Mass spectroscopy of $\Lambda\Lambda$ and $\Lambda\overline{\Lambda}$ systems in molecular model

D.P. Rathaud [1*] and Ajay Kumar Rai[1]
[1]*Department of Physics, Sardar Vallabhbhai National Institute of Technology, Surat-395007, Gujarat, INDIA.*

Introduction

Search for hadronic molecule is effortful experimental and theoretical task in the physics of strong interaction where under lying theory of quantum Chromodynamics (QCD) has been in dispute for decades by the apparent absence of multi-quark states. In the non-strange sector, the deuteron is the only known experimentally candidate as a hadronic molecule. Apart from deuteron, we are still searching other strong hadronic molecular candidates. There are large numbers of the hadronic molecules have been predicted in the various theoretical approaches [1, 2, 3, 4] in which H-dibaryon (in strange sector) is the most promising candidate with deep binding. Long ago, Jaffe was predicted H-dibaryon as a bound state of $\Lambda_s\Lambda_s$ with deep binding about 80 MeV [5], however, this deeply bound H-dibaryon with binding energy more than 7 MeV from the $\Lambda_s\Lambda_s$ threshold were ruled out by the discovery of the double Λ-nuclei [6, 7]. Recent lattice QCD prediction reported bound H-dibaryon with binding energy about 16 MeV at pion mass 389 MeV in Ref. [8], whereas in Ref.[9] this state has reported with binding energy about 30 - 40 MeV at pseudoscalar meson mass of 673 - 1015 MeV. In the present work, we calculated the binding energy of $\Lambda\Lambda$ and $\Lambda\overline{\Lambda}$ systems and searches the bound H-dibaryon witin the molecular model.

Theoretical Approach

We have determined the S-wave ground state energy of the di-hadronic molecule in the Ritz variational scheme. The two body di-hadronic Hamiltonian can be expressed as [10, 11, 12, 13, 14]

$$H = \sqrt{P^2 + m_d^2} + \sqrt{P^2 + m_b^2} + V_{hh}(r_{db}) \quad (1)$$

where m_d and m_b are the masses of constituents and P is the relative momentum of two hadrons, while the $V_{hh}(r_{db})$ is the interhadronic interaction potential. The interaction potential is considered as the s-wave One Boson Exchange (OBE) plus attractive screen Yukawa-like potential, namely

$$V_{hh}(r_{db}) = V_{OBE}(r_{db}) + V_Y(r_{db}) \quad (2)$$

here, to include the dipole like interaction we introduce the screen Yukawa-like potential as [10, 11]

$$V_Y = -\frac{k_{mol}}{r_{db}} e^{\frac{-c^2 r_{db}^2}{2}} \quad (3)$$

here, k_{mol} is the residual running coupling constant [15] and c is a screen fitting parameter. The OBE potential is the sum of the all one meson exchange, namely

$$V_{OBE} = V_{ps} + V_s + V_v \quad (4)$$

The explicit form of OBE potential and its parameters are expressed in Ref. [16] and we have taken the same. The color screening parameter 'c' is the only free parameter of the model and we fitted it to get the experimental binding energy of the deuteron. We fixed c=0.0686 GeV for entire calculation.

Results and Discussion

For $\Lambda_{s,c,b}\Lambda_{s,c,b}$ systems, the isospin-spin (I,S)=(0,0) channel is forbidden [17]. Hence, the allowed quantum number I$(J^P) = 0(1^+)$ is

*Electronic address: dharmeshphy@gmail.com

TABLE I: Mass Spectra, root mean square radius of $\Lambda_{s,c,b} - \Lambda_{s,c,b}$ and $\Lambda_{s,c,b} - \overline{\Lambda_{s,c,b}}$ systems. Here, $'\times'$ means this state is forbidden and $'-'$ means solution not found.

System $[I(J^P)]^Q$ - $[I(J^P)]^Q$	$I(J^P)$	μ GeV	μ GeV	B.E. MeV	B.E. MeV	Mass GeV	Mass GeV	$\sqrt{r^2}$ fm	$\sqrt{r^2}$ fm
		$\Lambda_s - \Lambda_s$	$\Lambda_s - \overline{\Lambda_s}$	$\Lambda_s - \Lambda_s$	$\Lambda_s - \overline{\Lambda_s}$	$\Lambda_s - \Lambda_s$	$\Lambda_s - \overline{\Lambda_s}$	$\Lambda_s - \Lambda_s$	$\Lambda_s - \overline{\Lambda_s}$
$[0(\frac{1}{2}^+)]^+$ - $[0(\frac{1}{2}^+)]^+$	0 (0^+)	$\times$	0.0049	$\times$	+0.0015	$\times$	2.223	$\times$	68.72
	0 (1^+)	0.0049	0.0049	+0.0015	+0.0015	2.223	2.223	68.74	68.74
		$\Lambda_c - \Lambda_c$	$\Lambda_c - \overline{\Lambda_c}$	$\Lambda_c - \Lambda_c$	$\Lambda_c - \overline{\Lambda_c}$	$\Lambda_c - \Lambda_c$	$\Lambda_c - \overline{\Lambda_c}$	$\Lambda_c - \Lambda_c$	$\Lambda_c - \overline{\Lambda_c}$
$[0(\frac{1}{2}^+)]^+$ - $[0(\frac{1}{2}^+)]^+$	0 (0^+)	$\times$	0.0012	$\times$	+0.0000	$\times$	4.572	$\times$	279
	0 (1^+)	0.0012	0.0012	+0.0000	+0.0000	4.572	4.572	279	279
		$\Lambda_b - \Lambda_b$	$\Lambda_b - \overline{\Lambda_b}$	$\Lambda_b - \Lambda_b$	$\Lambda_b - \overline{\Lambda_b}$	$\Lambda_b - \Lambda_b$	$\Lambda_b - \overline{\Lambda_b}$	$\Lambda_b - \Lambda_b$	$\Lambda_b - \overline{\Lambda_b}$
$[0(\frac{1}{2}^+)]^+$ - $[0(\frac{1}{2}^+)]^+$	0 (0^+)	$\times$	0.0002	$\times$	$+1.4 \times 10^{-7}$	$\times$	11.238	$\times$	1448
	0 (1^+)	0.0002	0.0002	$+1.4 \times 10^{-7}$	$+1.4 \times 10^{-7}$	11.238	11.238	1448	1448

possible for di-baryonic $\Lambda\Lambda$ systems, while for $\Lambda\overline{\Lambda}$ systems, I$(J^P) = 0(0^+)$, $0(1^+)$ are possible. For both $\Lambda_{s,c,b}\Lambda_{s,c,b}$ and $\Lambda_{s,c,b}\overline{\Lambda_{s,c,b}}$ systems, the η, σ and ω exchanges contribute to the net s-wave OBE potential, thus only these meson exchange have been considered in the calculations of $\Lambda\Lambda$ and $\Lambda\overline{\Lambda}$ systems. With all possible isospin-spin channels, the contribution of η exchange is almost negligible, moreover, it is repulsive in (I,S)=(0,0) channel for $\Lambda_{s,c,b}\overline{\Lambda_{s,c,b}}$ systems. On the other side, the σ and ω exchanges are shown the opposite nature to each other. Because of the cancellation, the effective s-wave OBE potential is too shallow to get bound state. We have not found any bound states with the possible quantum numbers for both the di-baryonic $\Lambda_{s,c,b}\Lambda_{s,c,b}$ and baryonium $\Lambda_{s,c,b}\overline{\Lambda_{s,c,b}}$ systems. In the present work, we have not found $\Lambda_s\Lambda_s$ bound state, even, we have not found bound state of heavy analog of H-dibaryon i.e. $\Lambda_c\Lambda_c$ and $\Lambda_b\Lambda_b$. Notwithstanding these $\Lambda\Lambda$ systems which are obtained as unbound or almost on threshold in our calculations, $\Lambda\overline{\Lambda}$ baryonium systems are also obtained as unbound.

References

[1] C. Patrignani et al. (Particle Data Group), Chin. Phys. C40, 100001 (2016).

[2] F.K. Guo et al., Rev. Mod. Phys. 90, 015004 (2018).

[3] R. Tiwari, D. P. Rathaud, A. K. Rai, arXiv:2108.06521v1 [hep-ph].

[4] R. Tiwari, D. P. Rathaud, A. K. Rai, arXiv:2108.04017v1 [hep-ph].

[5] R.L. Jaffe, Phys. Rev. Lett. 38, 195 (1977).

[6] Z.H. Luo, M. Loan, Y. Liu, Phys. Rev. D 84, 034502 (2011).

[7] H. Takahashi et al., Phys. Rev. Lett. 87, 212502 (2001).

[8] S.R. Beane et al. (NPLQCD Collaboration), Phys. Rev. Lett. 106, 162001 (2011).

[9] T. Inoue et al. (HAL QCD Collaboration), Phys. Rev. Lett. 106, 162002 (2011).

[10] D. P. Rathaud, R.Tiwari and A. K. Rai Indian J. Phys, **doi.org/10.1007/s12648-020-01954-6**, (2021).

[11] D. P. Rathaud and A. K. Rai, Few-Body Syst, **60**, 1 (2019).

[12] A. K. Rai and D. P. Rathaud, Eur. Phys. J. C, **75**, 462 (2015).

[13] D. P. Rathaud and A. K. Rai Eur. Phys. J. Plus, **132**, 370 (2017).

[14] D. P. Rathaud and A. K. Rai Indian J. Phys, **90**, 1299 (2016).

[15] Y. Koma, M. Koma, H. Wittig, Phys. Rev. Lett, **97**, 122003 (2006).

[16] R. Machleidt, K. Holinde, C. Elster, Physics Reports 149, 1 (1987)

[17] N. Lee et al., Phys. Rev. D 84, 014031 (2011).