Exploring the Masses of Exotic Heavy Pentaquarks

Ballari Chakrabarti
Department of Physics,
Jogamaya Devi College,
(Affiliated to University of Calcutta)
Kolkata, India.

Aim of the work :

- Probing the masses of exotic heavy pentaquarks considering a di-hadronic state consisting of a meson and a baryon.
- Taking interaction between the hadrons as Van der Waals' type of weak molecular interaction.
- Spin interaction also considered.
- Estimation of the masses of recently reported pentaquark charmonium states $P_c^*(4380)$ and $P_c^*(4450)$.
- Prediction of binding energies of the crypto exotic heavy pentaquark states such as $P_S^*(1)$, $P_S^*(2)$, $P_b^*(1)$, $P_b^*(2)$ and other exotic pentaquark states for the charm and bottom families.

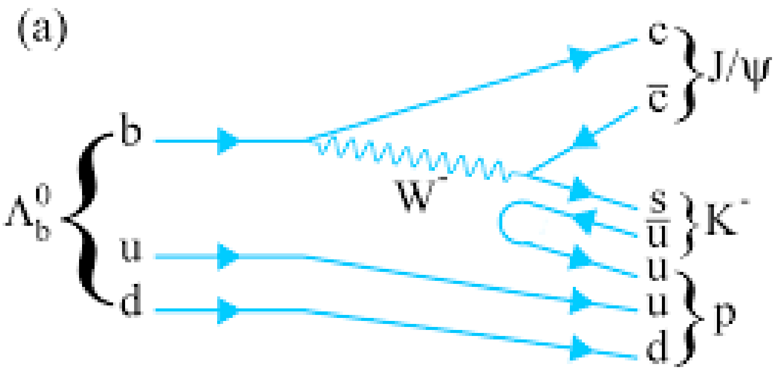
Introduction :

- Recent discovery of charmed pentaquarks $P_c^*(4380)$ and $P_c^*(4450)$ in LHCb experiment [1] inspired the research for other exotic heavy pentaquarks.

Decay of Λ_b^0 : $\Lambda_b^0 \rightarrow J/\Psi\ K^-\ p$. Intermediate states identified as $P_c^*(4380)$ and $P_c^*(4450)$ having width of 205±18±86 MeV and 39±5±19 MeV. Preferred J^P assignments are of opposite parity.

[1]. R. Aaij et al. (LHCb Collab.) Phys. Rev. Lett. **115** (2015) 072001.

Decay mode of Λ_b^0



$\Lambda_b^0 \rightarrow J/\Psi\ K^-\ p$

Methodology

- Assuming the pentaquark state as meson-baryon system the mass formula for the low-lying di-hadronic molecule runs as :

$$M_{Total} = M_1 + M_2 + E_{BE} + E_{SD} \qquad (1)$$

where M_1 and M_2 represent the masses of the constituent hadrons respectively, E_{BE} represents the binding energy of the di-hadronic system and E_{SD} represents the spin dependent term.

- The interaction potential between the meson-baryon system is taken to be Van der Waals' type of molecular interaction

$$V(r_{12}) = -(K_{mol}/r_{12})\, Exp(-C^2 r_{12}^2/2) \qquad (2)$$

where K_{mol} is the residual strength of the strong interaction molecular coupling and C is the effective color screening of the confined gluons.

- The binding energy can be expressed as

$$E_{BE} = \langle \Psi(r_{12}) | \; V(r_{12}) \; | \Psi(r_{12}) \rangle \qquad (3)$$

Using the wave function for the ground state of the di-hadronic molecule from Statistical Model [2] which runs as

$$|\Psi(r_{12})|^2 = (315/64\pi \, r_0^{9/2})(r_0 - r_{12})^{3/2} \, \Theta(r_0 - r_{12}) \qquad (4)$$

corresponding to the linear type of background potential. r_0 is the radius of the di-hadronic molecule, $\Theta(r_0 - r_{12})$ is the usual step function.

Employing the additive rule for the radii of constituent hadrons i.e. $r_0 = r_1 + r_2$, r_1 and r_2 representing the individual radii of the hadrons constituting the molecule.

[2] B.Chakrabarti et al. Physica Scripta **79** (2009) 025103.

- We have executed the binding energy using equation (2), (3) and (4) , which yields

  $E_{BE}=(2.25\ K_{mol}/r_0)[{}_2F_2[(1.5,1),(2.75,2.25),-\beta]]$ (5)

  if Re$\beta>0$, ${}_2F_2$ is the relevant hypergeometric function and $\beta=C^2 r_{12}{}^2/2$.

- Spin hyperfine interaction can be expressed as

  $E_{SD}=(8\alpha_s/9\ M_1\ M_2)(\mathbf{S_1.S_2})\ |\Psi(0)|^2$ (6)

  α_s is the strong interaction constant, $\mathbf{S_1}$ and $\mathbf{S_2}$ are the spins of the hadrons involved, $|\Psi(0)|^2$ is the di-hadronic wave function at the origin.

- Using this formulation the masses of several exotic heavy pentaquarks have been calculated and have been compared with experimental findings as well as with other theoretical estimates.

Input values :

- For evaluation of K_{mol} :

X(3872) [3] may be a mesonic molecule of D^0 and D^0 indicated by Swanson [4].

Radii for D^0 is assumed to be 4.5 GeV^{-1} [5] and the masses of them are taken to be 1864.5 MeV [6].

These are substituted in equation (1) to calculate the binding energy. This is then used in equation (5) to find out the value of K_{mol} .

It is found that K_{mol} = 0.65.

- C = 50 MeV [7]

[3] S. K. Choi et al. Phys. Rev. Lett. **91** (2003) 262001.

[4] E.S. Swanson Phys. Rep**. 429** (2006) 243.

[5] B.Chakrabarti et al. Mod. Phys. Lett. **A12** (1997) 2133.

[6] W.M.Yao et al. J.Phys. **G33** (2006) 1.

[7] A.K.Rai et al. Ind. J. Phys. **80** (2006) 387.

- Values of masses of mesons and baryons used from PDG values [8].
- Radii considered :

  $r(p)=6GeV^{-1}$, $r(n)=4.7GeV^{-1}$ [9]

  $r(K)=4.77GeV^{-1}$[10],

  $r(\phi)=5.0GeV^{-1}$, $r(\Upsilon)=1.63GeV^{-1}$ [11],

  $r(D^{-})=4.97GeV^{-1}$, $r(B_S)=3.67GeV^{-1}$, $r(B^0)=3.82GeV^{-1}$, $r(D_S)=4.8GeV^{-1}$ [12]

  $r(\Sigma)=3.9GeV^{-1}$, $r(\Delta)=5.98GeV^{-1}$ [13],

  $r(\Psi)=2.005GeV^{-1}$ [14].

[8] K.A.Olive et al. (PDG) Chinese Phys. **C38** (2014) 090001

[9] S.N.Banerjee et al, Can. J. Phys. **66** (1988) 749

[10] S.N.Banerjee et al, Int. J. Mod. Phys. **A2** (1987) 1829

[11] S.N.Banerjee et al, Int. J. Mod. Phys. **A4** (1989) 943, 5575

[12] B.Chakrabarti et al. Mod. Phys. Lett. **A12** (1997) 2133

[13] R. Ghosh et al J. Mod. Phys. **6** (2015) 2070

[14] C.Hong et al. Chinese Phys. Lett. **18** (2001) 1558

Estimation of the masses of pentaquark charmonium states $P_c^*(4380)$ and $P_c^*(4450)$

States (uudcc)	Molecular form considered	Estimated Mass in MeV [13]	Experimental Mass in MeV [1]
P_c^* (spin 3/2)	P – J/Ψ (uud - cc)	4171	4380±8±29
P_c^* (spin 5/2)	Δ – J/Ψ (uud – cc)	4492	4449±1.7±2.5

Estimation of the masses of the crypto-exotic heavy pentaquarks

States & Configuration	Molecular form considered	Estimated Mass in GeV	Experimental Mass in GeV	Others Mass in the GeV
P_s^* $(1/2)^+$ P_s^* $(3/2)^+$ (uudss)	$p + \phi$ $\Delta + \phi$	2.110 2.381	---- ----	2.303 [15] 2.373 [15]
P_b^* $(1/2)^+$ P_b^* $(3/2)^+$ (uudbb)	$p + \Upsilon$ $\Delta + \Upsilon$	10.639 10.881	---- ----	10.743 [15] 10.813 [15]

[15] V. Kopeliovich et al. arxiv: hep-ph 1510.05958

Estimation of other exotic heavy pentaquarks in charm sector

Particles & configuration	Molecular form considered	Estimated mass in GeV	Experimental mass in GeV	Others mass in GeV
Θ_c^0 (uuddc)	$p + D^-$ $n + D^0$	2.656 2.670	3.099±0.003 ±0.005 [16]	2.650 [17] 2.710 [18]
N_c^0 (uudsc)	$p + D^0$	2.752	-----	2.870 [18]
Ξ_c^0 (uussc)	$\Sigma^+ + D^0$	2.905	-----	3.135 [18]
Θ_{cs}^{++} (uudcs)	$p + D^0$	2.751	-----	2.427 [19]

[16] A.Akas et al. (H1 Collab.) Phys. Lett. B588 (2004) 17
[17] D.Diakonov arxiv: hep-ph 1003.2157
[18] R.L.Jaffe et al. Phys. Rev. Lett. **91**(2003)232003;
M. Karliner et al. Phys. Lett. **B575** (2003) 249
[19] N.Tazimi et al. arxiv: hep-ph 1601.00642

Estimation of other exotic heavy pentaquarks in bottom sector

Particles & configuration	Molecular form considered	Estimated mass in GeV	Experimental Mass in GeV	Others Mass in GeV
Θ_b^+ (uuddb)	$p + B^0$ $n + B^+$	6.043 6.067		6.050 [18]
N_b^+ (uudsb)	$p + B_s$	6.127		6.210 [18]
Ξ_b^+ (uussb)	$\Sigma^+ + B_s$	6.366		6.351 [18]
Θ_{bs}^+ (uudbs)	$p + B_s$	6.128		5.752 [19]

Conclusions :

- We have investigated several exotic heavy pentaquark systems as hadronic composites of a meson and a baryon in the context of Van der Waals' type of molecular interaction acting between them. Statistical Model wave function considered is good enough for describing the hadron.
- The estimated masses of $P_c^*(4380)$ and $P_c^*(4450)$ in this formulation compare favorably well with the experimental data [1].
- Other crypto-exotic heavy pentaquark masses such as $P_s^*(1/2)^+$ and $P_s^*(3/2)^+$ and $P_b^*(1/2)^+$ and $P_b^*(3/2)^+$ in the strange and bottom families have been predicted with the hope that these would be detected in near future.

- Heavy exotic pentaquarks consisting of at least one heavy quark in the charm and bottom families such as Θ_c^0 N_c^0 Ξ_c^0 Θ_b^+ N_b^+ Ξ_b^+ etc. have been probed and compared with other theoretical works.
- Treating the pentaquark as a hadronic composite system would enlighten us about the spectroscopy of the much awaited heavy pentaquarks.
- This naïve model could also be applied for the investigations of the other multiquark systems such as tetraquark , hexaquark systems also.
- Description of these pentaquarks have also been probed using diquark-diquark-antiquark model by us [20].

[20] A. Chandra et al. Mod. Phys. Lett. **A27** (2012) 1250006.