Spectroscopy of six-quark states as candidates for di-baryon states

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Introduction

Search for di-baryons is one of the most challenging theoretical and experimental problems in the physics of strong interaction and quantum chromodynamics (QCD. The possibility of exotic six-quark qqqqqq di-baryonic "hexaquark" state was first proposed by F. J. Dyson and N.Xuong [1] in 1964, just after Gell-Mann's proposition of the SU(3) quark model for hadrons [2]. However, this topic received serious attention only after Jaffe's proposal [3] of the so called "H dibaryon", a $\mid uuddss\rangle$ state corresponding to a bound $\Lambda - \Lambda$ system. Since then, worldwide activities of theoretical predictions as well as numerous experimental searches have been devoted for di-baryon states with and without strangeness. There were so many theoretical predictions of di-baryons which are quite different in different models. Till now deuteron is the only known di-baryon in the non-strange sector. From time to time experiments have indicated that di-baryons other than the deuteron might exist, but none of these experiments have been decisive, but recently, experiments at the Jülich Cooler Synchrotron (COSY) have found compelling evidence for a new state in the two-baryon system, with a mass of 2380 MeV, width of 80 MeV and quantum numbers $I(J^P) = 0(3^+)$ in their exclusive and kinematically complete high-statistics measurements of $np \to d\pi^0\pi^+$ two-pion production reactions [4].

Phenomenology

Many theoretical works have focused on the issue of resolving the structure of sixquark states as di-baryonic molecules or compact sixquark states. Investigations into the existence of multiquark states have begun in the early days of QCD [3, 5]. Understanding the mechanisms underlying confinement in QCD is among the most fundamental questions in hadronphysics. However, little success has been achieved even in understanding pentaquark states due to the non-perturbative nature of QCD at the hadronic scale. The hadron molecular considerations does simplify this difficulty by replacing interquark color interacion with a residual strong interactions between two color singlet hadrons. Though the interquark interaction within a hadron is understood in terms Cornell like potential (Coulomb plus linear form), it will be appropriate to consider a long range form for the residual hadron-hadron interaction of the Woods Saxon plus Coulomb type for the present study of di-baryonic molecules [6].

$$V(r) = \frac{-V_0}{1+\exp^{(\frac{r-R}{a})}} - \frac{K_c}{r} \tag{1}$$

Binding energy is obtained by numerically solving Schrödinger equation using mathematica notebook of Range-Kutta method. The non-relativistic Schrödinger bound-state mass(spin average mass) of the di-baryonic system is obtained as

$$M_{SA} = m_1 + m_2 + BE \tag{2}$$

We introduce j-j coupling term to obtain the hyperfine splitting of the different di-baryonic states. Accordingly, the di-baryonic molecular

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TABLE I: Mass spectra of di-baryon systems (in GeV)

System	R (fm)	BE	J^P	Mcw	$E_{hyp}{}^a$	M_J	Others
$\Delta-\Delta$	2.0	-0.084	3^+	2.379	0.0037	2.383	2.380^b ±0.010 [4]
			2^+		-0.0012	2.378	2.365 [7]
			1^+		-0.0046	2.375	2.460± 0.002[8]
$\Lambda-\Lambda$	0.5	-0.038	1^+	2.191	0.0002	2.192	2.150[3]
			0^+		-0.0005	2.191	
$N-\Delta$	1.75	-0.054	2^+	2.115	0.0010	2.116	2.170[9]
			1^+		-0.0017	2.113	2.225[10]
$\Sigma^+-\Sigma^+$	1.73	-0.064	1^+	2.313	0.0035	2.313	-
			0^+		-0.0010	2.312	
$\Sigma^{*+}-\Sigma^{*+}$	1.26	-0.059	3^+	2.704	0.0022	2.706	-
			2^+		-0.0007	2.703	
			1^+		-0.0027	2.701	
			0^+		-0.0037	2.700	
$\Xi^- - \Xi^-$	1.42	-0.060	1^+	2.518	0.0008	2.581	-
			0^+		-0.0008	2.580	
$\Xi^{-*}-\Xi^{-*}$	1.15	-0.053	3^+	2.608	0.0021	2.610	-
			2^+		-0.0007	2.607	
			1^+		-0.0025	2.605	
			0^+		-0.0035	2.604	

[a] $E_{hyp} = E(j_1, j_2; J)$.

[b] Exp.

mass is obtained as

$$M_J = M_{SA} + E_{(j_1,j_2;J)} \tag{3}$$

Where m_1 and m_2 are the masses of the constituent baryons, BE represents the binding energy of the di-baryonic system and $E_{(j_1,j_2;J)}$ represents the spin-dependent term. The hyperfine interaction is computed using the expression similar to the hyperfine interactions for quarkonia but without considering color factor and is taken as

$$E_{(j_1,j_2;J)} = \frac{2 < j_1.j_2 >_J |R_{n,l}(0)|^2}{3m_1m_2} \tag{4}$$

The optimized potential parameters for the binding energy of $\Delta-\Delta$ hexaquark state are as follows: a=0.2 fm; $V_0 = 0.3GeV$; $K_c = 0.392$. Here, R is taken as $R \geq \langle r\rangle_{h1} + \langle r\rangle_{h2}$ (0.5-2.0 fm), where $\langle r\rangle_{h1}, \langle r\rangle_{h2}$ are the rms radii of consituent hadrons.

Results and conclusion

The predicted mass spectrum of low lying di-baryonic states in the strange and non-strange sector is compared with the experimentally known results and other available theoretical results are listed in Table I. In the present work, we have used the mass of $\Delta-\Delta$ at 2.383 GeV with $J^P = 3^+$ state [4] and predicted other low lying di-baryonic states. It is to be noted that the spin coupling is very small (3-5 MeV). The mass of the positive parity molecular state $(\Sigma^{*+}-\Sigma^{*+})_{J=0,1,2,3}$ is predicted around 2.700 GeV. The mass of $N-\Delta$ state is found to be around 2.116 GeV which is slightly lesser than the other theoretically predicted values. Among di-baryon molecular states presented here in Table I, only few low lying state are known theoretically. Many of these states require further experimental support. Thus, in the absence of experimental results such calculations may be considered as guidelines for further theoretical or experimental investigations.

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