Mass spectra of hidden-charm molecular pentaquarks states

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Introduction

Very recently, the LHCb Collaboration has reprted two hidden-charmed resonances $P_c(4380)$and $P_c(4450)$ consistent with pentaquark states in the $\Lambda_b^0 \to K^- J/\psi p$ process 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]. The observation of the P_c states has aroused the theorist's strong interest in the hidden-charm pentaquark states. They have been studied in various frameworks, 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. An identification of pentaquark states as exotic hadron has been one of the long standing problems in the physics of strong interaction and quantum chromodynamics (QCD). A decade ago lots of discussion were made about pentaquarks states but due to lack of further experimental evidences the study of pentaquarks have been almost gone in the darkness. But, recent remarkable observation of two resonances i.e. $P_c(4380)$ and $P_c(4450)$ with hidden charm and the minimal quark content $c\bar{c}uud$ provided new impact for studies of pentaquark states and opens a new window to study the exotic hadronic matter.

Phenomenology

Many theoretical works have focused on the issue of resolving the structure of multiquark states as di-hadronic molecules [10–12]. 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 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

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

System	BE	J^P	I	Mcw	$E_{(j_1,j_2;J)}$	$E_{(i_1,i_2;I)}$	M_{Total}
$P-\eta_c$	-0.051	$1/2^-$	1/2	3.867	0.0	0.0	3.867
$P-J/\psi$	-0.052	$3/2^-$	1/2	3.983	0.0017	0.0	3.985
		$1/2^-$	1/2		-0.0035	0.0	3.979
N^*-J/ψ	-0.052	$3/2^-$	1/2		0.0017	0.0	3.984
		$1/2^-$	1/2		-0.0035	0.0	3.978
$\Lambda_c-\bar{D}^0$	-0.096	$1/2^-$	$1/2^+$	4.054	0.0000	0.0000	4.054
$\Lambda_c-\bar{D}^{*0}$	-0.102	$3/2^-$	1/2	4.190	0.0018	0.0	4.192
		$1/2^+$	1/2		-0.0036	0.0	4.186
$\Sigma_c-\bar{D}^0$	-0.101	$1/2^+$	3/2	4.215	0.0	0.0018	4.217
			1/2		0.0	-0.0036	4.211
${\Lambda_c}^*-D^0$	-0.105	$1/2^+$	$1/2^+$	4.315	0.0	0.0	4.351
${\Sigma_c}^*-\bar{D}^{*0}$	-0.109	$5/2^-$	3/2	4.414	0.0052	0.0017	4.421
			1/2		0.0052	-0.0035	4.415
		$3/2^-$	3/2		-0.0035	0.0017	4.412
			1/2		-0.0035	-0.0035	4.408
		$1/2^-$	3/2		-0.0008	0.0017	4.414
			1/2		-0.0008	-0.0035	4.409
${\Lambda_c}^*-\bar{D}^{*0}$	-0.113	$5/2^+$	1/2	4.521	0.0051	0.0	4.527
		$3/2^+$	1/2		-0.0034	0.0	4.518
		$1/2^+$	1/2		-0.0086	0.0	4.513
${\Sigma_c}^*-\bar{D}^0$	-0.109	$3/2^-$	3/2	4.414	0.0	0.0017	4.415
			1/2		0.0	-0.0035	4.410
${\Sigma_c}^{*+}-\bar{D}^{*+}$	-0.110	$5/2^-$	3/2	4.416	0.0052	0.0017	4.423
			1/2		0.0052	-0.0035	4.418
		$3/2^-$	3/2		-0.0035	0.0017	4.415
			1/2		-0.0035	-0.0035	4.409
		$1/2^+$	3/2		-0.0088	0.0017	4.405
			1/2		-0.0088	-0.0035	4.404
$\Sigma_c-\bar{D}^{*+}$	-0.108	$3/2^-$	3/2	4.354	0.0017	0.0017	4.358
			1/2		0.0017	-0.0035	4.353
		$1/2^-$	3/2		-0.0035	0.0017	4.353
			1/2		-0.0035	-0.0035	4.347

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interaction with a residual strong interactions between two color singlet hadrons. We study di-hadronic systems here by considering the molecular interaction between the two hadrons as the well known Yukawa type interaction V(r) and is given by

$$V(r) = \frac{-g^2}{r} e^{-kr} \tag{1}$$

Where g being the coupling constant and k is the molecular interaction strength. The potential parameters employed here are taken from Ref. [14]. By using Mathematica code [15] we obtained the binding energies and then computed the masses of low lying di-hadronic molecules same as done in Ref. [16]. The non-relativistic Schrödinger bound-state mass(spin average mass) of the di-hadronic system is obtained as

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

Where m_1 and m_2 are the masses of the constituent hadrons, BE represents the binding energy of the di-hadronic system. Further, we have added spin and isospin contribution. Accordingly, the mass of a di-hadronic molecular state is obtained as

$$M_{Total} = M_{cw} + E_{(j_1,j_2;J)} + E_{(i_1,i_2;I)} \tag{3}$$

The hyperfine interaction is computed using the expression similar to the hyperfine interactions for quarkonia but without considering color factor which is same as in Ref. [16].

Results and conclusion

The predicted mass spectra of low lying pentaquark states in the charm sector as di-hadronic molecular states using Yukawa type potential are listed in Table I. Our result supports the molecular assignment of $P_c(4380)$ and $P_c(4450)$ with the configurations $\Sigma_c^{*+} - \bar{D}^0$ with (I = 1/2, $J = 3/2^-$) and $\Sigma_c^{*+} - \bar{D}^{*0}$ with (I = 1/2, $J = 5/2^-$) respectively. The present study in molecular picture predicts the parity quantum numbers of both $P_c(4380)$ and $P_c(4450)$ states 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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