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An Effective Theory approach to $\bar{B}_s$ mesons involving $SU(3)$ Heavy Meson Symmetry and Constituent Quark-Model states

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The bottom partners of the $D^*_{s0}(2317)$ and $D_{s1}(2460)$ have not been measured yet but the existence of these bottom-strange $J^P = 0^+$ and $J^P = 1^+$ states is motivated by Heavy Quark Flavor Symmetry and Heavy Quark Spin Symmetry. Here we show the predictions for such heavy quark partners using a unitarized effective approach involving $SU(3)$ Chiral Heavy Meson Symmetry and incorporating explicit di-quark Fock components ($Q\bar{q}$) to the theory in a Heavy Quark Spin and Flavour Symmetry consistent way. We take advantage of the energy levels spectrum for 0^+ and 1^+ $\bar{B}_s$ mesons obtained in a recent lattice QCD simulation to constrain the coupling of the $Q\bar{q}$ components. By fitting the energy levels obtained with our model in finite volume to the lattice results we are able to make predictions for the exotic $\bar{B}_s$ mesons. Our predictions are compatible with the lattice QCD results and previous Chiral Heavy Meson Effective theory calculations.

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1. Introduction

The present contribution is based on the results obtained in Ref. [1], where the $B^{(*)}K$ interaction is studied incorporating a constituent quark model (CQM) state, i.e., a P-wave $b\bar{s}$ component interacting with the previous channels. The importance of including the effect of two-meson threhsolds was revealed after the discovery of the $D^*_{s0}(2317)$ and $D_{s1}(2560)$ resonances [2, 3], with a mass and width much lower than previous quark model and lattice QCD calculations. Both states were found around 100 MeV below naive quark model predictions, and below the DK and D^*K thresholds respectively. From the point of view of approximate Heavy Quark symmetries [4], Heavy Flavour Symmetry (HFS) states that a similar pattern should exist in the bottom sector, *i.e.*, HFS partners which will be denoted here as $\bar{B}^*_{s0}$ and $\bar{B}_{s1}$. Besides, Heavy Quark Spin Symmetry (HQSS) organizes the $Q\bar{q}$ mesons into doublets of degenerate mass (up to $\Lambda_{\rm QCD}/m_Q$ corrections), labelled by the spin and parity of the light degrees of freedom $j^P_{\bar{q}}$. In the following we will refer only to positive parity $j_{\bar{q}}$ doublets. In this picture, the lowest-lying 0^+ and 1^+ $c\bar{s}$ mesons ($j_{\bar{q}} = 1/2$) are described by the same dynamics, and according to HFS, will also govern the $\bar{B}^*_{s0}$ and $\bar{B}_{s1}$ HQSS doublet. As already mentioned, the study of these resonances is suitable to evaluate the interplay of CQM states and two-meson thresholds. This is an important issue in order to better understand the nature of these narrow resonances. We evaluate such interplay in an effective theory framework, where the degrees of freedom are the heavy $\bar{B}$, $\bar{B}^*$ mesons coupled to kaons in S-wave, together with scalar and axial CQM $b\bar{s}$ states. On the one hand, the coupling of $\bar{B}^{(*)}K$ channels is performed using a Heavy Meson Chiral Lagrangian [5], on the other hand the 0^+ and 1^+ CQM states are coupled to the two-meson channels in a HQSS invariant formalism [6]. There is no experimental evidence of the $(\bar{B}^*_{s0}, \bar{B}_{s1})$ $j_{\bar{q}} = 1/2$ doublet, contrary to the case of $j_{\bar{q}} = 3/2$ $(\bar{B}^*_{s1}(5830), \bar{B}^*_{s2}(5840))$ doublet. Here we will pay attention to the lattice QCD (LQCD) simulation of Ref. [7]. In that work, the isoscalar even-parity $\bar{B}K$ and $\bar{B}^*K$ energy levels are provided for a single lattice size, and two bound states are identified as members of the $j_{\bar{q}} = 1/2$ doublet after the infinite volume extrapolation. They also find evidence for the $j_{\bar{q}} = 3/2$ doublet above the $\bar{B}^{(*)}K$ thresholds. In the following sections we constrain the free parameters of our model in order to reproduce the LQCD results. With the parameters and their uncertainties fixed, we show the predictions for the $j_{\bar{q}} = 1/2$ doublet of $\bar{B}_s$ mesons.

2. Formalism

To describe the elastic S-wave $J^P = 0^+(1^+)$ $\bar{B}^{(*)}K$ isoscalar interaction we compute the leading order (LO) amplitudes from a Heavy Meson Chiral (HMχ) Lagrangian, see Ref. [1] for details and explicit formulae of the present section. Let us denote the HMχ elastic amplitude as V_c. The amplitude describing the coupling between CQM states and two-meson thresholds, denoted as $V_{b\bar{s}}$, depends on two undetermined low energy constants (LECs), the bare mass $\mathring{m}_{b\bar{s}}$ of the $0^+(1^+)$ CQM states, and a dimensionless constant c controlling the strength of the coupling. The bare mass must be interpreted as the mass of the CQM state in the limit of vanishing coupling to mesons, $c \to 0$, and thus it is not an observable. The interaction with two-meson channels ($c \neq 0$) renormalizes the bare value. In principle the value of c is independent of the flavour of the heavy quark and the SU(3) structure of the interaction, therefore up to HQSS corrections it can be used in both $J^P = 0^+$

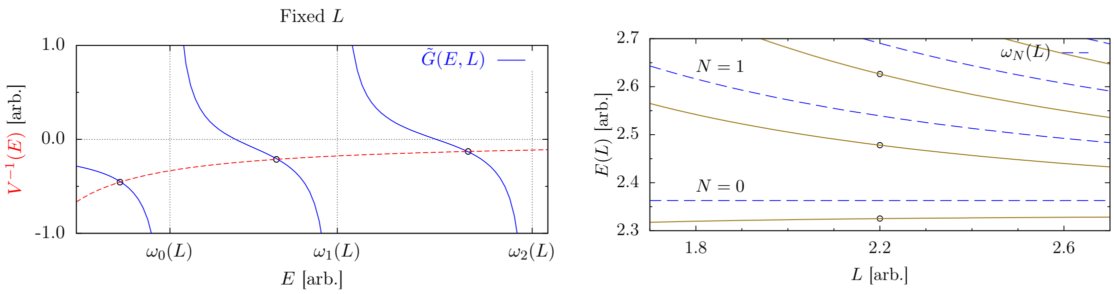

Figure 1: Example of a FV calculation in the case of an attractive interaction. Left panel: for a fixed size of the box the poles of $\tilde{T}(E,L)$ (zeros of $V^{-1}(E)-\tilde{G}(E,L)$) are represented with black circles. Note that the free energies $\omega_N(L)$ are the solutions in the case $V(E)\to 0$. Right panel: volume dependence of the energy levels (green solid lines) compared to the non-interacting case (dashed blue lines). The attractive interaction is causing the shift of the energy levels to lower energies.

and 1^+ sectors, as well as in the charm sector. The effect of the interplay between the CQM states and $\bar{B}^{(*)}K$ channels can be effectively taken into account in the $\bar{B}^{(*)}(p_1)K(p_2)\to\bar{B}^{(*)}(p_3)K(p_4)$ scattering as follows [8],

$$V(s) = V_c(s) + \frac{V_{b\bar{s}}(s)\,[V_{b\bar{s}}(s)]^*}{s-\overset{\circ}{m}{}^2_{b\bar{s}}}, \tag{2.1}$$

where the p_j $(j=1,2,3,4)$ label the four momentum of the particles and s is the Mandelstam variable $s=(p_1+p_2)^2$. In our study we will use two sets of $J^P=0^+$ and 1^+ $\overset{\circ}{m}_{b\bar{s}}$ values obtained in the CQM calculation of Ref. [9] and perform two independent fits to the LQCD data. We restore exact unitarity in our scattering amplitudes by solving the on-shell version of the factorized Bethe-Salpeter equation,

$$T(s) = \left(V^{-1}(s) - G(s)\right)^{-1}, \tag{2.2}$$

where $G(s)$ is the $B^{(*)}K$ loop function containing a Gaussian regulator which depends on a three momentum scale Λ. The poles on the complex s-plane of the unitary amplitudes in Eq. (2.2), in the proper Riemann sheet, will be identified with resonances or bound states. In the case of a bound state located at $s_P = M^2$, we define the coupling g by means of the residue of the unitary amplitude at the pole: $T\sim g^2/(s-M^2)$. With this value we are able to estimate the $B^{(*)}K$ contribution to the bound state wave function using the relation $P_{\bar{B}^{(*)}K} = -g^2\partial G/\partial s|_{s=M^2}$ [10]. The energy dependence of the LO amplitudes deviates this probability from 1, and in our case this dependence is enhanced by the inclusion of the CQM states, see Eq. (2.1). In order to compare with the LQCD results we perform a finite volume (FV) calculation [11]. We compute the energy levels obtained putting the interaction (2.2) in a box of size L, imposing periodic field boundary conditions at the sides of the box and setting the meson masses, free energy-momentum relation ($\omega(\vec{q})$) and volume size to the ones used in the simulation of Ref. [7]. The periodic boundary conditions force the quantization of the three-momenta $\vec{q}=2\pi\vec{n}/L$, $\vec{n}\in\mathbb{Z}^3$, equivalently $\vec{q}^{\,2}=4\pi^2/L^2\times N$ ($N\equiv\vec{n}^2=0,1,2,\ldots$), as a consequence the two-meson free states in the box are labelled by units of relative three-momentum, $\omega_N(L)$. Therefore we replace in Eq. (2.2) the three-momentum loop integral $G(s)$ by its FV counterpart,

$$\tilde{T}(E,L) = (V^{-1}(E) - \tilde{G}(E,L))^{-1}, \tag{2.3}$$

Set	c	Λ [MeV]	a^{th}	χ^2/d.o.f.
(a)	0.74 ± 0.05	730 ± 40	0.0909 ± 0.013	1.5
(b)	0.75 ± 0.04	650 ± 30	0.0907 ± 0.013	1.6

Table 1: Fit results for the two sets of $J^P = 0^+(1^+)$ CQM bare masses used: 5851(5883) MeV (set (a)) and 5801(5858) MeV (set (b)). The errors represent 1σ uncertainties calculated from a large number of parameter sets obtained from fits to synthetic LQCD datasets. The latter ones were randomly generated assuming the LQCD data Gaussian distributed. We recall here the value $a^{\text{lat}} = 0.0907 \pm 0.013$ fm [7].

where $\tilde{G}(E,L)$ is obtained from $G(s)$ by substituting $\int_{\mathbb{R}^3} d^3q/(2\pi)^3 \to \sum_{\vec{q}}/L^3$, and we have written in terms of $E = \sqrt{s}$ for convenience. The LO amplitudes of Eq. (2.1) do not have FV effects since they do not involve any three-momentum integral. The energy levels, for a fixed value of L, are obtained from the poles of $\tilde{T}(E,L)$ in Eq. (2.3). In figure 1 there is an example illustrating qualitatively how this proceedure gives rise to a tower of energy levels for a fixed L.

3. Results

In the previous section we have introduced the free parameters of the model: the coupling c between CQM states and two-meson states, the bare masses of the CQM scalar and axial states and the three-momentum cut-off Λ entering in the $G(s)$ regulator. We perform two independent fits to the LQCD $J^P = 0^+$ and 1^+ energy levels, where in each one we fix the values of the bare masses to the results of Ref. [9] for the scalar and axial CQM state: 5851 (0^+) and 5883 (1^+) MeV, 5801 (0^+) and 5858 (1^+) MeV. The two sets of masses are denoted set (a) and set (b) respectively.

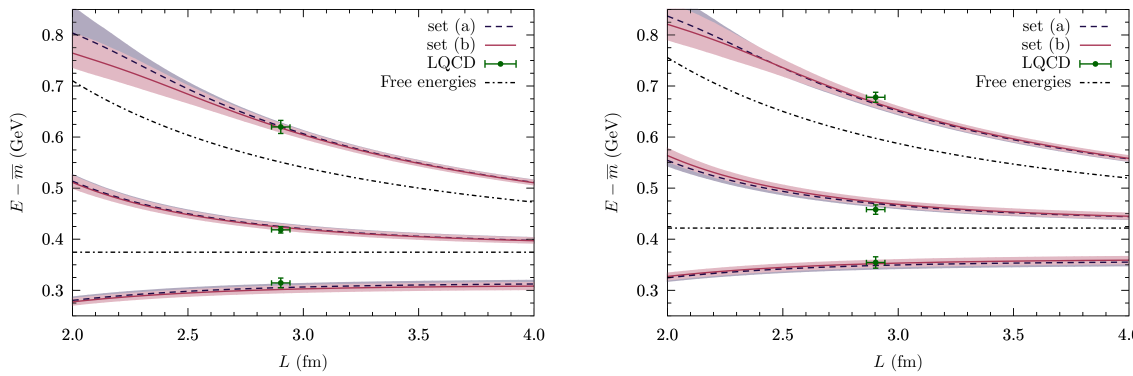

Figure 2: Volume dependence of the $\bar{B}K$ $J^P = 0^+$ (left panel) and $\bar{B}^*K$ $J^P = 1^+$ (right panel) energy levels obtained using two different sets of bare masses (dark-green dashed for set (a) and red solid bands for set (b)). The green points with error bars are the LQCD energy levels of Ref. [7]. As in Ref. [7] we show the value of the energy levels relative to the lattice spin-average mass $\bar{m} = (m_{\bar{B}_s} + 3m_{\bar{B}_s^*})/4$. The bands reflect the 1σ uncertainties propagated from the fitting parameters.

In figure 2 the 0^+ (left panel) and 1^+ (right panel) LQCD energy levels and uncertainties are represented as green points with error bars. As already mentioned in the previous section, in our FV calculation we set the meson masses to the values obtained in the simulation of Ref. [7]. Additionally, we shift the bare mass value in each case by the quantity $\Delta\bar{m} = \bar{m}^{\text{phy}} - \bar{m}^{\text{lat}}$ as follows: $\overset{\circ}{m}{}^{\text{FV}}_{b\bar{s}} = \overset{\circ}{m}_{b\bar{s}} - \Delta\bar{m}$. Above, $\bar{m}^{\text{lat}}$ denotes the spin-average mass $(m_{\bar{B}_s} + 3m_{\bar{B}_s^*})/4$ obtained in the lattice

set	J^P	$\overset{\circ}{m}_{b\bar{s}}$ [MeV]	M_b [MeV]	$P_{\bar{B}^{(*)}K}$ [%]	g [GeV]	M [MeV]	Γ [MeV]
(a)	0^+	5851	5711 ± 6	51.8 ± 1.5	31.8 ± 0.9	6300 ± 100	70^{+30}_{-40}
	1^+	5883	5752 ± 6	49.7 ± 1.4	32.3 ± 0.9	6300 ± 100	80^{+30}_{-50}
(b)	0^+	5801	5707 ± 6	45.8 ± 1.1	32.3 ± 0.8	6220 ± 70	80^{+30}_{-40}
	1^+	5858	5757 ± 6	48.3 ± 1.3	32.3 ± 0.8	6280 ± 70	70^{+30}_{-40}

Table 2: Poles of the unitary amplitudes obtained in the different sectors using the different sets of parameters. $\bar{B}^*_{s0}$ and $\bar{B}_{s1}$ candidates are obtained as bound states of mass M_b. We show the $\bar{B}^{(*)}K$ molecular amount in each bound state wave function, $P_{\bar{B}^{(*)}}K$, as well as the coupling g. Besides the bound state, another pole is found at energies far above threshold in the second Riemann sheet.

simulation and $\bar{m}^{\rm phy}$ the physical value. The coloured bands in figure 2 show our fit results using the two sets of bare masses mentioned above, where for each set we have minimized the following χ^2,

$$\chi^2(c,\Lambda,a^{\rm th}) = \sum_i \left(\frac{(Ea)_i^{\rm lat} - (Ea)_i^{\rm th}}{\Delta[(Ea)_i^{\rm lat}]}\right)^2 + \left(\frac{a^{\rm lat} - a^{\rm th}}{\Delta[a^{\rm lat}]}\right)^2, \tag{3.1}$$

with the sum over i running over the six LQCD energy levels (see figure 2). By using Eq. (3.1), instead of fitting the FV energies E directly to the LQCD energy levels $E^{\rm lat}$, we consider the latter in lattice units [7] together with the quantities $Ea^{\rm th}$, where we introduce $a^{\rm th}$ as an additional best-fit parameter in order to account for the lattice spacing $a^{\rm lat}$ uncertainties in the energy levels and in the unphysical meson masses. The fit results are summarized in Table 1 where we see that c is rather insensitive to the set of bare masses. On the other hand, there is some dependence of the three-momentum cut off on the bare masses, which is reasonable since the CQM bare masses depend on the renormalization scheme. In figure 2 we can appreciate how the energy levels are shifted towards lower energies compared to the free energies. In the case of the first energy level (the one of lower energy), this shift is revealing an attractive $\bar{B}^{(*)}K$ interaction at energies below the threshold energy, $\omega_0(L)$, as can be qualitatively seen in figure 1. With the parameters fixed in Table 1 we search for poles of the unitary amplitudes of Eq. (2.2). For both sets of bare masses and both J^P sectors we find a bound state below threshold, clear candidates to be identified with the $\bar{B}^*_{s0}$ and $\bar{B}_{s1}$ states. Apart from the bound states, in each case we find an additional pole in the second Riemann sheet with mass M and width Γ. From the values of table 2 we can see that this resonance pole is located far above the $\bar{B}^{(*)}K$ threshold. This pole has its origin on the bare mass pole of the LO amplitude in Eq. (2.1), which has been renormalized by $\bar{B}^{(*)}K$ loops, shifted to higher energies acquiring a sizeable width. At such high energies further channels as well as higher orders corrections become important, therefore the predictions in Table 2 concerning this state would be affected and are not as robust as the ones for bound states. Finally, it is worth mentioning that the masses predicted here for the $j_{\bar{q}} = 1/2$ HQSS doublet are in remarkable good agreement with the LQCD predictions of Ref. [7]: 5711 ± 23 and 5750 ± 25 MeV for the $\bar{B}^*_{s0}$ and $\bar{B}_{s1}$ respectively. The values obtained here are also compatible whithin uncertainties with other HMχ effective theory predictions which do not include explicit coupling to $Q\bar{q}$ Fock components, see Refs. [12, 13, 14, 15, 16]. We obtain a $\bar{B}^{(*)}K$ contribution to the bound state wave function of the order of ~ 50 % in all the cases. This value is lower than the $\sim 70\%$ obtained in effective theory calculations for the D^*_{s0} state, see *e.g.* Refs. [17, 18].

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