Open-flavor strong decays of open-charm and open-bottom mesons in the $^3P_0$ model

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We provide results for the open-flavor strong decays of open-charm ($D$ and $D_s$) and open-bottom ($B$, $B_s$, and $B_{s1}$) mesons. The decays are calculated in a modified version of the $^3P_0$ pair-creation model, assuming harmonic oscillator wave functions. The spectra of open-charm and open-bottom mesons used in the calculations are computed within the relativized quark model developed by Godfrey and Isgur. The results are compared with the existing experimental data.

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I. INTRODUCTION

Since the discovery of the $J/\Psi$ and $\Upsilon$ resonances in the 1970s, heavy meson physics (including the physics of charmonia \[1\,2\], bottomonia \[3\,4\], open-charm \[5\,50\] and open-bottom \[7\,9\] mesons) has been extensively studied, and is still a subject of intensive theoretical and experimental research \[10\,11\]. Recently, both the charmonium and bottomonium spectra have been enriched by the discovery of new particles \[10\,11\]. The knowledge of open-charm and open-bottom mesons has improved substantially with the experimental observation of new resonances, including the $D^*_0(2400)$ \[12\,13\], $D^*_1(2430)^0$ \[13\] and $B_1(5721)$ \[14\,15\]. See Table I. The properties and quantum numbers of a large part of the newly-observed open-charm and open-bottom mesons are still not well established. Some examples are $D^*_0(2600)$ \[16\,17\], $D(2740)^0$ \[16\,17\] and $B_1(5970)^0$ \[16\,18\]. This has led to remarkable theoretical efforts to provide the experimentalists with predictions regarding spectrum, decay modes, and so on, and attempts to make quark model assignments for observed new states.

Important information on mesons can be extracted from their possible decay modes, including electromagnetic, weak and strong decays. The possibility to provide a theoretical description of strong (open- and hidden-flavor) decays relies mainly on phenomenological models, because the operators that describe the strong transitions between hadrons, arising from non-perturbative QCD, are essentially unknown. In the open-flavor case, they include “hadrodynamic” models, pair-creation models and elementary meson emission models \[19\].

In this paper, we focus on the $^3P_0$ pair-creation model, in which the decays proceed via the production of $q\bar{q}$ pairs with vacuum quantum numbers, i.e. $J^{PC} = 0^{++}$, somewhere in the hadronic medium \[20\]. An important feature of the $^3P_0$ model, apart from its simplicity, is that it provides the gross features of several transitions with only one free parameter, the pair-creation strength $\gamma_0$, which is a free constant to be fitted to the experimental data. More recent studies have also discussed the possibility of substituting the constant pair-creation vertex of the model with a more refined one \[21\,22\]. Extensively applied to the study of open-flavor strong decays of light mesons \[21\,27\,28\] and baryons \[29\,31\], the $^3P_0$ pair-creation model has also been used to compute the decays of charmonia \[32\,33\], bottomonia \[34\], open-charm \[26\,37\,38\] and open-bottom \[39\] mesons.

The aim of the present paper is to provide a classification of open-charm and open-bottom mesons in terms of their masses, calculated within Godfrey and Isgur’s relativized model \[40\,41\], quantum numbers, and open-flavor amplitudes, evaluated within a modified version of the $^3P_0$ pair-creation model \[44\,56\,42\]. As widely shown by previous quark model calculations, we expect to obtain a good overall description of the properties of these mesons, with the possible exception of states close to meson-meson decay thresholds, like $D^*_0(2400)$ and $D^{*0}(2317)$ \[13\,14\]. Indeed, it is well known that the quenched approximation may fail for states in the region around the opening of meson-meson decay thresholds, where it is believed that continuum-coupling effects play an important role \[51\,52\,53\,45\,46\]. A study of these particular states in the context of coupled-channel models will be addressed in a future publication.

II. FORMALISM

A. $^3P_0$ pair-creation model

In the $^3P_0$ pair-creation model, the open-flavor strong decay of a hadron $A$ into hadrons $B$ and $C$ takes place in its rest frame, via the creation of an additional $q\bar{q}$ pair characterized by $J^{PC} = 0^{++}$ quantum numbers \[20\,24\,43\]. The decay widths $A \rightarrow BC$ are calculated as
TABLE I: Experimental total decay widths and masses of $D_s$, $D_s$, $B$, and $B_s$ mesons, extracted from the PDG. States labeled by $\dagger$ are omitted from the PDG summary table.

| State       | $J^P$ | Exp. Mass [MeV] | $\Gamma_{\text{tot}}^\text{exp}$ [MeV] |
|-------------|-------|-----------------|-----------------------------------------|
| $D_s^+(2007)^0$ | $0^+$ | 2006.85 ± 0.05  | < 21                                    |
| $D_s^+(2400)^0$ | $0^+$ | 2318 ± 29       | 267 ± 40                                |
| $D_s^++(2420)^0$ | $0^+$ | 2420.8 ± 0.5    | 31.7 ± 2.5                              |
| $D_s^+(2430)^0$ | $1^+$ | 2427 ± 26 ± 25  | 384.7 ± 77 ± 74                         |
| $D_s^+(2460)^0$ | $0^+$ | 2459.6 ± 0.6    | < 3.5                                   |
| $D_s^+(2536)^0$ | $1^+$ | 2535.10 ± 0.06  | 0.92 ± 0.03 ± 0.04                      |
| $D_s^+(2460)^0$ | $0^+$ | 2640.57 ± 0.15  | 47.7 ± 1.3                              |
| $D_s^+(2550)^0$ | $0^+$ | 2564 ± 20       | 135 ± 17                                |
| $D_s^+(2573)^0$ | $2^+$ | 2569.1 ± 0.8    | 16.9 ± 0.8                              |
| $D_s^+(2700)^0$ | $1^+$ | 2708.3 ± 4.0    | 120 ± 11                                |
| $D_s^+(2860)^0$ | $1^+$ | 2859 ± 12 ± 24  | 159 ± 23 ± 77                           |
| $D_s^+(2860)^0$ | $3^+$ | 2860.5 ± 2.6 ± 6.5 | 53 ± 7 ± 7    |
quantum number. Therefore, states with different spins but the same angular momentum, $|n^1L_J\rangle$ and $|n^2L_J\rangle$, can mix via the spin-orbit interaction. For example, this happens in the case of $^3P_0$ and $^3P_1$ states, where we consider the linear combinations

$$|nP\rangle = \cos \theta_{nP} |n^1P_1\rangle + \sin \theta_{nP} |n^3P_1\rangle$$  \hspace{1cm} (9a)

and

$$|nP\rangle = -\sin \theta_{nP} |n^1P_1\rangle + \cos \theta_{nP} |n^3P_1\rangle.$$  \hspace{1cm} (9b)

For more details, see Refs. [40][41].

The spectrum of open-charm and open-bottom states, obtained by solving the eigenvalue problem of Eq. [41] with the values of the model parameters of Ref. [40], is reported in Tables III, IV, and V.

### III. RESULTS AND DISCUSSION

Below, we provide our $^3P_0$ model results for the open-flavor strong decays of open-charm ($D$ and $D_s$) and open-bottom ($B$, $B_s$, and $B_c$) mesons in the $^3P_0$ pair-creation model. The decays are computed according to the formalism of Sec. II A with the values of the model parameters of Table III and Refs. [31][32]. When available, we calculate the amplitudes by using the experimental values of the meson masses, extracted from the PDG [10]; otherwise, we use the relativized QM predictions reported in the third column of Tables III, IV, and V.

Finally, our results for charmed, charmed-strange, bottomed, bottomed-strange, and bottomed-charm mesons are reported in Tables III, IV, V, VI, and VII respectively. See also Table I which shows the existing experimental
TABLE IV: As Table III, but for $Γ$

| Sector | $J^P$ | Mass [MeV] | $DK$ | $DK^*$ | $D^+K^*$ | $D^*\eta_f$ | $D^*\phi$ | $D_s^*\phi$ |
|--------|-------|------------|------|--------|-----------|-------------|-----------|
| $D_{s1}(2460)$ or $D_{s1}(1P_3)$ | 1$^+$ | 2549, 2459.5 | $-$ | $-$ | 46 | $-$ | $-$ | $-$ |
| $D_{s1}(2536)$ or $D_{s1}(1P'1_3)$ | 1$^+$ | 2556, 2535.10 | $-$ | 56 | (54) | $-$ | $-$ | $-$ |
| $D_{s2}(2575)$ or $D_{s2}(1P_2)$ | 2$^+$ | 2591, 2569.1 | 4 | 0 | $-$ | $-$ | $-$ | $-$ |
| $D_{s0}(2S_0)$ | 0 | 2675 | $-$ | 53 | $-$ | $-$ | $-$ | $-$ |
| $D_{s1}(2700)$ or $D_{s1}(2S_1)$ | 1$^-$ | 2735, 2708.3 | $-$ | 28 | $-$ | 42 | $-$ | $-$ |
| $D_{s1}(2860)$ or $D_{s1}(1D_1)$ | 1$^-$ | 2898, 2859 | $-$ | 43 | $-$ | 23 | $-$ | $-$ |
| $D_{s3}(2860)$ or $D_{s3}(1D_3)$ | 3$^-$ | $-$ | $-$ | $-$ | 10 | $(14)$ | $(5)$ | $(0)$ |

Our theoretical results of Table III reproduce the global trend of the PDG data [10] (see also Table II), with a few exceptions.

In more detail, starting from the $D$ sector, our result for the open-flavor width of the $D^*(2007)^0$, $Γ_{th} = 4$ keV, is compatible with the total experimental width $Γ_{tot} = 2.1$ MeV [10]. A more refined prediction would require the introduction of coupled-channel effects, the mass of the $D^*(2007)^0$ being very close to $D\eta$ threshold. The same applies to $D_s(2400)$, where the presence of higher Fock components in the meson wave function may lower the relativized QM prediction for the mass, 2398 MeV, down to the experimental value, 2318 ± 29 MeV, and also contribute to the open-flavor amplitude. In the $D_1(2420)$ case, which should mainly decay into $D^*\pi$ with the possible chain $D^*\pi \rightarrow D\pi\pi$, our $^3P_0$ model prediction is compatible with the data, while this is not true for $D_1(2430)$, being $Γ_{th} < Γ_{tot}$. Nevertheless, it is worth noting that, in this second case, the experimental error is still very large; moreover, if $D_1(2420)$ and $D_1(2430)$ are mixed by spin-orbit forces, their open-flavor widths are likely to be of the same order of magnitude. Our results for the total open-flavor widths of $D_2(2460)$ and $D_2(2550)$ are compatible with the present experimental data, being $Γ_{th} < Γ_{tot}$; there is no experimental information on the partial open-flavor widths. Coupled-channel effects may play an important role in the $D_2^*(2460)$ case, which is very close to $D\eta$ and $D\eta K$ thresholds.

Moving to the $D_s$ sector, our predictions for $D_{s1}(2460)$ are compatible with the data [10], while those for $D_{s1}(2536)$ are not. The former meson has a narrow width and mainly decays to $D_s^*$ via photon or $\pi^0$ emission, which are normally suppressed decay modes [50]. Because of the large mass difference between $D_{s1}(2460)$ and $D_{s1}(2536)$, which cannot be explained in terms of hyperfine or spin-orbit splittings, these mesons may have exotic nature. Our results for the total widths of $D_{s2}(2573)$, $D_{s2}(2700)$, $D_{s1}(2860)$ and $D_{s3}(2860)$ are compatible with the experimental data [10], being $Γ_{th} < Γ_{tot}$. We cannot say much on the single channels, as the PDG only

for the total widths of $D$, $D_s$, $B$, and $B_s$ resonances. There are no data available for higher $B_s$ resonances [10].

The calculated mixing angles are: $θ_{4P} = 37.5^\circ$, $θ_{2P} = 30.4^\circ$, $θ_{3P} = 27.7^\circ$, $θ_{1D} = 38.5^\circ$, $θ_{2D} = 37.7^\circ$, $θ_{3D} = 37.2^\circ$. In the $1P_s = 1P'_s$ and $D_{s3}(2860)$ cases, the values in parentheses are calculated by using the relativized QM predictions for the decaying meson masses.
TABLE V: As Table III, but for $B$ fractions, except that, in the $D^+$ prediction is very sensitive to the value of the decaying φ excluded from the PDG summary table [10].

provide some preliminary results for a few branching fractions, except that, in the $D_s^*(2573)$ case, our predictions are compatible with $\Gamma(D^+K)/\Gamma(DK) < 0.33$ [10]. In the $D_{s1}^*(2860)$ case, we also show predictions extracted by using the relativized QM mass for the decaying meson because: I) There is a large difference between experimental and calculated masses; II) The experimental and $\cal{P}$ masses; III) The experimental and calculated masses are not very reliable as, at the moment, the state is excluded from the PDG summary table [10].

Finally, we discuss our predictions for the $B$ and $B_s$ sectors. Our results for the total open-flavor widths of $B_s^*(5747)$ and $B_s^*(5840)$ and for the ratio $\Gamma(B_s^*(5747)\rightarrow B_s^* \pi) / \Gamma(B_s^*(5747)\rightarrow B_s^* \eta)$ are compatible with the experimental data [10] [51]. By contrast, our result for the open-flavor width of $B_{s1}(5830)$ is incompatible with the data. Our prediction is very sensitive to the value of the decaying meson mass – as $B_{s1}(5830)$ is close to the $B^*K$ threshold and thus a few MeV mass difference can produce large deviations in the calculated decay amplitude.

IV. SUMMARY AND CONCLUSION

We computed the open-flavor strong decays of open-charm and open-bottom mesons within a modified version of the $^3P_0$ pair-creation model [20] [29].

In the $^3P_0$ model, the open-flavor decays take place in the rest frame of the initial state, via the production of a light $q\bar{q}$ pair (i.e. $q = u, d$ or $s$) with $^3P_0$ quantum numbers. Heavy quark pair production is heavily suppressed, as required by the phenomenology, by substituting the pair-creation strength, $\gamma_0$, with an effective one, $\gamma_{eff}$. Moreover, the non-point-like nature of the pair of produced quarks is taken into account by
introducing a quark form-factor \( \frac{34}{36}, \frac{42}{52}, \frac{52}{50} \) into the model transition operator. The values of the \( ^3P_0 \) model parameters in the SU(4) and SU(5) sectors were extracted from our previous studies on \( cc \), \( bb \) and \( b\bar{b} \) meson spectroscopy and decays, where they were fitted to the existing experimental data \( [10] \).

The open-charm and open-bottom meson spectra we needed in our calculation were predicted within Godfrey and Isgur’s relativized quark model \( [30] \). This is one of the most powerful tools for the study of \( q\bar{q} \) meson spectroscopy, and provides a description of the meson spectrum in the light, strange, \( cc, \ldots \), sectors with a universal set of parameters; moreover, 30 years since its formulation, it still gives a good overall description of the experimental data.

As discussed in our previous papers \( [34, 36] \), there may be substantial deviations between the experimental values of the masses and QM predictions \( [40] \) in the case of resonances lying close to meson-meson decay thresholds. In these cases, continuum coupling effects may be important and determine a downward energy shift for the bare meson masses, thus improving the fit to the data; coupled-channel effects may also contribute to the open-flavor amplitudes. Such mesons may have an exotic nature, such as tetraquarks, meson-meson molecules or \( q\bar{q} \) mesons plus continuum components. For example, this may be the case of \( D(1S_1), D^*_0(2400) \) and \( D^*_s(2317) \) \( [43, 44] \), where QM predictions are incompatible with the present experimental data \( [10] \). The possible interpretations for suspected exotic open-charm and open-bottom mesons will be discussed in a future paper.

In conclusion, we think that our predictions can be

| State | \( J^P \) | Mass [MeV] | \( BK \) | \( B^*K \) | \( B^*K^* \) | \( B_s\eta \) | \( B_s\eta' \) | \( B_s\phi \) |
|-------|--------|------------|--------|----------|----------|---------|---------|---------|
| \( B_s(5830) \) or \( B_s(1P_1) \) | \( 1^+ \) | 5857.5, 5828.63 | - | 85 (30) | - | - | - | - |
| \( B_s(1P_0) \) | \( 0^+ \) | 5830 | 298 | - | - | - | - | - |
| \( B_s(2P_0) \) | \( 2^+ \) | 5875.9, 5839.84 | 1 | 0 | - | - | - | - |

TABLE VI: As Table III, but for \( B_s \) mesons. The calculated mixing angles are: \( \theta_1P = 39.1^\circ, \theta_2P = 33.1^\circ, \theta_3P = 31.6^\circ, \theta_1D = 40.0^\circ, \theta_2D = 39.5^\circ, \theta_3D = 39.1^\circ \). In the \( B_s(5830) \) case, the value in brackets is calculated by using the experimental value for the mass, without mixing with \( B_s(1P_1) \).
where $\Phi$ are quark-antiquark mesons. The SU(2) flavor matrix element and $n_\text{f}$ quark in $A$ flavor couplings of the properties of open-charm and open-bottom mesons and in the search for new resonances.

**Flavor couplings in the $^{3}P_0$ pair-creation model**

In the following, we show how to calculate the SU(5) flavor couplings of the $^{3}P_0$ pair-creation model. The SU(4) couplings can be computed analogously.

We consider the transition $A \rightarrow BC$, where $A$, $B$ and $C$ are quark-antiquark mesons. The SU(5) flavor couplings can be written as the scalar product between initial, $|A(q_1\bar{q}_2)\Phi_0(q_3\bar{q}_4)|$, and final states, $|B(q_4)C(q_3\bar{q}_2)|$, where $\Phi_0$ is the SU(5) flavor singlet

$$|\Phi_0\rangle = \frac{1}{\sqrt{n_\text{f}}} \sum_{i=1}^{n_\text{f}} |q_3\bar{q}_4\rangle$$

[10]

and $n_\text{f} = 5$ is the dimension of the SU(5) flavor group. In general, two different diagrams can contribute to the flavor matrix element $\langle BC|A\Phi_0\rangle$: in the first one, the quark in $A$ ends up in $B$, while in the second one it ends up in $C$. In the majority of cases, one of these two diagrams vanishes; however, for some matrix elements, both must be taken into account [34-35, 42]. Finally, the flavor matrix elements can be calculated as:

$$\langle B^0\pi^0|B^0\Phi_0\rangle_{\text{flavor}} = -\frac{1}{\sqrt{10}} \left[ \langle dbud|baru\rangle + \langle d\bar{d}dd|dbu\rangle \right].$$

As an example, we calculate the $B^0 \rightarrow B^0\pi^0$ flavor coupling. The flavor matrix element can be written as

$$\langle B^0\pi^0|B^0\Phi_0\rangle_{\text{flavor}} = -\frac{1}{\sqrt{10}} \left[ \langle dbud|baru\rangle + \langle d\bar{d}dd|dbu\rangle \right].$$

The only surviving contribution in Eq. (12) is $\langle dbud|baru\rangle$; the others, like $\langle dbud|baru\rangle$ or $\langle d\bar{d}dd|dbu\rangle$, are null [see Eq. (11)]. In conclusion, after dividing Eq. (12) by the corresponding SU(2) Clebsch-Gordan coefficient, we get

$$\langle B^0\pi^0|B^0\Phi_0\rangle_{\text{flavor}} = -\frac{1}{\sqrt{10}}.$$
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