Possibility of $P_c(4380)$ and $P_c(4450)$ penta-quark states as candidates for charmed meson-baryon molecular states

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Introduction

The recent discovery of two hidden-charm resonances by the LHCb Collaboration in the $J/\psi p$ invariant mass distribution denoted as P_c, with masses (widths) $(4380 \pm 8 \pm 29)$ MeV ($(205 \pm 18 \pm 86)$ MeV) and $(4449.8 \pm 1.7 \pm 2.5)$ MeV ($(39 \pm 5 \pm 19)$ MeV), respectively [1] has immediately attracted a lot of attention from the whole community since they could be the long-searching-for pentaquark states in the heavy flavor sector. The high mass and the decay channel $J/\psi p$ suggest that these two states must have minimal quark content of $c\bar{c}uud$, which can be called pentaquark-charmonium states. Soon after the experimental results released, much theoretical effort was paid into this field and many ideas were inspired.There have been several attempted assignments, such as the molecule-like pentaquark states [2], the diquark-diquark-antiquark type pentaquark states [5, 6], the diquark-triquark type pentaquark states [7], re-scattering effects [8], etc. Search for pentaquarks is one of the most challenging theoretical and experimental problems in the physics of strong interaction and quantum chromodynamics (QCD). The last rise and down of the pentaquark study happened at ten years ago due to claim of finding of the strange pentaquark Θ by the LEPS collaboration [9]. But now this topic received serious attention since discovery of P_c has rekindled the hope for long searched mysterious pentaquark states.

Phenomenology

Many theoretical works have focused on the issue of resolving the structure of pentaquark states as di-hadronic molecules or compact five quark states[10–12]. In the pioneer paper [13], Gell-Mann indicated that the multiquark states should exist along with the simplest structures for baryons which are composed of three valence quarks and mesons which contain a quark and an antiquark. Investigations into the existence of multiquark states have begun in the early days of QCD [11, 12]. Understanding the mechanisms underlying confinement in QCD is among the most fundamental questions in hadron physics. However, little success has been achieved 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. Thus, for the present study of di-hadronic molecules, we employ Woods Saxon plus Coulomb type of potential between two color singlet hadrons of the form

$$V(r) = \frac{-V_0}{1 + \exp^{(\frac{r-R}{a})}} - \frac{4\alpha_s}{3r} \qquad (1)$$

The potential parameters employed here are taken from Ref. [14]. 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. Binding energy is obtained by numerically solving Schrödinger equation using mathematica notebook of Range-Kutta method. The nonrelativistic Schrödinger bound-state mass(spin average mass) of the di-hadronic system is ob-

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TABLE I: Mass spectra of di-hadronic molecular states (in GeV)

System	BE	J^P	Mcw	$E_{hyp}{}^a$	M_J	Others
$\Lambda_c - D^{*0}$	-0.049	$(1/2)^-$	4.243	-0.0001	4.242	
		$(3/2)^-$		0.0005	4.243	
$\Sigma_c^+ - \bar{D}^0$	-0.051	$(1/2)^-$	4.367	0.0	4.367	
$\Sigma_c^{*+} - \bar{D}^0$	-0.101	$(3/2)^-$	4.375	0.0	4.375	$4.380^{\pm 0.008}_{\pm 0.029}$[1]^b
						4.417 [3]
						4.370 [4]
$\Sigma_c^{++} - D^-$	-0.054	$(1/2)^-$	4.371	0.0	4.371	
$\Sigma_c^{*+} - \bar{D}^{*0}$	-0.091	$(5/2)^-$	4.436	0.0012	4.437	$4.449^{\pm 0.0017}_{\pm 0.0025}$[1]^b
		$(3/2)^-$		-0.0008	4.435	4.481 [3]
		$(1/2)^-$		-0.0020	4.433	4.460 [4]
$\Sigma_c^{*++} - D^{*-}$	-0.089	$(5/2)^-$	4.437	0.0016	4.438	
		$(3/2)^-$		-0.0011	4.435	
		$(1/2)^-$		-0.0027	4.434	

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

tained as

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

Further, we introduce j-j coupling term to obtain the hyperfine splitting of the different di-hadronic states. Accordingly, the mass of a di-hadronic molecular state represented by J 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 hadrons, BE represents the binding energy of the di-hadronic 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

$$E_{(j_1,j_2;J)} = \frac{2 < j_1.j_2 >_J |R(0)|^2}{3 m_1 m_2} \tag{4}$$

Results and conclusion

The predicted mass spectrum of low lying pentaquark states as di-hadronic molecular states is compared with the experimentally known results and other available theoretical results are listed in Table I. In the present study, we have predicted $P_c(4380)$ as loosely bound state of $\Sigma_c^{*+} - \bar{D}^0(3/2^-)$ and $P_c(4450)$ state as of $\Sigma_c^{*+} - \bar{D}^{*0}(5/2^-)$. The present study in molecular picture predicts the parity quantum numbers of both $P_c(4380)$ and $P_c(4450)$ as negative which is in agreement with Ref.[2]. Although the present data of LHCb favors $P_c(4380)$ and $P_c(4450)$ have opposite parities, they have also mentioned in their paper that the same parities are not excluded [1]. There is high probability that both states may be identified to possess the same negative parity when more data and analysis are available in the near future. If it really turns out so, then the physics will be very interesting. Thus, in the absence of more experimental measurements these calculations may be considered as one of the guidelines for further experimental investigations for other predicted states within the mass range of $4.0 - 5.0$ *GeV*.

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