [20].

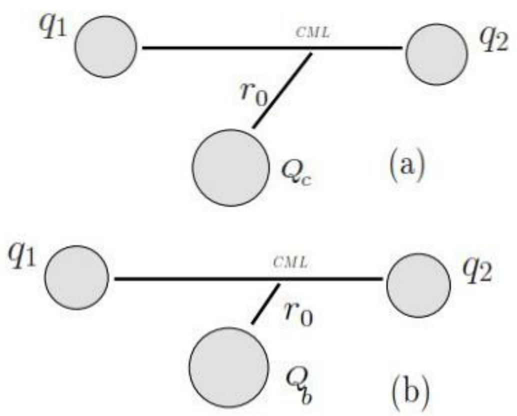

FIG.3 :schematic picture of a Ground-state spin 1/2 heavy baryon with a charmed heavy quark (a) , and a bottom heavy quark (b).

This findings based on HQS limit of HQLD approximation shows a dominance of collinear-type configuration,which confirms the results of QCD sum rules[16]and lattice calculatios[17]We have obtained the average distance, $r^{0*}$ between the heavy quark and the center of mass of light diquark for charmed and bottom baryons with spin 3/2 Table .5.One sees that this average distance for the spin 3/2 state heavy baryons is smaller than the spin 1/2 states.This distance splitting between states belonging to same representation is caused by the chromomagnetic interaction and usually can be ignored in HQS limitd with $M_Q \rightarrow \infty$ approximation.The picture is depicted in Fig.4.

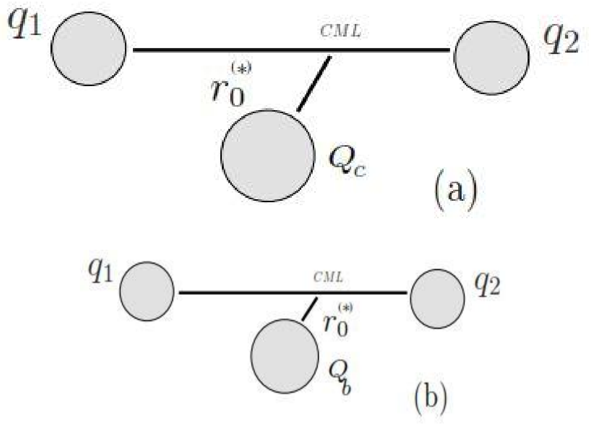

FIG.4:schematic picture of a Ground-state spin 3/2heavy baryon with a charmed heavy quark ( a ) and a bottom heavy quark ( b ).

TABLE 5

Charmed and bottom baryons with spin 3/2 ,their masses ( Ref [18-19] their SU(3) multiplets and the relative distance $r_0$* , between heavy quark and light diquark center of mass.

| Heavy baryon | Mass GeV) | SU(3) multiplet | $r_0^*$(MeV $^{-1}$) |
|---|---|---|---|
| $\Sigma_c^{++,+0*}$<br>$\Sigma_b^{++,+0*}$ | 2.518-5.833 | 6 | 0.00477-0.00190 |
| $\Omega_c^0$ $\Omega_b^0$ | 2.768-6.000 | 6 | 0.00297-0.00162 |
| $\Xi'_c{}^{+0*}$<br>$\Xi'_b{}^{+0*}$ | 2.646-5.900 | 6 | 0.00350-0.00180 |

We also accommodated the masses of the p-wave charmed baryons, Table.6 these states have orbital angular momentum,$E_L \neq 0$ between the heavy quark and the center of mass of light diquark. By using of the exciting energy $E_L$ we have evaluated the average distance between heavy quark and the center of mass of the light diquark for each heavy baryon state.

TABLE 6

Wave charmed baryons and their orbital kinetic energy, $E_L$ and relative distance between heavy quark and light diquark center of mass, Experimental masses have been taken from ( Ref [21] ).

| Heavy baryon | $J^P$ | SU(3) multiplet | Mass (GeV) | $E_L$ (Mev) | Rp (MeV$^{-1}$) |
|---|---|---|---|---|---|
| $\Lambda_c^+$ | ½ - | 3 bar | 2.593 | 523 | 0.00238 |
| $\Lambda_c^+$ | 3/2- | 3 bar | 2.593 | 555 | 0.00231 |
| $\Sigma_c^{+,+0}$ | 3/2- | 6 | 2.800 | 477 | 0.00209 |
| $\Xi_c^+$ | ½- | 3 bar | 2.790 | 560 | 0.00203 |
| $\Xi_c^0$ | ½- | 3 bar | 2.790 | 560 | 0.00203 |
| $\Xi_c^+$ | 3/2- | 3 bar | 2.815 | 585 | 0.00199 |
| $\Xi_c^0$ | 3/2- | 3 bar | 2.815 | 585 | 0.00199 |

One sees that this distance, for the p - wave state heavy baryons is smaller than the S -wave states, $r_p < r_0$ , $r_0^*$. The picture is depigted in Fig.5

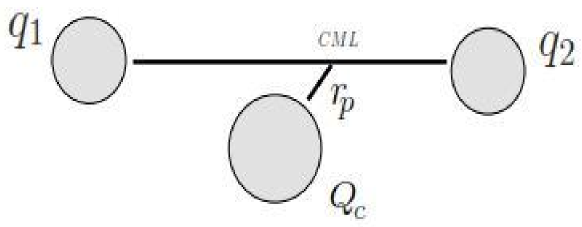

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FIG 5: :schematic picture of a p- wave heavy baryon with a charmed heavy quark.

It seems that the higher binding of these bound states is caused by their higher mass in campare with s-wave states. Because of the unknown $J^P$ quantum numbers for most excited heavy baryons, Λc ( 2765 ) , Λc ( 2880 ) and Λc ( 2940 ) it is not determined if they are excitations of the Λc or Σc .TABLE 7 shows our predictions for the quantum numbers of these states.

TABLE 7

S - wave ,P - wave and D - wave charmed baryons and their excitation kinetic energy and relative distance , r , between heavy quark and light diquark center of mass .Experimental masses have been taken from ( Ref [22] ).

| Heavy-baryon | J(p) | SU(3) Multiplet | Mass (GeV) | Orbital | Er (Mev) | Or-bital | $E_L$ (MeV) | r (Mev-1) |
|---|---|---|---|---|---|---|---|---|
| Λc | 1/2(+) | 3bar | 2.765 | 2s | 695 | —— | —— | 0.00207 |
| Σc | 3/2(-) | 6 | 2.765 | —— | —— | 1p | 442 | 0.00217 |
| Λc | 5/2(+) | 3bar | 2.880 | —— | —— | 1D | 810 | 0.00212 |
| Σc | 3/2(+) | 6 | 2.940 | 2s | 617 | ----- | ----- | 0.00184 |

One sees that the relative distance, r , between the heavy quark and the center of mass of light diquark for Λc 5/2 (+)is only 0.00018 MeV$^{-1}$ smaller in campare with this distance for Λc 3/2 ( - ) state that confirms these states being excitations of the heavy baryons belonging to the same 3 bar SU(3) multiplet. We have considered similar distance splitting for predicting other heavy baryon quantum numbers listed in Table .7.

## 3 CONCLUSION

Uunderstanding of low-energy properties of QCD by quark dynamic features in phenomenological models depends on the true degrees of freedom of any model.In our model we studied the ground state properties of heavy baryons and extended it to the description of their excited states. Our calculations performed in the framework of the heavy - quark light diquark HQLD sector of NRQCD which is a heavy quark effective theory HQET. Also we used the heavy quark symmetry, HQS ,where QCD dynamics of light diquark is independent of the flavor and spin of heavy quark.Thus we reduced a very complicated three-body problem to a simple two-body problem . For the ground state heavy charmed and bottom baryons we calculated the average distance between heavy quark and the center of mass of light diquark. Here we considered only the kinetic energy of the light diquark with respect to the heavy quark . There are strong indications in QCD sum rules and lattice calculations for a collinear-type configuration for the heavy baryon system,where the heavy quark is too close to the center of mass of light diquark, which is in agreement with our findings.We also accommodated the masses of the s -wave charmed baryons, these states have orbital angular momentum $E_L \neq 0$ between the heavy quark and the center of mass of light diquark and the rlative distance between the heavy quark and the center of mass of light diquark is smaller in campare with s –wave states.We find that experimental data for the ground and excited states of heavy baryons can be accommodated in the HQS limit of HQLD sector of NRQCD theory for heavy baryons, by treating a heavy baryon as the bound state of the heavy quark and light diquark, considering radial and orbitl excitations only between these constituents.We emphasize that a combined study of light, heavy and doubly heavy baryons is needed to confirm these achievements.

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