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Hidden-charm and hidden-bottom pentaquark states

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We investigate the hidden-charm pentaquarks and the hidden-bottom pentaquarks as, respectively, $\bar{D}^{(*)}\Lambda_c$, $\bar{D}^{(*)}\Sigma_c^{(*)}$ and $\bar{B}^{(*)}\Lambda_b$, $\bar{B}^{(*)}\Sigma_b^{(*)}$ molecules coupled to the five-quark states [4]. The hidden-charm and -bottom pentaquark states have been described by taking into account both the meson-baryon channels, which encodes the dynamics at long distances, and a compact five quark core, which encodes the short distance part. As a result of our calculation, we find that, unlike the charmed sector, in the bottom sector, the pion exchange interaction is strong enough to produce resonant and bound states. As the hidden-bottom pentaquarks are more likely to form than their hidden-charm counterparts, the bottom sector is the more interesting environment to look for new pentaquark states.

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1. Introduction

In 2015, the Large Hadron Collider beauty experiment (LHCb) collaboration reported the observation of two hidden-charm pentaquarks, $P_c^+(4380)$ and $P_c^+(4450)$, in $\Lambda_b^0 \to J/\psi K^- p$ decay [1–3]. These two pentaquark states are found to have masses of $4380 \pm 8 \pm 28$ MeV and $4449.8 \pm 1.7 \pm 2.5$ MeV, with corresponding widths of $205 \pm 18 \pm 86$ MeV and $39 \pm 5 \pm 19$ MeV. The preferred assigned quantum numbers $(J^P_{P_c^+(4380)}, J^P_{P_c^+(4450)}) = (3/2^-, 5/2^+)$ give the best fit solution, but $(3/2^+, 5/2^-)$ and $(5/2^-, 3/2^+)$ are also acceptable.

Even before the observation by LHCb, extensive studies for light pentaquark and multi-quark states have been performed. For example, in 2012, Yuan *et al.* in [5] studied the $uudc\bar{c}$ and $udsc\bar{c}$ systems by the non-relativistic harmonic oscillator Hamiltonian based on three kinds of interactions: a chromomagnetic interaction, a flavor-spin-dependent interaction and an instanton-induced interaction. In [6], Santopinto *et al.* investigated the hidden-charm pentaquark states as five-quark compact states showing that the ground state multiplet of the charmonium pentaquark states is a $SU_f(3)$ octet, predicting the octet pentaquark masses and suggesting possible decay channels for the hidden-charm pentaquark states. The hidden-charm and hidden-bottom pentaquark masses have been calculated also by Wu *et al.* in [7], by means of a color-magnetic interaction between the three light quarks and the $c\bar{c}$ ($b\bar{b}$) pair in a color octet state. The hidden-charm pentaquark states have also been investigated by Takeuchi *et al.* [8] by a quark cluster model. In [8] she discussed also the structure of the five-quark states which appears in the scattering states. The P_c^+ pentaquarks have been found just below the $\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c$ thresholds. Thus, the $\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c$ molecular components are expected to be dominant [9–22]. The experience tells us that, when more than one quantum state is allowed for a given quantum number configuration, the hadronic resonant states are unavoidably mixtures of these states. Therefore, an important issue is to clarify how these components are mixed in physical hadrons. In the current problem of pentaquark, there are two competing sets of channels: the meson-baryon channels and the five-quark channels. The coupling to the five-quark states is described as a short-range potential between the meson and the baryon, while the long-range force is given by the one-pion exchange potential. In this way we could study the bound and resonant hidden-charm and hidden-bottom pentaquark states by solving the coupled channel Schrödinger equation for the isospin $I = \frac{1}{2}$ states with $J^P = \frac{1}{2}^-, \frac{3}{2}^-$, and $\frac{5}{2}^-$.

2. The model

As we have discussed previously, the two competing sets of channels to take into account in order to study the pentaquark states are the meson-baryon (MB) channels, which describe the dynamics at long distances and the five-quark (5q) channels, which describe the dynamics at short distances, *i.e.*, in the order of 1 fm or less (see Fig. 1). The bound and resonant states are obtained by solving the coupled-channel Schrödinger equation for ψ^{MB}, with the one pion exchange potential, OPEP, $V^\pi(r)$, and a five-quark $5q$ potential, $V^{5q}(r)$:

$$\left(K^{MB} + V^\pi + V\frac{1}{E - H^{5q}}V^\dagger\right)\psi^{MB} = E\psi^{MB}. \tag{2.1}$$

where the K^{MB} is the kinetic energy of each MB channel and and H^{5q} stands for the $5q$ channels. The last term on the left-hand side is due to the elimination of the $5q$ channels, and is regarded as an effective interaction for the MB channels. Thus, the total interaction for the MB channels is defined by

$$U = V^{\pi} + V \frac{1}{E - H^{5q}} V^{\dagger}. \tag{2.2}$$

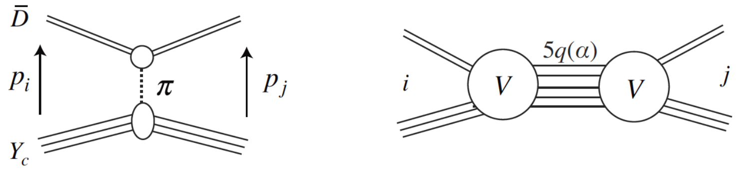

Figure 1: One pion exchange potential (left) and the effective interaction due to the coupling to the five-quark channel (right). The meson-baryon channels are represented by D and Y_c, i and j are, respectively, the initial and the final channels, while a five-quark channel is denoted by α.

3. Results

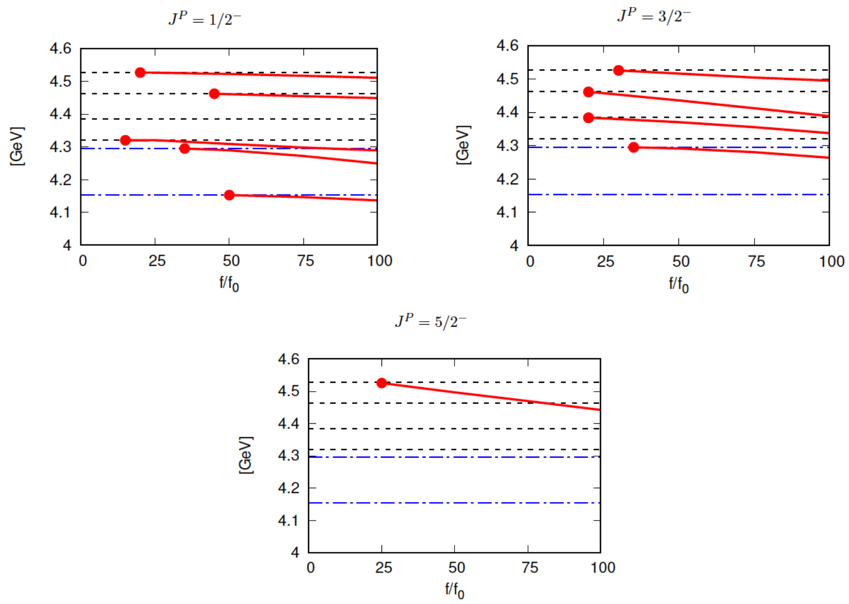

Figure 2: Bound and resonant state energies of the hidden-charm molecules (solid lines) with various coupling constants f. Dot-dashed lines are the $\bar{D}\Lambda_c$ and $\bar{D}^*\Lambda_c$ thresholds. Dashed lines are the $\bar{D}\Sigma_c, \bar{D}\Sigma_c^*, \bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$ thresholds. The lowest threshold, $\bar{D}\Lambda_c$, is at 4150 MeV and the state whose energy is lower than the threshold is a bound state (APS copyright [4]).

Fig. 2 shows the numerical results of the hidden-charm meson-baryon molecules: the bound and resonant state energies of the hidden-charm molecules are presented as a function of different values of the coupling constant $\frac{f}{f_0}$, which is a free parameter introduced to parametrise the coupling strength between the meson-baryon and the compact five-quark channels.

The filled circles show the minimum coupling constant value necessary for the formation of a resonant or bound state. For example, for $J^P = \frac{5}{2}^-$, one resonance appears below the $\bar{D}^*\Sigma_c^*$ threshold when the coupling constant $\frac{f}{f_0}$ is larger than 25. When the energy of a resonant state is lower than the lowest threshold, which in the charmed sector is $\bar{D}\Lambda_c$, about 4150 MeV, the resonant state becomes a bound state. We observe that in these calculations all the meson-baryon components and the compact structure of the pentaquark states are taken into account at the same time, by solving the coupled channel Schrödinger equation 2.1, whose eigenvalues, plotted in Fig. 2 as functions of the coupling constant $\frac{f}{f_0}$, are the resonant and the bound state energies. Thus, a resonant or a bound state arises from the interactions between all the meson-baryon and the compact five-quark channels and the fact that a state appears close to a particular meson-baryon threshold has not a particular meaning.

In the hidden-charm sector, the one pion exchange potential (OPEP) is not enough strong to produce bound and resonant pentaquark states. In fact, as one can see from Fig. 2, no states are produced when the coupling constant $\frac{f}{f_0}$ is switched off, $\frac{f}{f_0} = 0$.

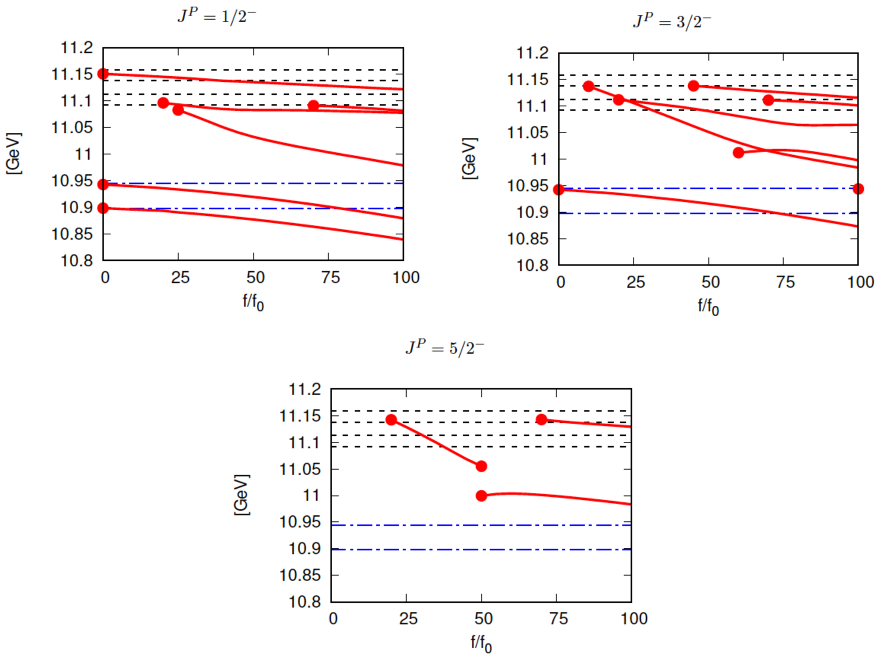

Figure 3: Bound and resonant state energies of the hidden-bottom molecules (solid lines) with various coupling constants f. Dot-dashed lines are the $\bar{B}\Lambda_b$ and $\bar{B}^*\Lambda_b$ thresholds. Dashed lines are the $\bar{B}\Sigma_b, \bar{B}\Sigma_b^*, \bar{B}^*\Sigma_b$ and $\bar{B}^*\Sigma_b^*$ thresholds. The lowest threshold, $\bar{B}\Lambda_b$, is at about 10900 MeV and the state whose energy is lower than the threshold is a bound state (APS copyright [4]).

Fig. 3 is the equivalent of fig. 2 but for the bottom sector. The bottom sector is more interesting as many resonant and bound states appear. As one can see from Fig. 3, in fact, unlike the charmed sector, some bound states are produced even without introducing the five-quark potential, *i.e.*, even when $\frac{f}{f_0} = 0$. The only possibility is that the attractive interaction provided by OPEP is strong enough to bind the meson and baryon in order to produce stable hidden pentaquark structures. Moreover, the number of resonant and bound states increases when one switches on the 5q potential.

4. Conclusion

This study showed how the negative parity hidden-charm and hidden-bottom pentaquark states are produced from the interplay between the S-wave configurations of open flavour channels and a compact five-quark core. We found that, in the hidden-bottom sector, the pentaquark states are produced even without introducing a coupling interaction between the compact five-quark configuration and the meson-baryon molecular configuration. Thus, as a matter of fact, the hidden-bottom pentaquark states are more likely to form rather than their hidden-charm counterparts [4]. For this reason, the hidden-bottom sector is the more interesting environment to search the pentaquark states and we encourage the experimentalists to search the hidden-bottom pentaquark states [4].

References

[1] R. Aaij *et al.* [LHCb Collaboration], *Phys. Rev. Lett.* **115**, 072001 (2015) [hep-ph150703414].

[2] R. Aaij *et al.* [LHCb Collaboration], *Phys. Rev. Lett.* **117**, 082002 (2016) [hep-ph/160405708].

[3] R. Aaij *et al.* [LHCb Collaboration], *Phys. Rev. Lett.* **117**, 082003 (2016); **117**, 109902 (2016); **118**, 119901 (2017) [hep-ph/160606999].

[4] Y. Yamaguchi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, *Phys. Rev. D* **96**, 114031 (2017) [hep-ph/1709.00819].

[5] S. G. Yuan, K. W. Wei, J. He, H. S. Xu, and B. S. Zou, *Eur. Phys. J. A* **48**, 61 (2012) [nucl-th/12010807].

[6] E. Santopinto and A. Giachino, *Phys. Rev. D* **96**, 014014 (2017) [hep-ph/160403769].

[7] J. Wu, Y. R. Liu, K. Chen, X. Liu, and S. L. Zhu, *Phys. Rev. D* **95**, 034002 (2017) [hep-ph/170103873].

[8] S. Takeuchi and M. Takizawa, *Phys. Lett. B* **764**, 254 (2017) [hep-ph/160805475].

[9] J. J. Wu, R. Molina, E. Oset, and B. S. Zou, *Phys. Rev. Lett.* **105**, 232001 (2010) [nucl-th/10070573].

[10] J. J. Wu, R. Molina, E. Oset, and B. S. Zou, *Phys. Rev. C* **84**, 015202 (2011) [nucl-th 10112399].

[11] C. Garcia-Recio, J. Nieves, O. Romanets, L. L. Salcedo, and L. Tolos, *Phys. Rev. D* **87**, 074034 (2013) [hep-ph/13026938].

[12] M. Karliner and J. L. Rosner, *Phys. Rev. Lett.* **115**, 122001 (2015) [hep-ph/1506.06386].

[13] R. Chen, X. Liu, X. Q. Li, and S. L. Zhu, *Phys. Rev. Lett.* **115**, 132002 (2015) [hep-ph/1507.03704].

[14] L. Roca, J. Nieves, and E. Oset, *Phys. Rev. D* **92**, 094003 (2015) [hep-ph 1507.04249].

[15] J. He, *Phys. Lett. B* **753**, 547 (2016) [hep-ph/150705200].

[16] U. G. Meißner and J. A. Oller, *Phys. Lett. B* **751**, 59 (2015) [hep-ph/150707478].

[17] H. X. Chen, W. Chen, X. Liu, T. G. Steele, and S. L. Zhu, *Phys. Rev. Lett.* **115**, 172001 (2015) [hep-ph/150703717].

[18] T. Uchino, W. H. Liang, and E. Oset, *Eur. Phys. J. A* **52**, 43 (2016) [hep-ph/1504.05726].

[19] T. J. Burns, *Eur. Phys. J. A* **51**, 152 (2015) [hep-ph/150902460].

[20] Y. Shimizu, D. Suenaga, and M. Harada, *Phys. Rev. D* **93**, 114003 (2016) [hep-ph/160302376].

[21] Y. Yamaguchi and E. Santopinto, *Phys. Rev. D* **96**, 014018 (2017) [hep-ph/160608330].

[22] Y. Shimizu and M. Harada, *Phys. Rev. D* **96**, 094012 (2017) [hep-ph/1708.04743].