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Hidden-charm and -bottom pentaquarks as meson-baryon molecules coupled to the five-quark states

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The hidden-charm and hidden-bottom pentaquarks are investigated as meson-baryon molecules coupled to the five-quark states. As a result of our calculation, we find that, in the charm sector, one needs the five-quark potential in addition to the pion exchange potential in order to produce bound and resonant states, whereas, in the bottom sector, the pion exchange interaction is strong enough to produce states. Thus, from this investigation, it emerges that the hidden-bottom pentaquarks are more likely to form than their hidden-charm counterparts; for this reason, we suggest that the experimentalists should look for pentaquark states in the bottom sector.

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1. Background

In 2015, the Large Hadron Collider beauty experiment (LHCb) collaboration observed two hidden-charm pentaquarks, $P_c^+(4380)$ and $P_c^+(4450)$, in $\Lambda_b^0 \to J/\psi K^- p$ decay [1, 2, 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 spin-parity J^P of these states has not yet been determined. The parities of these states are preferred to be opposite, and one state has $J = 3/2$ and the other $J = 5/2$. $(J^P_{P_c^+(4380)}, J^P_{P_c^+(4450)}) = (3/2^-, 5/2^+)$ gives the best fit solution, but $(3/2^+, 5/2^-)$ and $(5/2^-, 3/2^+)$ are also acceptable.

Hidden-charm pentaquark states, such as $uudc\bar{c}$ and $udsc\bar{c}$ compact structures, have been studied so far. Before P_c^+ observed by LHCb, Yuan *et al.* in [4] studied the $uudc\bar{c}$ and $udsc\bar{c}$ systems by the non-relativistic harmonic oscillator Hamiltonian with three kinds of the schematic interactions: a chromomagnetic interaction, a flavor-spin-dependent interaction and an instanton-induced interaction. In [5], Santopinto *et al.* investigated the hidden-charm pentaquark states as five-quark compact states in the $S-$wave by using a constituent quark model approach. The hidden-charm and hidden-bottom pentaquark masses have been calculated by Wu *et al.* in [6], 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. Takeuchi *et al.* [7] has also investigated the hidden-charm pentaquark states by the quark cluster model, and discussed the structure of the five-quark states which appears in the scattering states.

Despite many theoretical works and implications, there is so far no clear evidence of such compact multiquark states. By contrast, it is widely accepted that there are candidates for hadronic molecular states. In general, if more than one state is allowed for a given set of quantum numbers, 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. This problem prompted us to investigate the hidden-charm pentaquarks and the hidden bottom pentaquarks as meson-baryon molecules coupled to the five-quark states. Now, 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 [8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21]. The coupling to the five-quark states is described as the short-range potential between the meson and the baryon, while the long-range force is given by the one-pion exchange potential. By solving the coupled channel Schrödinger equation, we study the bound and resonant hidden-charm and hidden-bottom pentaquark states for $J^P = \frac{1}{2}^-$, $\frac{3}{2}^-$, and $\frac{5}{2}^-$ with isospin $I = \frac{1}{2}$.

2. The model

In the current problem of pentaquark, there are two competing sets of channels: 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 (in the order of 1 fm or less). Thus, our model Hamiltonian, expanded by the open-charm MB and $5q$ channels, is written as [22]:

$$H = \begin{pmatrix} H^{MB} & V \\ V^\dagger & H^{5q} \end{pmatrix}, \tag{2.1}$$

where the MB part H^{MB} contains K_i; the kinetic energy of each MB channel i and V^{π}_{ij}; the OPEP potential, and H^{5q} stands for the $5q$ channels. The off-diagonal part in Eq. 2.1, V, represents the transition between the MB and $5q$ channels. The bound and resonant states are obtained by solving the coupled-channel Schrödinger equation for ψ^{MB}, with the OPEP, $V^{\pi}(r)$, and $5q$ potential, $V^{5q}(r)$:

$$\left(K^{MB}+V^{\pi}+V\frac{1}{E-H^{5q}}V^{\dagger}\right)\psi^{MB}=E\psi^{MB}. \tag{2.2}$$

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.

3. Results

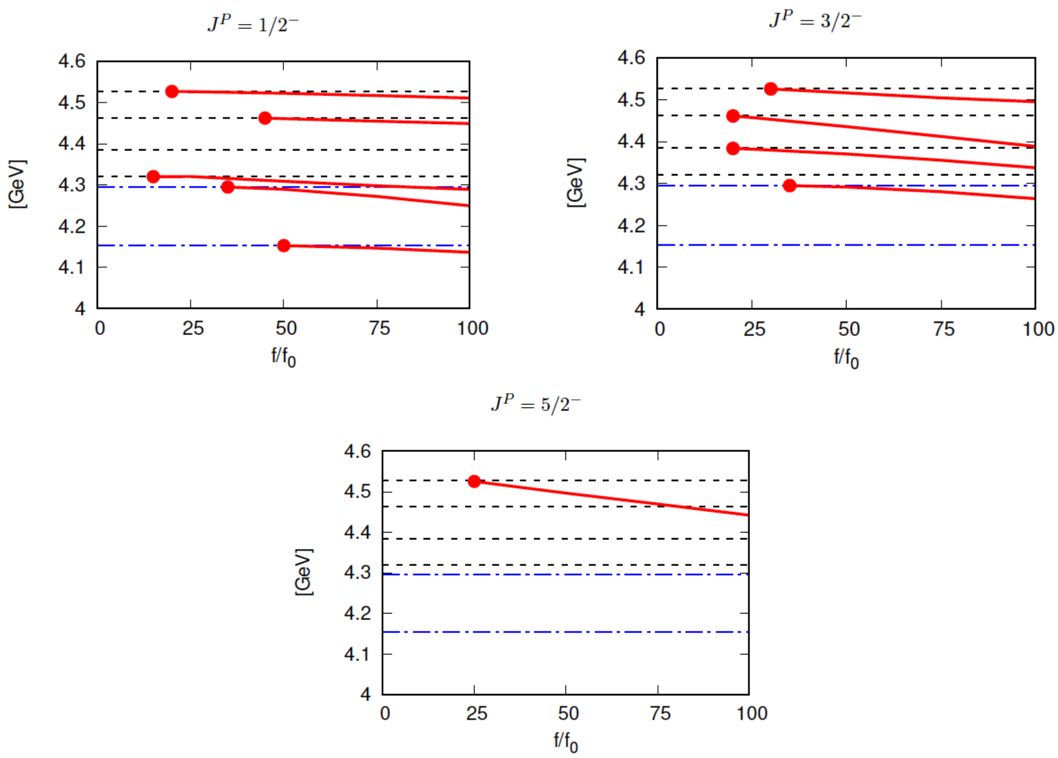

Figure 1: Bound and resonant state energies of the hidden-charm molecules (solid lines) with various coupling constants f. Dot-dashed lines are the $\bar{D}\Lambda_c$ and $\bar{D}^*\Lambda_c$ thresholds. Dashed lines are the $\bar{D}\Sigma_c, \bar{D}\Sigma_c^*, \bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$ 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 [22]).

Figure 1 shows the dependence of the obtained energy spectra for $J^P = \frac{1}{2}^-, \frac{3}{2}^-$ and $\frac{5}{2}^-$ on the coupling constant of the model, $\frac{f}{f_0}$. This coupling constant is a free parameter proportional to the coupling strength between the Meson-Baryon and the compact five-quark channels. The filled circle in figures shows the starting point where the state is found. 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, $\bar{D}\Lambda_c$, which is about 4150 MeV, the resonant state becomes a bound state. As one can see from Fig. 1, when the five-quark potential is turned-off, i.e. when $\frac{f}{f_0} = 0$, there are no resonant states and no bound states for any value of quantum numbers J^P. Thus, in the hidden-charm sector, the One Pion Exchange Potential (OPEP) is not strong enough to produce bound and resonant pentaquark states.

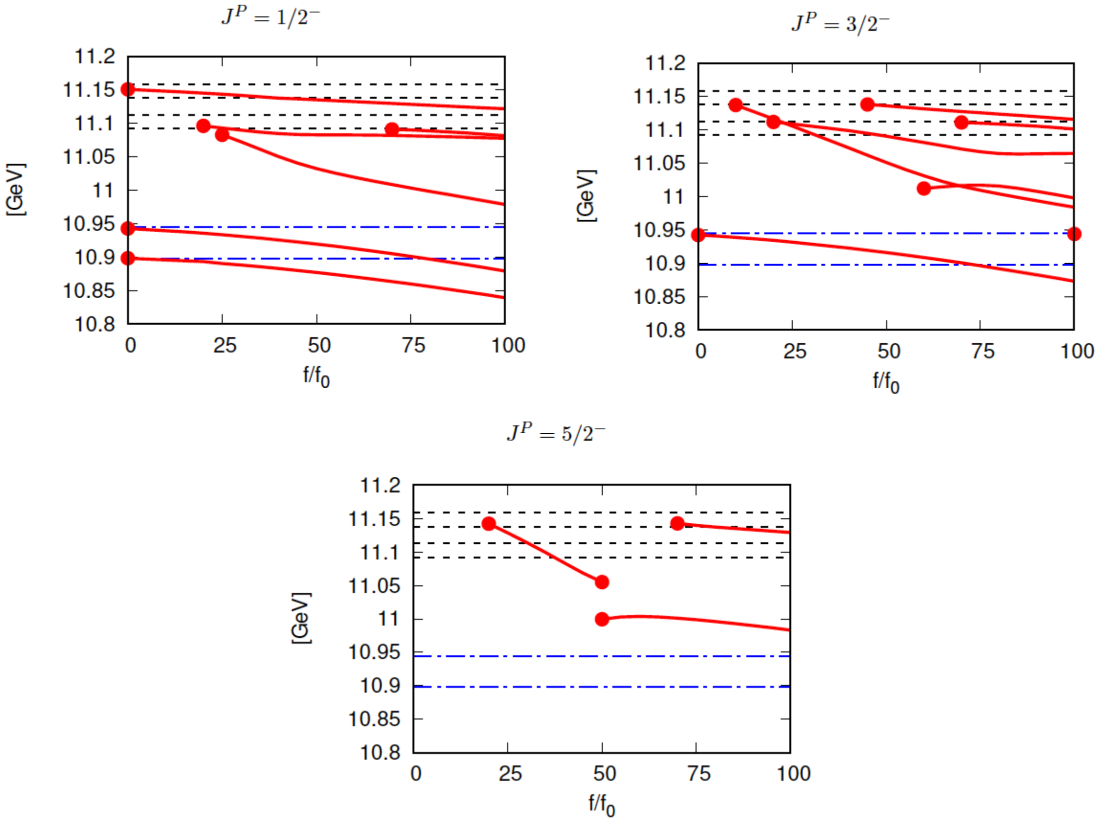

Figure 2: Bound and resonant state energies of the hidden-bottom molecules (solid lines) with various coupling constants f. Dot-dashed lines are the $\bar{B}\Lambda_b$ and $\bar{B}^*\Lambda_b$ thresholds. Dashed lines are the $\bar{B}\Sigma_b, \bar{B}\Sigma_b^*, \bar{B}^*\Sigma_b$ and $\bar{B}^*\Sigma_b^*$ 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 [22]).

Fig. 2 is the equivalent of fig. 1 but for the bottom sector. As one can see from Fig. 2, in the bottom sector, many bound states appear. Unlike the charmed sector, some bound states are produced even without introducing the five-quark potential. As a matter of fact in the bottom sector the OPEP alone provides sufficiently strong attraction to generate several bound and resonant states. Moreover, the number of resonant and bound states increases when the $5q$ potential is switched on.

4. Conclusion

As a result of our investigation, we found that the hidden-bottom pentaquarks are more likely to form rather than the hidden-charm pentaquarks. The hidden-bottom sector is the more interesting environment to search the pentaquark states. For this reason, we suggest to the experimentalists to look for hidden bottom pentaquark states.

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