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Heavy exotic molecules with charm and bottom

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A R T I C L E I N F O

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A B S T R A C T

We revisit the formation of pion-mediated heavy-light exotic molecules with both charm and bottom and their chiral partners under the general strictures of both heavy-quark and chiral symmetry. The chiral exotic partners with good parity formed using the $(0^+, 1^+)$ multiplet are about twice more bound than their primary exotic partners formed using the $(0^-, 1^-)$ multiplet. The chiral couplings across the multiplets $(0^\pm, 1^\pm)$ cause the chiral exotic partners to unbind, and the primary exotic molecules to be about twice more bound, for $J \leq 1$. Our multi-channel coupling results show that only the charm isosinglet exotic molecules with $J^{PC} = 1^{++}$ bind, which we identify as the reported neutral $X(3872)$. Also, the bottom isotriplet exotic with $J^{PC} = 1^{+-}$ binds, which we identify as a mixture of the reported charged exotics $Z_b^+(10610)$ and $Z_b^+(10650)$. The bound isosinglet with $J^{PC} = 1^{++}$ is suggested as a possible neutral $X_b(10532)$ not yet reported.

1. Introduction

A decade ago, both the BaBar Collaboration [1] and the CLEOII Collaboration [2] have reported narrow peaks in the $D_s^+\pi^0$ (2317 MeV) and the $D_s^{*+}\pi^0$ (2460 GeV) channels as expected from general chiral symmetry arguments [3,4]. In QCD the light quark sector (u, d, s) is dominated by the spontaneous breaking of chiral symmetry, while the heavy quark sector (c, b, t) is characterized by heavy-quark symmetry [5]. The combination of both symmetries led to the conclusion that the heavy-light doublet $(0^-, 1^-) = (D, D^*)$ has a chiral partner $(0^+, 1^+) = (\tilde{D}, \tilde{D}^*)$ that is about one constituent mass heavier [3,4].

Recently, the Belle Collaboration [6] and the BESIII Collaboration [7] have reported the observations of multiquark exotics. A major provider for these exotics is $\Upsilon(10860)$ and its ideal location near the thresholds for $B\bar{B}^*\pi$ (10744) and $B^*\bar{B}^*\pi$ (10790) decays. The smallness of the available phase space in the hadronic decay of $\Upsilon(10860)$ calls for a compound with a long life-time, perhaps in a molecular configuration with heavy meson constituents. Several heavy exotic molecules with quantum numbers uncommensurate with the excited states of charmonia and bottomia have been reported, such as the neutral $X(3872)$ and the charged $Z_c(3900)^\pm$ and $Z_b(10610)^\pm$. More of these exotics are expected to be unravelled by the DO Collaboration at Fermilab [8], and the LHCb Collaboration at CERN [9].

Theoretical arguments have predicted the occurrence of some of these exotics as molecular bound states mediated by one-pion exchange much like deuterons or deusons [10,11]. A number of molecular estimates regarding the occurrence of doubly heavy exotic mesons with both charm and bottom content were suggested by many [11–16]. Non-molecular heavy exotics were also discussed using constituent quark models [17], heavy solitonic baryons [18,19], instantons [20] and QCD sum rules [21]. The molecular mechanism favors the formation of shallow bound states near threshold, while the non-molecular mechanism suggests the existence of deeply bound states. The currently reported exotics by the various experimental collaborations are in support of the molecular configurations.

The purpose of this paper is to revisit the formation of heavy-light molecules under the general strictures of chiral and heavy quark symmetry, including the mixing between the heavy doublets and their chiral partners which was partially considered in [11–15]. In leading order, chiral symmetry fixes the intra- and cross-multiplet couplings. In particular, bound molecules $\bar{D}D$ with charm and $\bar{B}B$ with bottom may form through channel mixing, despite the absence of a direct pion coupling by parity. The P-wave inter-multiplet mixing in the $(0^-, 1^-)$ is enhanced by the almost degeneracy of the constituents by heavy-quark symmetry, while the S-wave cross-multiplet mixing in the $(0^\pm, 1^\pm)$ is still substantial due to the closeness of the constituents by chiral symmetry.

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The latter prevents the formation of dual chiral molecules such as $\bar{\tilde{D}}\tilde{D}$ with charm and $\bar{\tilde{B}}\tilde{B}$ with bottom, as we will show. Throughout, the coupling to the low-lying resonances in the continuum with more model assumptions will be ignored for simplicity. Also interactions mediated by shorter range massive vectors and axials will be mostly cutoff through the use of a core cutoff in the pion mediated potential of 1 GeV. Only the channels with total angular momenta $J \leq 1$ will be discussed.

The organization of the paper is as follows: In section 2 we briefly derive the essential construct for doubly charmed exotic molecules using the strictures of chiral and heavy quark symmetries and explicit the coupled channel problem for the lowest bound states. We also show how the same coupled channel problem carries to the chiral partners. In section 3, we extend our analysis to the doubly bottom exotic molecules and their chiral partners. Our conclusions are given in section 4.

2. Charmed exotics molecules

2.1. $(0^-, 1^-)$ multiplet

The low energy effective action of heavy-light mesons interacting with pions is constrained by both chiral and heavy quark symmetry. In short, the leading part of the heavy-light Lagrangian for the charmed multiplet $(0^-, 1^-)$ with pions reads [3,5]

$$\begin{aligned}\mathcal{L} \approx & +2i\left(\bar{D}\partial_0 D + \bar{\vec{D}}\cdot\partial_0\vec{D}\right) \\ & - \Delta m_D \bar{D}D - \Delta m_{\vec{D}} \bar{\vec{D}}\vec{D} \\ & + i\frac{g_H}{f_\pi}\mathrm{Tr}\partial_i\pi\left(D_i D^\dagger - D D_i^\dagger + \epsilon_{ijk} D_k D_j^\dagger\right) \end{aligned} \quad (1)$$

with $\Delta m_i = m_i - m_C$ of the order of a quark constituent mass. The molecular exotics of the type $D\bar{D}^*$ and alike, follow from (1) through one-pion exchange. The non-relativistic character of the molecules yields naturally to a Hamiltonian description.

For all available 2-body channels, the pertinent matrix entries for the interaction are readily found in the form

$$\begin{aligned} \left\langle \vec{v}_3\vec{v}_4^{\star}|V|\vec{v}_1\vec{v}_2^{\star}\right\rangle &= -C(\vec{v}_3\times\vec{v}_1)\cdot\nabla(\vec{v}_2\times\vec{v}_4)\cdot\nabla V(r) \\ \left\langle 0\bar{0}|V|\vec{v}_1\vec{v}_2^{\star}\right\rangle &= C\vec{v}_1\cdot\nabla\vec{v}_2\cdot\nabla V(r) \\ \left\langle \vec{v}_2\bar{0}|V|0\vec{v}_1^{\star}\right\rangle &= -C\vec{v}_1\cdot\nabla\vec{v}_2\cdot\nabla V(r) \\ \left\langle 0\vec{v}_3^{\star}|V|\vec{v}_1\vec{v}_2^{\star}\right\rangle &= -C\vec{v}_1\cdot\nabla(\vec{v}_2\times\vec{v}_3)\cdot\nabla V(r) \\ \left\langle \bar{0}\vec{v}_3|V|\vec{v}_1\vec{v}_2^{\star}\right\rangle &= C\vec{v}_2\cdot\nabla(\vec{v}_3\times\vec{v}_1)\cdot\nabla V(r) \end{aligned} \quad (2)$$

with the isospin factor

$$C = \vec{I}_1\cdot\vec{I}_2 = \left(\frac{1}{4}\bigg|_{I=1}, -\frac{3}{4}\bigg|_{I=0}\right) \quad (3)$$

The spin polarizations of D^* and its conjugate $\bar{D}^*$ are referred to as $\vec{v}$ and $\vec{v}^*$ respectively. Here $V(r)$ is the regulated one-pion exchange using the standard monopole form factor by analogy with the pion–nucleon form factor [22]. Denoting by $D_{0\bar{0}}(\vec{r})$ the wave function of the molecular scalar, by $\bar{Y}_{0\bar{i}}(\vec{r})$ and $Y_{i\bar{0}}(\vec{r})$ the wavefunctions of the molecular vectors, and by $T_{i\bar{j}}(\vec{r})$ the wavefunction of the molecular tensors, we can rewrite (2) as

$$\begin{aligned} (VT)_{k\bar{l}} &= C\epsilon_{kim}\epsilon_{\bar{l}\bar{j}n}\partial_{mn}VT_{i\bar{j}} \\ (VT)_{0\bar{0}} &= C\partial_{i\bar{j}}VT_{i\bar{j}} \\ (V\bar{Y})_{k\bar{0}} &= -C\partial_k\partial_{\bar{j}}V(r)\bar{Y}_{0\bar{j}} \\ (VT)_{0\bar{k}} &= C\epsilon_{\bar{k}\bar{l}j}\partial_i\partial_j V(r)T_{i\bar{l}} \\ (VT)_{\bar{0}k} &= C\epsilon_{klj}\partial_{\bar{i}}\partial_j V(r)T_{l\bar{i}} \end{aligned} \quad (4)$$

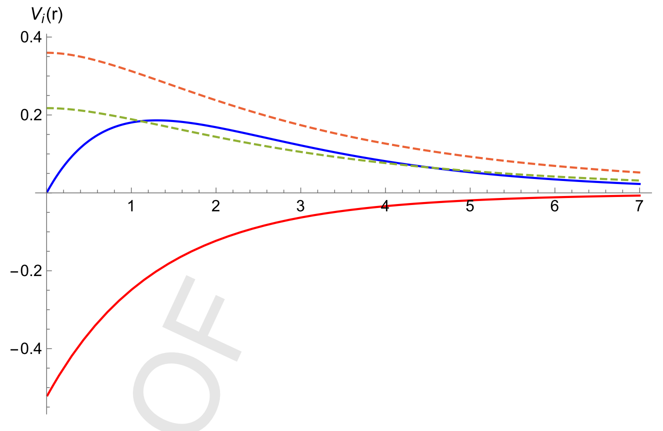

Fig. 1. Typical $V_1(r)$ (lower-full-red) and $V_2(r)$ (upper-full-blue) pion induced potentials compared to $\Delta_1^2 V(r)$ (lower-green-dashed) and $\Delta_2^2 V(r)$ (upper-orange-dashed) to be defined below. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The explicit reduction of the molecular wavefunctions will be detailed below, for all channels with $J \leq 1$.

The one-pion mediated interaction is defined with a core cutoff $\Lambda \gg m_\pi$ [11,22]

$$V(r) = \left(\frac{g_H}{f_\pi}\right)^2 \frac{1}{4\pi}\left(\frac{e^{-m_\pi r}}{r} - \frac{e^{-\Lambda r}}{r} - (\Lambda^2 - m_\pi^2)\frac{e^{-\Lambda r}}{2\Lambda}\right) \quad (5)$$

Once inserted in (4) it contributes a scalar and a tensor through

$$\partial_i\partial_j V(\vec{r}) = \delta_{ij}V_1(r) + r_i r_j V_2(r) \quad (6)$$

which are shown in Fig. 1 for $g_H = 0.6$ [3,4] and $\Lambda = 1$ GeV in units of Λ. The strength of the regulated one-pion exchange potential increases with increasing cutoff Λ. The dependence of the results on the choice of core cutoff Λ is the major uncertainty of the molecular analysis to follow. The tensor contribution in (6) is at the origin of the notorious D-wave admixing in the deuteron state [22], and is distinctly different from the gluonic based exchanges in heavy quarkonia [17].

2.2. $(0^+, 1^+)$ chiral partners and their mixing

The leading part of the heavy-light chiral doublers Lagrangian for the charmed $(0^+, 1^+)$ multiplet with pions reads [3]

$$\begin{aligned}\tilde{\mathcal{L}} \approx & +2i\left(\bar{\tilde{D}}\partial_0\tilde{D} + \bar{\vec{\tilde{D}}}\cdot\partial_0\vec{\tilde{D}}\right) \\ & - \Delta m_{\tilde{D}}\bar{\tilde{D}}\tilde{D} - \Delta m_{\vec{\tilde{D}}}\bar{\vec{\tilde{D}}}\vec{\tilde{D}} \\ & + i\frac{g_H}{f_\pi}\mathrm{Tr}\partial_i\pi\left(i(\tilde{D}_i\tilde{D}^\dagger + \tilde{D}\tilde{D}_i^\dagger) + \epsilon_{ijk}\tilde{D}_k\tilde{D}_j^\dagger\right)\end{aligned} \quad (7)$$

with again $\Delta m_{\tilde{i}} = m_{\tilde{i}} - m_C$ of the order of a quark constituent mass. The $(0^+, 1^+)$ multiplet mixes with the $(0^-, 1^-)$ by chiral symmetry. The leading part of the interaction in the chirally mixed parity channels reads [3,4]

$$\delta\mathcal{L} = \frac{g_{HG}}{f_\pi}\mathrm{Tr}\,\partial_0\pi\left(\tilde{D}_i^\dagger D_i - i\tilde{D}^\dagger D + \mathrm{c.c.}\right) \quad (8)$$

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