A Primary Study of Heavy Baryons $\Lambda_Q$, $\Sigma_Q$, $\Xi_Q$ and $\Omega_Q$

ZHAO Qiao-Yan¹*, ZHANG Dan¹‡ and ZHANG Qiu-Yang ²

¹School of Physical Science and Technology, Inner Mongolia University, Hohhot 010021, P.R. China
²Graduate School of Zhejiang Gongshang University, Hangzhou 310018, P.R. China

We perform a preliminary study of the $\frac{1}{2}^+$ and $\frac{3}{2}^+$ ground-state baryons containing a heavy quark in the framework of the chiral SU(3) quark model. By using the calculus of variations, masses of $\Lambda_Q$, $\Sigma_Q$, $\Xi_Q$, $\Omega_Q$, $\Sigma_Q^*$, $\Xi_Q^*$ and $\Omega_Q^*$, where $Q$ means $c$ or $b$ quark, are calculated. With taking reasonable model parameters, the numerical results of established heavy baryons are generally in agreement with the available experimental data, except that those of $\Xi_Q^*$ are somewhat heavier. For $\Omega_Q$ with undetermined experimental mass and unobserved $\Xi_Q^*$, reasonable theoretical predictions are obtained. Interactions inside baryons are also discussed.

PACS numbers: 12.39.-x, 14.20.Lq, 14.20.Mr

Baryons containing heavy quarks have always been interesting. In the last decade a significant progress was achieved in the experimental and theoretical studies of heavy hadrons. In particular, the spectroscopy of baryons containing a singly heavy quark has obtained special attention, mainly due to the recent experimental discoveries 1. In these baryons, a heavy quark can be used as a ‘flavor tag’ to help us to go further in understanding the nonperturbative QCD rather than doing the light baryons 2. On the other hand, heavy baryons provide a laboratory to study the dynamics of light quarks in the environment of heavy quarks, such as their chiral symmetry 3.

Up to date, the $\frac{1}{2}^+$ antitriplet charmed baryon states ($\Lambda_c^+$, $\Xi_c^+$, $\Xi_c^0$) [3], the $\frac{3}{2}^+$ and $\frac{5}{2}^+$ sextet charmed baryon states ($\Omega_c^0$, $\Sigma_c^-$, $\Xi_c^-$) [4] and ($\Omega_c^0$, $\Sigma_c^-$, $\Xi_c^-$) [10, 11] have been established, while for $S$-wave bottom baryons, only the $\Lambda_b$ [12], $\Sigma_b$, $\Xi_b^+$, $\Xi_b^0$ and $\Omega_b$ [15, 16] have been observed [17]. Accordingly, a large number of theoretical investigations have been carried out by kinds of QCD-inspired models or methods to study masses of the observed and expected heavy baryons. Such as various quark models [2, 18–20], QCD sum rules [21, 22], lattice QCD [24, 25], bag model [26] and so on.

The chiral SU(3) quark model is a useful nonperturbative theoretical tool in studying the light hadron physics. It has been quite successful in reproducing the energies of the baryon ground states, the binding energy of the deuteron, the nucleon-nucleon ($NN$), hyperon-nucleon ($YN$), kaon-nucleon ($KN$) and antikaon-nucleon ($KN$) scattering processes [27, 28]. The valuable information has also been obtained from many works on strong interactions and multiquark clusters in this model [29]. Recently it has been extended to study the states including heavy quarks [30–32], and provided interesting results. All these successes inspire us to investigate masses of baryons with one heavy quark following the above approaches. First, we briefly introduce the framework of the chiral SU(3) quark model, which includes the Hamiltonian and model parameters. Then the calculated masses of the $\frac{1}{2}^+$ and $\frac{3}{2}^+$ ground-state heavy baryons involving a heavy quark are shown and discussed.

The chiral SU(3) quark model has been widely described in the literature [27, 32] and we recommend the reader to obtain details from those references. Here we just give the salient feature of this model. The total Hamiltonian of the heavy baryon containing one heavy quark $(Qqq)$ can be written as

\[ H = \sum_{i=1}^{3} T_i - T_G + V_{qq} + \sum V_{Qq}, \]  

(1)

where $T_i$ is the kinetic energy operator for a single quark, and $T_G$ is that for the center-of-mass motion. $V_{qq}$ represents the interaction between two light quarks $(qq)$.

\[ V_{qq} = V_{qq}^{OGE} + V_{qq}^{con f} + V_{qq}^{ch}, \]  

(2)

where $V_{qq}^{OGE}$ is the one-gluon-exchange (OGE) interaction, which governs the short-range perturbative QCD behavior. $V_{qq}^{con f}$ is the confinement potential, which provides the non-perturbative QCD effect in the long distance, taken as the linear form in this work. $V_{qq}^{ch}$ represents the chiral fields induced effective quark-quark potential, and describes the non-perturbative QCD effect of the low-momentum medium-distance range. In the chiral SU(3) quark model, it includes the scalar boson and the pseudoscalar boson exchanges,

\[ V_{qq}^{ch} = \sum_{a=0}^{8} V_{\sigma_a} + \sum_{a=0}^{8} V_{\pi_a}. \]  

(3)

Here $\sigma_0, ..., \sigma_8$ are the scalar nonet fields, and $\pi_0, ..., \pi_8$ are the pseudoscalar nonet fields. The detailed expressions of every parts can be found in Refs. [27, 32]. $V_{Qq}$ in Eq. (1) is the interaction between heavy and light quark pairs $(Qq)$,

\[ V_{Qq} = V_{Qq}^{OGE} + V_{Qq}^{con f}. \]  

(4)
\( V^{OGE}_{Qq} \) and \( V^{conf}_{Qq} \) have the same forms as those of light quark pairs. Note that following the previous works \[30–32\], for \( Qq \) pairs, the Goldstone boson exchanges will not be considered in a primary study.

### TABLE I: Model parameters for light quarks. The meson masses and the cutoff masses: \( m_{a} = 313 \text{ MeV}, \quad m_{b} = 470 \text{ MeV}, \quad m_{c} = 595 \text{ MeV}, \quad m_{s} = 886 \text{ MeV}, \quad m_{u} = 917 \text{ MeV}, \quad m_{d} = 2621 \text{ MeV} \), and \( \Lambda = 1100 \text{ MeV} \) for all mesons.

| Parameter | Value |
|-----------|-------|
| \( m_{u} \) (MeV) | 313 |
| \( m_{s} \) (MeV) | 470 |
| \( m_{c} \) (MeV) | 595 |
| \( m_{d} \) (MeV) | 886 |
| \( m_{s} \) (MeV) | 917 |
| \( m_{t} \) (MeV) | 2621 |
| \( a_{uu} \) (MeV) | 90.4 |
| \( a_{ss} \) (MeV) | 155.3 |
| \( a_{uu} \) (MeV) | -79.6 |
| \( a_{ss} \) (MeV) | -76.1 |
| \( a_{uu} \) (MeV) | -87.6 |

The model parameters for light quarks are taken from the previous work \[27\], which can give a satisfactory description of the energies of the baryon ground states, the binding energy of deuteron, the \( NN \) scattering phase shifts, and the \( NY \) cross sections. As shown in Table II the up (down) quark mass \( m_{u(d)} \) and the strange quark mass \( m_{s} \) are taken to be the usual values: \( m_{u(d)} = 313 \text{ MeV} \) and \( m_{s} = 470 \text{ MeV} \). The coupling constant for scalar and pseudoscalar chiral field coupling \( (g_{ch}) \) is determined according to the relation

\[
\frac{g_{ch}^2}{4\pi} = \frac{9}{25} \frac{g_{NN\pi}^2}{4\pi} m_N^2,
\]

with empirical value \( g_{NN\pi}^2/4\pi = 13.67 \). The masses of mesons are taken to be the experimental values, except for the \( \sigma \) meson. The \( m_{s} \) is adjusted to fit the binding energy of the deuteron. The cutoff radius \( \Lambda^{-1} \) is taken to be the value close to the chiral symmetry breaking scale \[33\]. The OGE coupling constants \( g_{u}, g_{s} \) and the confinement strengths \( a_{uu}, a_{ss} \) can be derived from the masses of ground state baryons.

To investigate the heavy quark mass dependence, the mass of charm quark \( m_{c} \) is taken as several typical values 1430 MeV \[30\], 1550 MeV \[34\], 1870 MeV \[35\]. The mass of bottom quark \( m_{b} \) is taken as 4720 MeV \[31\], 5100 MeV \[36\], 5250 MeV \[35\].

### TABLE II: Model parameters for heavy quarks.

| Parameter | Value |
|-----------|-------|
| \( g_{c} \) (MeV) | 0.35 |
| \( m_{c} \) (MeV) | 1430 |
| \( a_{uu} \) (MeV) | 305 |
| \( a_{ss} \) (MeV) | 30 |
| \( a_{uu} \) (MeV) | 90 |
| \( a_{ss} \) (MeV) | 155 |
| \( a_{uu} \) (MeV) | -79.6 |
| \( a_{ss} \) (MeV) | -76.1 |
| \( a_{uu} \) (MeV) | -87.6 |

To test their effects on other parameters and on the spectrum, the OGE coupling constants for heavy quarks are taken as three values in an estimated range \[30\], i.e. \( g_{c} = 0.53, 0.58, 0.60 \) and \( g_{b} = 0.50, 0.52, 0.60 \). The confinement strengths including a heavy quark \( (a_{QQ}, a_{Q}^0, a_{Q}^0) \) are determined by fitting the masses of heavy mesons \( D, D^*, D_s, D_s^* \) and \( B, B^+, B_s, B_s^* \) respectively. The parameters about heavy quarks are tabulated in Table III. The corresponding numerical masses of heavy mesons are exactly consistent with the experimental values. As an example, the results with \( g_{c} = 0.58, m_{c} = 1550 \text{ MeV} \) and \( g_{b} = 0.52, m_{b} = 5100 \text{ MeV} \) are listed in Table III.

### TABLE III: Masses (MeV) of mesons with a heavy quark. \( g_{c} = 0.58, m_{c} = 1550 \text{ MeV} \) and \( g_{b} = 0.52, m_{b} = 5100 \text{ MeV} \). Experimental data are taken from PDG \[17\].

| \( D \) | \( D^* \) | \( D_s \) | \( D_s^* \) | \( B \) | \( B^+ \) | \( B_s \) | \( B_s^* \) |
|-------|-------|-------|-------|-------|-------|-------|-------|
| 1869.6 | 2007.0 | 1968.5 | 2112.3 | 5279.2 | 5325.1 | 5366.3 | 5415.4 |
| Theo. | 1869.8 | 2007.1 | 1968.6 | 2112.3 | 5279.3 | 5325.1 | 5366.0 | 5415.3 |

\[17\] PDG, Particle Data Group, 2021.
With all parameters determined, masses of the $\frac{1}{2}^+$ lowest lying ground-state $\Lambda_Q$, $\Sigma_Q$, $\Xi_Q$, $\Omega_Q$ and $\frac{3}{2}^+$ $S$-wave $\Sigma^*_Q$, $\Xi^*_Q$, $\Omega^*_Q$, where $Q$ means $c$ or $b$ quark, can be calculated by the calculus of variations. The harmonic-oscillator width $b_n$ is taken as the variational parameter. Compared to the experimental data, the numerical results can be found in Table IV, and some other theoretical predictions are illustrated as well.

TABLE IV: Masses (MeV) of baryons with a heavy quark, accompanied by some other theoretical predictions. Experimental data are taken from PDG [17].

| $g_c$ | 1350 | 2307.7 | 2473.7 | 2541.9 | 2692.5 | 2536.7 | 2653.3 | 2766.7 |
|-------|------|--------|--------|--------|--------|--------|--------|--------|
|       |      | $\Lambda_c$ | $\Sigma_c$ | $\Xi_c$ | $\Omega_c$ |         |         |         |
| 0.53  | 1.50 | 1.85   | 2.15   | 2.64   | 2.82   | 2.99   | 3.31   | 3.72   |
| 0.58  | 1.50 | 1.85   | 2.15   | 2.64   | 2.82   | 2.99   | 3.31   | 3.72   |
| 0.60  | 1.50 | 1.85   | 2.15   | 2.64   | 2.82   | 2.99   | 3.31   | 3.72   |

Exp. | 2286.5 | 2453.8 | 2471.0 | 2697.5 | 2518.0 | 2646.6 | 2768.3 |

Ref. [19] | 2297 | 2459 | 2481 | 2698 | 2518 | 2654 | 2768 |
Ref. [21] | 2271 | 2411 | 2432 | 2657 | 2534 | 2634 | 2790 |
Ref. [22] | 2290 | 2452 | 2473 | 2678 | 2538 | 2680 | 2752 |

Note that $J^P$ of baryons with $^∗$ are $\frac{1}{2}^+$, and others are $\frac{3}{2}^+$. In addition, the last line ‘Q’ lists the masses (MeV) of heavy hadrons with $g_c = 0.58$, $m_c = 1550$ MeV, and $g_b = 0.52$, $m_b = 5100$ MeV after varying the confinement strengths.

From Table IV we can see that for $J^P = \frac{1}{2}^+$, the numerical values of $\Lambda_c$ are generally about 20 MeV higher than the experimental one. For $\Sigma_c$, the largest difference is 64 MeV (2518.2 MeV–2453.8 MeV), while the closest mass (2452.3 MeV) is obtained with $g_c = 0.6$ and $m_c = 1430$. The results of $\Xi_c$ are somewhat poor, which are about 62 ~ 88 MeV higher. The results of $\Omega_c$ are at most 16 MeV far from the observed value, but the exact mass (2697.7 MeV) appears when $g_c = 0.5$ and $m_c = 1550$. Predictions of baryons with $b$ quark are about 25 MeV heavier for $\Lambda_b$, and 76 ~ 95 MeV higher for $\Xi_b$. The nearest value of $\Sigma_b$ (5815.0 MeV) can be found when $g_b = 0.6$ and $m_b = 4720$, and others are 29 ~ 55 MeV heavier. For $\Omega_b$ with uncertain experimental data, our average results are compatible with the observed value (6054.4 MeV) from Ref. 10 and the theoretical predictions from Refs. 21, 24. When $J^P = \frac{3}{2}^+$ the situation has been improved. The calculated values which are consistent with the experimental ones are obtained by $g_c = 0.6$ and $m_c = 1430$ for $\Sigma^*_c$ (2516.6 MeV), $g_c = 0.58$ and $m_c = 1550$ for $\Xi^*_c$ (2648.6 MeV), $g_c = 0.6$ and $m_c = 1550$ for $\Omega^*_c$ (2769.6 MeV), $g_b = 0.6$ and $m_b = 4720$ for $\Sigma^*_b$ (5838.3 MeV). For unobserved $\Xi^*_c$ and $\Omega^*_c$, our predictions are similar to those from Ref. 10. It is worth noting that Ref. 32 give predictions of $\Lambda_c$ ($M_{\Lambda_c} = 2269$ MeV) and $\Xi_c$ ($M_{\Xi_c} = 2436$ MeV) using the same model as ours by taking $g_c = 0.53$ and $m_c = 1550$ MeV. While compared with our present results, their corresponding meson masses $m_D = 1883$ MeV, $m_D'$ = 1947 MeV become far away from the experimental values.

To lower the calculated values, we vary the confinement parameters in a reasonable range, which means that masses of heavy mesons are roughly consistent with the experimental data. When confinement strengths are changed, the results of $\Sigma_Q$ are in good agreement with the observed ones, and masses of $\Xi_Q$ are decreased by 10 ~ 20 MeV. Most of $\Lambda_c$ masses are also decreased, and the smallest one (2292.6 MeV) is only 6 MeV higher. However, little action is played for the calculation of $\Lambda_b$. In general, the numerical values are reduced less than 20 MeV for $\Omega_Q$, 60 MeV for $\Sigma_Q$, 50 MeV for $\Xi_Q$, and 30 MeV for $\Omega_Q$, which leads to the predictions being 10 ~ 30 MeV lower than the available observed ones. It should be noted that after changing the parameters, compared with the experimental data, the corresponding calculated masses of some heavy mesons are about 1% shifted. This relatively small difference can be acceptable in theory. As an example, with $g_c = 0.58$, $m_c = 1550$ MeV, and $g_b = 0.52$, $m_b = 5100$ MeV, the changed confinement parameters and corresponding masses of mesons are listed in Table V and those of baryons are illustrated in the
TABLE V: Masses (MeV) of heavy mesons after varying confinement strengths with \( g_0 = 0.58 \), \( m_c = 1550 \) MeV, and \( g_0 = 0.52 \), \( m_b = 5100 \) MeV. Same units of \( a_{QQ}, a_{Qq} \) as in Table II.

| \( a_{cu} \) | \( a_{cs} \) | \( a_{u}^{*} \) | \( a_{gs} \) | \( a_{bu} \) | \( a_{gb} \) | \( a_{bu}^{*} \) | \( a_{gb}^{*} \) |
|------------|------------|------------|------------|------------|------------|------------|------------|
| 295.3      | 238.7      | -198.0     | -136.5     | 247.6      | 164.5      | -200.8     | -130.0     |
| D          | D          | D          | B          | B          | B          | B          | B          |
| 1859.1     | 1993.7     | 1964.8     | 2098.1     | 5292.1     | 5325.1     | 5386.0     | 5415.3     |

TABLE VI: The effects of meson exchanges between light quark pairs.

| \( J^* \) | Baryons | Attractions | Repulsions | No effects |
|----------|---------|-------------|------------|------------|
| \( \frac{1}{2} \) | \( \Lambda_Q \) | \( \pi, \epsilon, \sigma \) | \( \eta, \eta', \sigma' \) | \( K, \kappa \) |
| \( \Sigma_Q \) | \( \pi, \eta, \eta', \sigma', \epsilon, \sigma \) | | \( K, \kappa \) |
| \( 0^+ \) | \( \Xi_Q \) | \( \kappa, \eta, \sigma \) | \( \eta, \kappa, \epsilon \) | \( \pi, \sigma' \) |
| \( \Omega_Q \) | \( \epsilon, \sigma \) | | \( \kappa, \pi, \eta, \eta', \sigma', \kappa \) |

Next, let us turn to interactions in these heavy baryons. The effects of meson exchanges between light quarks are shown in Table VI, which are only related to changes, with \( g_0 \) increasing, the OGE attractions will increase, and accordingly the confinement attractions decrease (or repulsions increase). This is obvious. Here unchanged \( m_Q \) indicates that the total force for a heavy baryon is changeless. The attraction of OGE grows, which certainly accompanies by that of confinement reducing with other conditions fixed. On the other hand, when \( g_Q \) does not change, the forces of OGE almost keep invariable. With \( m_Q \) increasing, confinement attractions will increase (or repulsions will decrease). Similarly, \( m_Q \) growing implies that the total force becomes larger for the baryon cluster, the confinements need more attractive when other factors remain unchanged.

In summary, we have performed a primary study on \( \frac{1}{2}^{-} \) and \( \frac{3}{2}^{-} \) ground-state baryons with one heavy quark (c or b) in the chiral SU(3) quark model. The calculated masses of established heavy baryons are generally in agreement with the available experimental data, except that those of \( \Xi_Q \) are somewhat heavier. Reasonable theoretical predictions of \( \Omega_b \) with uncertain experimental mass and unobserved \( \Xi_b^* \), \( \Omega_b^* \) are presented. Meanwhile, interactions inside baryons are analyzed, too. It is suggested that our predictions could serve as a useful complementary tool for the interpretation of heavy hadron spectra. However, there are several problems in our present study deserving further discussions, for example, the effects of vector meson exchanges. Furthermore, we hope that the same approach is applied to explore more properties of heavy baryons (such as the spectra of baryons with two or three heavy quarks, or strong interactions including heavy baryons), and test the model parameters compared to the experimental data. All these topics will be researched in future.

Acknowledgments

Authors would like to thank Professor Zhang Zong-Ye and Post-doctor Wang Wen-Ling for helpful discussions. This work was supported by the China Postdoctoral Science Foundation Funded Project (20100471491), the Natural Science Foundation of Inner Mongolia (2010MS0101), the Inner Mongolia Educational Foundation (NJzy08006), SPH-IMU (Z20090143), and the Graduate Program of Inner Mongolia University.

[1] (For review see e.g., ) Rosner J L 2007 J. Phys. G 34 s127, and references therein
[2] Roberts W, and Pervin Muslema 2008 Int. J. Phys. A 23 2817, and references therein
[3] Cheng H Y 2007 ECONF C 070805 35 Cheng H Y and Chua C K 2007 Phy. Rev. D 75 014006
[4] Aubert B et al. [BABAR Collaboration] 2005 Phys. Rev. D 72 052006
[5] Lesiak T et al. [BELLE Collaboration] 2005 Phys. Lett. B 605 237
[6] Aubert B et al. [BABAR Collaboration] 2007 Phys. Rev. Lett. 99 062001
[7] Artuso M et al. [CLEO Collaboration] 2002 Phys. Rev. D 65 071101
[8] Jessop C P et al. [CLEO Collaboration] 1999 Phys. Rev. Lett. 82 492
[9] Aubert B et al. [BABAR Collaboration] 2006 Phys. Rev. Lett. 97 232001
[10] Athar S B et al. [CLEO Collaboration] 2005 Phys. Rev. D 71 051101
[11] Aubert B et al. [BABAR Collaboration] 2008 Phys. Rev. D 77 012002
[12] Acosta D et al. [CDF Collaboration] 2006 Phys. Rev. Lett. 96 202001
[13] Aaltonen T et al. [CDF Collaboration] 2007 Phys. Rev. Lett. 99 202001
[14] Abazov V et al. [D0 Collaboration] 2007 Phys. Rev. Lett.
Aaltonen T et al. [CDF Collaboration] 2007 Phys. Rev. D 99 052002

Abazov V et al. [D0 Collaboration] 2008 Phys. Rev. Lett. 101 232002

Aaltonen T et al. [CDF Collaboration] 2009 Phys. Rev. D 80 072003

[(for review see)
Nakamura K et al. [Particle Data Group] 2010 J. Phys. G 37 075021

Capstick S and Isgur N 1986 Phys. Rev. D 34 2809

Ebert D, Faustov R N, and Galkin V O 2005 Phys. Rev. D 72 034026; 2008 Phys. Lett. B 659 612

Valcarce A, Garcilazo H, and Vijande J 2008 Eur. Phys. J. A 37 217

LIU Xiang, Chen Hua-Xing, LIU Yan-Rui, Hosaka Atsushi, and ZHU Shi-Lin 2008 Phys. Rev. D 77 014031

ZHANG Jian-Rong and HUANG F 2008 Phys. Rev. D 77 094002; 2008 Phys. Rev. D 78 094015; 2009 Chin. Phys. C 33 1385

Mathur N, Lewis R, and Woloshyn R M 2002 Phys. Rev. D 66 014502

LIU Liuming, Liu Huey-Wen, Orginos Kostas, and Walker-Loud Andre 2010 Phys. Rev. D 81 094505

Andrius Bernotas, Vytautas Simonis 2009 Lith. J. Phys. 49 19

ZHANG Z Y, YU Y W, SHEN P N, DAI L R, Faessler A, and Straub U 1997 Nucl. Phys. A 625 59

HUANG F, ZHANG Z Y, and YU Y W 2004 Phys. Rev. C 70 044004; 2004 Commun. Theor. Phys. 42 577

HUANG F, and ZHANG Z Y 2004 Phys. Rev. C 70 064004

HUANG F, WANG W L, and ZHANG Z Y 2008 Int. J. Mod. Phys. A 23 3057

ZHANG D, HUANG F, ZHANG Z Y, and YU Y W 2005 Nucl. Phys. A 756 215

WANG W L, HUANG F, ZHANG Z Y, YU Y W, and LIU F 2007 J. Phys. G 34 1771; 2007 Eur. Phys. J. A 32 293; 2007 Commun. Theor. Phys. 48 695

PHUANG F, ZHANG Z Y, and YU Y W 2006 Phys. Rev. C 73 025207; 2005 Phys. Rev. C 71 064001

ZHANG D, HUANG F, DAI L R, YU Y W, and ZHANG Z Y 2007 Phys. Rev. C 75 024001

WANG W L, HUANG F, ZHANG Z Y, and LIU F 2008 J. Phys. G 35 085003; 2010 Mod. Phys. Lett. A 25 1325

ZHANG H X, ZHANG M, and ZHANG Z Y 2007 Chin. Phys. Lett. 24 2533

ZHANG H X, WANG W L, DAI Y -B, and ZHANG Z Y 2008 Commun. Theor. Phys. 49 414

ZHANG M, ZHANG H X, and ZHANG Z Y 2007 Commun. Theor. Phys. 50 437

LIU Y R, and ZHANG Z Y 2009 Phys. Rev. C 79 035206; 2009 Phys. Rev. C 80 015208

WANG W L, HUANG F, ZHANG Z Y, and ZOU B S [arXiv:1101.0453 [nucl-th]]

Obukhovsky I T and Kusainov A M 1990 Phys. Lett. B 238 142

Kusaino A M, Neudatchin V G, and Obukhovsky I T 1991 Phys. Rev. C 44 2343

Buchmann A, Fernandez E, and Yazaki K 1991 Phys. Lett. B 269 35

Henley E M and Miller G A 1991 Phys. Lett. B 251 453

Vijande J, Garcilazo H, Valcarce A, and Fernandez F 2004 Phys. Rev. D 70 054022

Silvestre-Brac B and Semay C 1993 Z Phys. C 57 273

Vijande J, Fernandez F and Valcarce A 2005 J. Phys. G 31 481