PROCEEDINGS OF SCIENCE

Masses of T_{4c} tetra quark state in a relativistic formalism

P C Vinodkumar[*†]
Department of Physics, Sardar Patel University, Vallabh Vidyanagar, 388120, India
E-mail: p.c.vinodkumar@gmail.com

Tanvi Bhavsar
Department of Physics, Sardar Patel University, Vallabh Vidyanagar, 388120, India
E-mail: tanvibhavsar1992@yahoo.com

Manan Shah
P. D. Patel Institute of Applied Sciences, CHARUSAT, Changa, 388421, India
E-mail: mnshah09@gmail.com

After the discovery of X(3872) many new and unexplained X Y Z states have been discovered experimentally in recent times [1]. It has helped in our faith towards the existence of multi quark states. Most of these unknown states consist of hidden heavy quark anti quark pair with combinations of quark/antiquark in the lighter sector (cq$\bar{c}\bar{q}$ or bq$\bar{b}\bar{q}$ where q $\in$ u, d, s). However, the tetra quark state containing all heavy flavor like T_4Q (Q $\in$ c, b, $\bar{c}$ and $\bar{b}$) has not been investigated rigorously. So we have selected a single flavor (all charm) tetra quark system to study the mass spectra and hadronic decays. Based on diquark - antidiquark model we have developed a relativistic approach to study exotic hadron spectroscopy, where in, the four body system is considered as three subsequent two body systems. We have solved Dirac equation by using Cornell like confinement potential for two body Interaction and for the construction of tetra quark system (cc$\bar{c}\bar{c}$). The Spin dependent parts are also employed to understand the splitting structure of tetra quarks. The contribution of each term is well analyzed. Our predicted mass for first radially excited state with JPC value 0^{++}, 1^{+-}, 2^{++} are 6.495, 6.595 and 6.68 which are in a good agreement with other theoretical model predictions [2]. More experiments and theoretical attempts are required to understand the interactions and nature of all heavy tetra quark states. We hope that forthcoming experiments such as Belle II and LHC at 13 TeV gives more information about doubly hidden charm tetra quark hadronic state.

XVII International Conference on Hadron Spectroscopy and Structure - Hadron2017
25-29 September, 2017
University of Salamanca, Salamanca, Spain

*Speaker.
†A footnote may follow.

PoS(Hadron2017)118

1. Introduction

In QED, the multi-lepton bound states exist with the composition of $e^+e^-\mu^+\mu^-$ and $e^+e^-e^+e^-$ [3, 4]. While in QCD there exist the multiquark bound states and they compose of quarks and anti-quarks. Study of quarks are important as quarks are fundamental building block of matter but we don't have much knowledge about the behaviour of quarks at low energy than at thousands of times higher energies in the Large Hadron collider. The tetraquark is one of the challenging predictions of quantum chromodynamics because it requires accurate experimental confirmation. The present challenge for theorists is to develop a quark model which gives the information about multi quark structure and its decay properties. The concept of tetraquark was first introduced in 1976. Zachary S. Brown and Kostas Orginos have used lattice QCD to study the heavy-light heavy-light tetraquark bound states [6]. The all charm tetraquark was first studied by Iwasaky in 1975 [5]. His assumption for the possibility of T_{4c} is based on a string model of hadron and a generalized OZI rule and he has also estimated the mass of the ground state tetraquark is around 6 GeV.

In this paper, we have developed the relativistic quark model based on the Dirac formalism to calculate the mass spectra of tetraquarks with charm flavours. The four body system consist of diquark-antidiquark. The paper is outlined as follows. In Sec. 2, we discuss theoretical formalism and in section 3, we presented our results on the masses together with the contributions from hyperfine interactions of all charm tetraquark. In section 4, we discuss the present results and compared with other theoretical model.

2. Potential model of quarkonium system

The quark and antiquark inside the meson have definite energy states. One of the very successful approach to construct the mesonic system is to solve Dirac equation for the quark anti-quark in a confinement potential. For the present study we have considered the confinement through a linear potential. The form of the model potential is expressed as,

$$V(r) = \frac{1}{2}(1+\gamma_0)(\lambda r^{1.0} + V_0) \tag{2.1}$$

Where, λ is the potential strength. V_0 is a constant negative potential depth [7, 8, 9].

The wave function which satisfy Dirac equation with a general potential is given by [10, 11],

$$(\vec{\alpha}\cdot\vec{p} + m_Q)\psi_q(\vec{r}) = [E_q - V(r)\gamma_0]\,\psi_q(\vec{r}), \tag{2.2}$$

$$[\gamma^0 E_q - \vec{\alpha}.\vec{p} - m_q - V(r)]\psi_q(\vec{r}) = 0, \tag{2.3}$$

where

$$\alpha = \begin{pmatrix} 0 & \sigma \\ \sigma & 0 \end{pmatrix}; \gamma^0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}; \gamma^i = \begin{pmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{pmatrix} \tag{2.4}$$

V(r) is a potential which consist scalar + vector part. The solution of Dirac equation can be written as two component (positive and negative energies in the zeroth order) form as [7, 8, 9, 11],

$$\psi^{(+)}_{nlj}(\vec{r}) = N_{nlj}\begin{pmatrix} ig(r)/r \\ (\sigma.\hat{r})f(r)/r \end{pmatrix}\mathscr{Y}_{ljm}(\hat{r}) \tag{2.5}$$

$$\psi^{(-)}_{nlj}(\vec{r}) = N_{nlj}\begin{pmatrix} i(\sigma.\hat{r})f(r)/r \\ g(r)/r \end{pmatrix}(-1)^{j+m_j-l}\mathscr{Y}_{ljm}(\hat{r}) \tag{2.6}$$

and N_{nlj} is the overall normalization constant [7, 8, 9, 11]. The reduced radial part $g(r)$ and $f(r)$ of the Dirac spinor $\psi_{nlj}(r)$ are the solutions of the equations given by [7, 8, 9, 11]

$$\frac{d^2g(r)}{dr^2} + \left[(E_D+m_q)[E_D-m_q-V(r)] - \frac{\kappa(\kappa+1)}{r^2}\right]g(r) = 0 \tag{2.7}$$

and

$$\frac{d^2f(r)}{dr^2} + \left[(E_D+m_q)[E_D-m_q-V(r)] - \frac{\kappa(\kappa-1)}{r^2}\right]f(r) = 0 \tag{2.8}$$

By converting these equation into dimensionless form [7, 8, 9, 10] as,

$$\frac{d^2g(\rho)}{d\rho^2} + \left[\varepsilon - \rho^{1.0} - \frac{\kappa(\kappa+1)}{\rho^2}\right]f(\rho) = 0 \;\; and \;\; \frac{d^2f(\rho)}{d\rho^2} + \left[\varepsilon - \rho^{1.0} - \frac{\kappa(\kappa-1)}{\rho^2}\right]g(\rho) = 0$$

where $\rho = \frac{r}{r_0}$ is a dimensionless variable with suitably chosen scale factor $r_0 = \frac{r}{[(E+m)\lambda]^{\frac{-1}{3}}}$ and corresponding energy eigen value is given by [7, 8, 9],

$$\varepsilon = (E_D - m_q - V_0)(m_q + E_D)^{\frac{1}{3}}\lambda^{\frac{-2}{3}} \tag{2.9}$$

The solution of $f(\rho)$ and $g(\rho)$ are also normalized [7, 8, 9],

$$\int_0^\infty \left[f^2(\rho) + g^2(\rho)\right]d\rho = 1 \tag{2.10}$$

Now the wave function for quarkonium system can be constructed by using positive and negative energy solutions of Dirac equation. Mass of particular Quark-Anti quark system can be written as [7, 8, 9],

$$M_{Q\bar{Q}} = E_D^Q + E_D^{\bar{Q}} - E_{cm} \tag{2.11}$$

here, E_{cm} is the center of mass correction which absorb in our potential parameter V_0.

In this calculation, we incorporate the j-j coupling with total binding energy of system and total mass of the particular state is represented by $M_{^{2s+1}L_J}$ as [7, 8, 9],

$$M_{^{2s+1}L_J} = M_{Q\bar{Q}}(n_1l_1j_1, n_2l_2j_2) + \langle V^{j_1j_2}_{Q\bar{Q}}\rangle \tag{2.12}$$

where the j-j coupling term is expressed as [7, 8, 9],

$$\langle V^{j_1j_2}_{Q\bar{Q}}\rangle = \frac{\sigma\langle j_1j_2JM|\widehat{j_1}\widehat{j_2}|j_1j_2JM\rangle}{(E_Q+m_Q)(E_{\bar{Q}}+m_{\bar{Q}})} \tag{2.13}$$

here, σ is j - j coupling constant and $\langle j_1j_2JM|\widehat{j_1}\widehat{j_2}|j_1j_2JM\rangle$ contains the square of the Clebsch-Gordan coefficient.

Table 1: S-wave mass spectrum for $cc\bar{c}\bar{c}$(in GeV).

state	Sd	Ld	S$\bar{d}$	L$\bar{d}$	Jd	J$\bar{d}$	J=Jd+J$\bar{d}$	mass	[12]	[13]
1s	0	0	0	0	0	0	0	5.927	5.907	5.617-6.24
	1	0	0	0	1	0	1	6.059	6.012	5.720-6.137
	1	0	1	0	1	1	0	6.189	6.222	5.777-6.194
							1	6.190	-	-
							2	6.193	-	-
2s	0	0	0	0	0	0	0	6.498	6.568	-
	1	0	0	0	1	0	1	6.595	6.632	-
	1	0	1	0	1	1	0	6.688	6.760	-
							1	6.689	-	-
							2	6.692	-	-
3s	0	0	0	0	0	0	0	7.059	-	-
	1	0	0	0	1	0	1	7.139	-	-
	1	0	1	0	1	1	0	7.217	-	-
							1	7.218	-	-
							2	7.220	-	-

3. Result and discussion

The masses of all charm tetraquark are computed by using Dirac formalism using linear plus confinement potential. We have also considered various combinations of the orbital and spin excitations. From our relativistic quark model we have also predicted hyperfine splitting for $^5S_1$ state. Masses for the first radial excited states are in good accordance with available theoretical results.

References

[1] Lu Zhao, Wei-Zhen Deng, and Shi-Lin Zhu1, Phys. Rev. D 90, 094031 (2014).

[2] Wei Chen et. al., arXiv:1605.01647v1 [hep-ph] 5 May, 2016

[3] D. B. Cassidy and A. Mills, Nature 449, 195 (2007).

[4] E. A. Hylleraas and A. Ore, Phys. Rev. 71, 493 (1947).

[5] Y. Iwasaki, Prog. Theor. Phys. 54, 492 (1975)

[6] Zachary S. Brown and Kostas Orginos, Phys. Rev. D 86, 114506 (2012)

[7] Manan Shah, Bhavin Patel, P. C. Vinodkumar,Eur. Phys. J. C **76**: 36 (2016).

[8] Manan Shah, Bhavin Patel and P. C. Vinodkumar, Phys. Rev. D **90**: 014009 (2014).

[9] Manan Shah, Bhavin Patel and P. C. Vinodkumar, Phys. Rev. D **93**: 094028 (2016).

[10] Quantum mechanics, second edition, G. Aruldhas.

[11] Relativistic Quantum mechancs wave eqautions by W.Greiner.

[12] V.R. Debastiani, Master's dissertation, Spectroscopy of all charm tetraquark,2016.

[13] J.Wu, Y.R.liu, K.Chen, X.Liu and S.L.Zhu , arXiv:1605.01134[hep-ph]