I. INTRODUCTION

Meson spectroscopy has undergone a renaissance in recent years with the discovery of many new hadronic states, both those that are well described by quark models but also many poorly understood states such as the enigmatic XYZ charmonium and bottomonium-like states. In the bottom meson sector, the CDF and D0 collaborations at Fermilab, and more recently the LHCb experiment at CERN, have observed $P$-wave $B$ and $B_s$ states. In parallel to these advancements in experiment, lattice QCD is also making strides in calculating hadron masses and other properties. Progress in both experiment and theory go hand in hand in advancing our understanding of hadron physics and QCD in the soft regime. Understanding the properties of the $B$ mesons can play an important role in this enterprise as, in the heavy quark limit, $B$ mesons can be viewed as the hydrogen “atoms” of QCD with a light quark interacting with a heavy static quark. Understanding the $B$ mesons will give a more complete understanding of excited mesons and will also help put the newly discovered excited charmed mesons into the larger context. The significantly higher statistics expected at the LHC increases the likelihood of observing many new excited $B$ mesons which will give us the opportunity to study $B_{(s)}$ meson spectroscopy in greater detail than previously possible. In anticipation of these experimental developments it will be useful to predict the properties of these states, both as guidance to help experimental searches, and also to test our theoretical understanding against experimental measurements once they have been observed.

In this paper we study $B$ meson spectroscopy using the constituent quark model to calculate masses and wavefunctions. For unequal mass quarks and antiquarks $C$-parity is not a good quantum number so that states with the same parity and spin can mix (such as the $^3P_1$ and $^1P_1$ states). The relevant mixing angle is also calculated using the quark model. The wavefunctions are used to calculate radiative transition widths and as input to calculate strong decays using the $^3P_0$ quark pair creation model. We use two different relativistic quark models to gauge variations in predictions from details of the models. The quark models are based on a relativistic kinetic energy term with a short distance one-gluon-exchange potential with a strong coupling constant that runs and a linear confining potential. We make predictions of properties which will be useful for both finding and understanding these states which are the mass predictions, $E1$ and $M1$ radiative transitions, and strong partial and total decay widths obtained using the $^3P_0$ pair creation model for states above threshold. We put these results together to help identify recently observed excited $B$ mesons and to discuss the most likely means of observing excited $B$ and $B_s$ mesons and strategies for searching for them.

II. SPECTROSCOPY

We consider two relativized quark models. The first is the model of Godfrey and Isgur which has been a useful guide to mesons, from the lightest isovector mesons to the heaviest bottomonium states. The second model is due to Swanson and collaborators which incorporates recent developments in effective field theory and lattice gauge theory. By considering two models we may be able to better gauge the predictive limitations of our results.

A. The relativized quark model

The relativized quark model incorporates a relativistic dispersion relation for the quark kinetic energy and an instantaneous interaction comprised of a short distance one-gluon-exchange Lorentz vector potential and a Lorentz scalar linear confining potential:

$$H = H_0 + V_{qq} \langle \hat{p}, \hat{r} \rangle$$

(1)
where the relativistic kinetic term is given by
\[ H_0 = \sqrt{\vec{p}_q^2 + m_q^2} + \sqrt{\vec{p}_{\bar{q}}^2 + m_{\bar{q}}^2}. \] (2)

Just as in the nonrelativistic model, the quark-antiquark potential \( V_{q\bar{q}}(\vec{p}, \vec{r}) \) assumed here incorporates spin-dependent interactions that arise from the nonrelativistic reduction of the full interaction. The colour Coulomb potential and the spin-dependent potentials arising from one-gluon-exchange include a QCD-motivated running coupling \( \alpha_s(r) \), all terms in the potential are modified by a flavor-dependent potential smearing parameter \( \sigma \), and quark masses in the spin-dependent interactions are replaced with quark kinetic energies. To first order in \((v_q/c)^2\), \( V_{q\bar{q}}(\vec{p}, \vec{r}) \) reduces to the standard nonrelativistic result. Details of the model and the method of solution can be found in Ref. [6].

For the case of a quark and antiquark of unequal mass charge conjugation parity is no longer a good quantum number so that states with different total spins but with the same total angular momentum, such as the \( ^3P_1 - ^1P_1 \) and \( ^3D_2 - ^1D_2 \) pairs, can mix via the spin orbit interaction or some other mechanism. Consequently, the physical \( j = 1 \) \( P \)-wave states are linear combinations of \( ^3P_1 \) and \( ^1P_1 \) which we describe by:
\[ P = \frac{1}{2} P_1 \cos \theta_{nP} + \frac{1}{2} P_1 \sin \theta_{nP} \]
\[ P' = -\frac{1}{2} P_1 \sin \theta_{nP} + \frac{1}{2} P_1 \cos \theta_{nP} \] (3)
with analogous notation for the corresponding \( L = D, F, \) etc. pairs. In Eq. (3) \( P = L = 1 \) designates the relative angular momentum of the \( q\bar{q} \) pair and the subscript \( J = 1 \) is the total angular momentum of the \( q\bar{q} \) pair which is equal to \( L \). Our notation implicitly implies \( L - S \) coupling between the quark spins and the relative orbital angular momentum. In the heavy quark limit in which the heavy quark mass \( m_Q \rightarrow \infty \), the states can be described by the total angular momentum of the light quark, \( j \), which couples to the spin of the heavy quark and corresponds to \( j - j \) coupling. This limit gives rise to two doublets which for \( L = 1 \) have \( j = 1/2 \) and \( j = 3/2 \) and corresponds to two physically independent mixing angles \( \theta_{1P} = -\tan^{-1}(\sqrt{2}) \approx -54.7^\circ \) and \( \theta_{1P} = \tan^{-1}(1/\sqrt{2}) \approx 35.3^\circ \) [14]. Some authors prefer to use the \( j - j \) basis [14] but since we solve our Hamiltonian equations assuming \( L - S \) eigenstates and then include the \( LS \) mixing we use the notation of Eq. (3).

It is straightforward to transform between the \( L - S \) basis and the \( j - j \) basis. It will turn out that radiative transitions are particularly sensitive to the \( ^3L_L - ^3L_{L} \) mixing angle with predictions from different models in some cases giving radically different results. We also note that the definition of the mixing angles are fraught with ambiguities. For example, charge conjugating \( q\bar{q} \) into \( b\bar{q} \) flips the sign of the angle and the phase convention depends on the order of coupling \( \vec{L}, \vec{S_q}, \) and \( \vec{S}_\bar{q} \) [13].

The Hamiltonian problem was solved using the following parameters: the slope of the linear confining potential is 0.18 GeV\(^2\), \( m_q = 0.220 \) GeV, \( m_s = 0.419 \) GeV and \( m_b = 4.977 \) GeV. Other parameters can be found in Ref. [6]. Predicted masses and mixing angles are given in Figs. 1 and 2 and in Tables [11].

### B. Alternate Relativized Model

The second relativized model has been developed in response to recent results from effective field theory and lattice gauge theory. The starting point is the general expression for the spin-dependent interactions in QCD as obtained from potential nonrelativistic quantum chromodynamics (pNRQCD) [15]. This interaction is described in terms of factorized scale-dependent Wilson coefficients and scale-dependent matrix elements of chromo-magnetic and -electric operators. The quark-antiquark interaction is modelled as the sum of a central confining term and the spin-dependent interaction (spin-independent corrections of order \( mv^2 \) also exist, but these are assumed to be subsumed into the central potential):
\[ V_{q\bar{q}} = V_{conf} + V_{SD}, \]
where \( V_{conf} \) is the standard Coulomb-linear scalar form
\[ V_{conf}(r) = -\frac{C_F}{r} \frac{\alpha_s(r)}{r} + br. \] (5)

At lowest order in \( \alpha_s \) the form of the spin-dependent interactions is given below [16]:
\[ V_{SD}(r) = \left( \frac{\sigma_q}{4m_q^2} + \frac{\sigma_{\bar{q}}}{4m_{\bar{q}}^2} \right) \cdot L \left( \frac{1}{r} \frac{dV_{conf}}{dr} + \frac{2}{r} \frac{dV_1}{dr} \right) + \left( \frac{\sigma_q + \sigma_{\bar{q}}}{2m_qm_{\bar{q}}} \right) \cdot L \left( \frac{1}{r} \frac{dV_2}{dr} \right) + \frac{1}{12m_qm_{\bar{q}}} \left( 3\sigma_q \cdot \vec{r} \sigma_{\bar{q}} \cdot \vec{r} - \sigma_q \cdot \sigma_{\bar{q}} \right) V_3 + \frac{1}{12m_qm_{\bar{q}}} \sigma_q \cdot \sigma_{\bar{q}} V_4 + \frac{1}{2} \left( \frac{\sigma_q}{m_q^2} - \frac{\sigma_{\bar{q}}}{m_{\bar{q}}^2} \right) \cdot L + \left( \frac{\sigma_q - \sigma_{\bar{q}}}{m_qm_{\bar{q}}} \right) \cdot L V_5. \] (6)
Here \( L = L_q = -L_{\bar{q}}, r = |r| = |r_q - r_{\bar{q}}| \) is the quark separation and the \( V_i = V_i(m_q, m_{\bar{q}}; r) \) are the QCD matrix elements mentioned above. The first four \( V_i \) are order \( \alpha_s \) in perturbation theory, while \( V_5 \) is order \( \alpha_s^2 \).

The alternate relativized model (ARM) assumes relativistic quark kinetic energies and a running coupling in the Coulombic interaction. The running coupling is motivated by the persistent over-estimation of heavy meson decay constants [10], and by fits to different flavor sectors of the meson spectrum. The form used is related to the Fourier transform of
\[ \alpha(k) = 4\pi \frac{\beta_0}{\log \left( \exp\left( \frac{4\pi}{m_q} \right) + \frac{k^2}{\pi^2}\right)}], \] (7)
which has the expected ultraviolet behavior along with a postulated infrared fixed point. The leading coefficient
TABLE I: Predicted masses (in MeV), spin-orbit mixing angles and effective harmonic oscillator parameters, $\beta_{eff}$ (in GeV). Columns 2-5 show the results using the Godfrey-Isgur relativized quark model described in Sec. II A and columns 6-9 show the results using the alternate relativized model described in Sec. II B. The $P_1 - P_1'$, $D_2 - D_2'$, $F_3 - F_3$ and $G_4 - G_4'$ states and mixing angles are defined using the convention of Eq. 3. Where two values of $\beta_{eff}$ are listed, the first (second) refers to the singlet (triplet) state.

| State | Mass | $\beta_{eff}$ | Mass | $\beta_{eff}$ | Mass | $\beta_{eff}$ | Mass | $\beta_{eff}$ |
|-------|------|-------------|------|-------------|------|-------------|------|-------------|
| $1^3S_1$ | 5371 | 0.542 | 5450 | 0.595 | 5316 | 0.586 | 5400 | 0.616 |
| $1^1S_0$ | 5312 | 0.580 | 5394 | 0.636 | 5275 | 0.628 | 5366 | 0.651 |
| $1^3P_2$ | 5797 | 0.472 | 5876 | 0.504 | 5754 | 0.465 | 5836 | 0.487 |
| $1^3P_1$ | 5777 | 0.499, 0.511 | 5857 | 0.528, 0.538 | 5738 | 0.481, 0.492 | 5822 | 0.500, 0.507 |
| $1^3P_0$ | 5784 | 5861 | 5753 | 5830 |
| $1^1P_0$ | 5756 | 0.536 | 5831 | 0.563 | 5720 | 0.525 | 5805 | 0.531 |
| $\theta_{1P}$ | 30.28$^\circ$ | 39.12$^\circ$ | 43.6$^\circ$ | 37.9$^\circ$ |
| $2^3S_1$ | 5933 | 0.468 | 6012 | 0.497 | 5864 | 0.460 | 5948 | 0.477 |
| $2^1S_0$ | 5904 | 0.477 | 5984 | 0.508 | 5834 | 0.476 | 5925 | 0.489 |
| $1^3D_3$ | 6106 | 0.444 | 6179 | 0.467 | 6026 | 0.428 | 6109 | 0.443 |
| $1^3D_2$ | 6095 | 0.469, 0.463 | 6169 | 0.482, 0.487 | 6012 | 0.434, 0.436 | 6098 | 0.449, 0.450 |
| $1^3D_1$ | 6124 | 6196 | 6072 | 6133 |
| $1^1D_1$ | 6110 | 0.488 | 6182 | 0.504 | 6053 | 0.447 | 6119 | 0.459 |
| $\theta_{1D}$ | 39.69$^\circ$ | 40.00$^\circ$ | 48.7$^\circ$ | 48.0$^\circ$ |
| $2^3P_2$ | 6213 | 0.440 | 6295 | 0.462 | 6141 | 0.413 | 6220 | 0.428 |
| $2^1P_1$ | 6197 | 0.452, 0.456 | 6279 | 0.472, 0.474 | 6126 | 0.423, 0.426 | 6208 | 0.435, 0.438 |
| $2^3P_1$ | 6228 | 6296 | 6132 | 6211 |
| $2^1P_0$ | 6213 | 0.466 | 6279 | 0.483 | 6106 | 0.439 | 6191 | 0.447 |
| $\theta_{2P}$ | 32.28$^\circ$ | 33.05$^\circ$ | 39.35$^\circ$ | 32.1$^\circ$ |
| $3^3S_1$ | 6355 | 0.437 | 6429 | 0.456 | 6240 | 0.412 | 6319 | 0.424 |
| $3^1S_0$ | 6335 | 0.442 | 6410 | 0.462 | 6216 | 0.421 | 6301 | 0.431 |
| $1^3F_4$ | 6364 | 0.429 | 6432 | 0.446 | 6244 | 0.408 | 6328 | 0.419 |
| $1^3F_3$ | 6358 | 0.442, 0.446 | 6425 | 0.457, 0.460 | 6231 | 0.408, 0.408 | 6318 | 0.421, 0.421 |
| $1^3F_2$ | 6396 | 6462 | 6316 | 6369 |
| $1^3F_1$ | 6387 | 0.460 | 6454 | 0.472 | 6302 | 0.409 | 6358 | 0.423 |
| $\theta_{1F}$ | 41.13$^\circ$ | 41.14$^\circ$ | 48.05$^\circ$ | 47.7$^\circ$ |
| $2^3D_3$ | 6460 | 0.424 | 6535 | 0.442 | 6347 | 0.394 | 6428 | 0.405 |
| $2^3D_2$ | 6450 | 0.438, 0.434 | 6526 | 0.449, 0.452 | 6334 | 0.399, 0.401 | 6417 | 0.410, 0.411 |
| $2^3D_1$ | 6486 | 6553 | 6377 | 6442 |
| $2^1D_1$ | 6475 | 0.448 | 6542 | 0.460 | 6357 | 0.410 | 6427 | 0.418 |
| $\theta_{2D}$ | 38.96$^\circ$ | 39.46$^\circ$ | 48.2$^\circ$ | 47.3$^\circ$ |
| $3^3P_2$ | 6570 | 0.422 | 6648 | 0.439 | 6451 | 0.388 | 6527 | 0.399 |
| $3^3P_1$ | 6557 | 0.430, 0.432 | 6635 | 0.445, 0.445 | 6438 | 0.394, 0.395 | 6516 | 0.403, 0.404 |
| $3^1P_1$ | 6585 | 6650 | 6443 | 6519 |
| $3^3P_0$ | 6576 | 0.437 | 6639 | 0.451 | 6422 | 0.401 | 6504 | 0.409 |
| $\theta_{3P}$ | 31.57$^\circ$ | 31.59$^\circ$ | 41.9$^\circ$ | 39.2$^\circ$ |
| $1^3G_5$ | 6592 | 0.419 | 6654 | 0.433 | 6433 | 0.395 | 6517 | 0.403 |
| $1^3G_4$ | 6588 | 0.429, 0.431 | 6650 | 0.441, 0.443 | 6420 | 0.392, 0.391 | 6507 | 0.403, 0.402 |
| $1^3G_1$ | 6628 | 6690 | 6521 | 6568 |
| $1^3G_0$ | 6622 | 0.442 | 6685 | 0.452 | 6508 | 0.389 | 6558 | 0.402 |
| $\theta_{1G}$ | 41.90$^\circ$ | 41.87$^\circ$ | 47.5$^\circ$ | 47.3$^\circ$ |
of the QCD beta function is taken to be $\beta_0 = 9$ and $\alpha_0$ and $\Lambda$ are free parameters to be fit to the spectrum and heavy meson decay constants.

Traditionally the forms for the potentials $V_i$ have been obtained by making nonrelativistic reductions of interaction kernels of the type

$$\frac{1}{2} \int d^3x d^3y \bar{\psi}(x) \Gamma \psi(x) V(x-y) \bar{\psi}(y) \Gamma \psi(y), \quad (8)$$

where the Dirac matrices are typically chosen to be unity or $\gamma_0$ (these correspond to “scalar” or “vector” interaction models respectively). However, QCD need not be so simple and we have therefore chosen to refer to lattice computations to model the interaction matrix elements. Direct measurement of the gluonic matrix elements reveal that $V_3$ and $V_4$ are short-ranged (as expected for vector interactions), while $V_2$ and $V_5$ contain long-ranged components [17]. However the latter do not follow the expectations of “scalar confinement” [18], rather the string tension appearing in $V_1$ is reduced with respect to $V_{con,f}$ and there should be no long range interaction in $V_2$. We thus model the gluonic matrix elements as follows:

$$V_1 = (1 - \epsilon)br \quad (9)$$
$$V_2 = ebr - C_F\alpha_S r \quad (10)$$
$$V_3 = 3C_F\alpha_h \frac{br}{r} \quad (11)$$
$$V_4 = C_F\alpha_h \frac{b^2_0 e^{-br}}{r} \quad (12)$$
$$V_5 = 0 \quad (13)$$

Lattice results indicate [17] that $\epsilon \approx \frac{1}{4}$, which is fixed in the following. The form of $V_4$ is based on the running coupling employed and $V_5$ has been taken to be zero (it was not measured in the lattice computation). The latter point is nontrivial since the perturbative expression for $V_5$ contains logarithms of ratios of quark masses, and therefore can be important in open flavor mesons. This point is discussed more in Ref. [11]. More details on the model construction are in Ref. [12].

| State  | Mass     | $\beta_{eff}$ | GI $b\bar{q}$ | Mass     | $\beta_{eff}$ | GI $b\bar{s}$ | ARM $b\bar{q}$ | Mass     | $\beta_{eff}$ | ARM $b\bar{s}$ |
|--------|----------|---------------|--------------|----------|---------------|--------------|--------------|----------|---------------|--------------|
| $2^1F_3$ | 6798     | 0.411         | 6748         | 0.428    | 6524          | 0.383        | 7022         | 0.411    | 6748          | 0.428        |
| $2F_3$  | 6673     | 0.423, 0.425  | 6742         | 0.435, 0.436 | 6511   | 0.384, 0.385 | 6595         | 0.394, 0.392 |
| $2F_3'$ | 6711     | 6775          | 6583         | 6638     |               |              |              |          |               |              |
| $2^3F_2$ | 6704     | 0.434         | 6768         | 0.436    | 6568          | 0.387        | 6627         | 0.397    |               |              |
| $\theta_{2F}$ | 40.86°   | 40.97°        | 47.9°        | 47.5°    |               |              |              |          |               |              |
| $4^1S_1$ | 7070     | 0.421         | 6773         | 0.436    | 6541          | 0.387        | 6617         | 0.397    |               |              |
| $4^1S_0$ | 6689     | 0.424         | 6759         | 0.440    | 6520          | 0.393        | 6601         | 0.402    |               |              |
| $3^1D_3$ | 6775     | 0.418         | 6849         | 0.426    | 6623          | 0.375        | 6699         | 0.384    |               |              |
| $3D_2$  | 6767     | 0.419, 0.421  | 6841         | 0.431, 0.432 | 6610   | 0.379, 0.381 | 6689         | 0.388, 0.389 |
| $3D_2'$ | 6800     | 6864          | 6642         | 6708     |               |              |              |          |               |              |
| $3^1D_1$ | 6792     | 0.427         | 6855         | 0.438    | 6622          | 0.388        | 6693         | 0.394    |               |              |
| $\theta_{3D}$ | 38.56°   | 39.14°        | 47.7°        | 46.8°    |               |              |              |          |               |              |
| $4^1P_2$ | 6883     | 0.411         | 6956         | 0.424    | 6717          | 0.372        | 6790         | 0.381    |               |              |
| $4P_1$  | 6872     | 0.416, 0.417  | 6946         | 0.429, 0.429 | 6705   | 0.376, 0.376 | 6780         | 0.384, 0.384 |
| $4P_1'$ | 6897     | 6950          | 6710         | 6783     |               |              |              |          |               |              |
| $4^1P_0$ | 6890     | 0.420         | 6950         | 0.432    | 6693          | 0.380        | 6770         | 0.387    |               |              |
| $\theta_{4P}$ | 31.00°   | 30.39°        | 48.6°        | 47.4°    |               |              |              |          |               |              |
| $2^1G_5$ | 6879     | 0.407         | 6942         | 0.419    | 6685          | 0.375        | 6766         | 0.383    |               |              |
| $2G_4$  | 6875     | 0.415, 0.416  | 6938         | 0.425, 0.426 | 6672   | 0.374, 0.374 | 6756         | 0.383, 0.382 |
| $2G_4'$ | 6914     | 6975          | 6764         | 6812     |               |              |              |          |               |              |
| $2^1G_3$ | 6909     | 0.424         | 6970         | 0.432    | 6750          | 0.373        | 6801         | 0.383    |               |              |
| $\theta_{2G}$ | 41.76°   | 41.78°        | 47.4°        | 47.2°    |               |              |              |          |               |              |
| $5^1S_1$ | 7008     | 0.411         | 7076         | 0.428    | 6800          | 0.372        | 6873         | 0.380    |               |              |
| $5^1S_0$ | 6997     | 0.416         | 7063         | 0.426    | 6781          | 0.376        | 6858         | 0.383    |               |              |
A fit to 60 meson masses yields quark masses of $m_u = 0.4585$ GeV, $m_s = 0.5919$ GeV, $m_c = 1.772$ GeV, and $m_h = 5.145$ GeV. Potential parameters are $b = 0.1213$ GeV$^2$, $a_h = 0.1536$, and $b_h = 2.138$ GeV.

C. Comparison to Previous Work

There is a long history of studying open flavor mesons in constituent quark models. Here we review some of the recent literature, noting similarities and differences with the current approach.

A notable early contribution was due to Di Pierro and Eichten, who examined the $D$, $D_s$, $B$, and $B_s$ spectra with a constituent quark model based on the Dirac equation for the light quark in the potential generated by the heavy quark[19]. Strong decays of these states by pseudoscalar meson emission were then computed with the chiral quark model of Manohar and Georgi[20].

The unusual mass of the $D_s(2317)$ generated a series of papers on open flavor meson spectroscopy. Here we mention that of Close and Swanson, who computed the $D$ and $D_s$ spectra using a simple nonrelativistic quark model with a central Cornell potential and a smeared hyperfine interaction[21]. Strong decays were computed with the $^3P_0$ model with SHO mesonic wavefunctions and effective meson widths (as is done here). Radiative transitions, including those from molecular states, were also presented.

The $D_s(2317)$ also motivated the analysis of Ref. [11]. The novel feature of this investigation was the use of $O(a_s^2)$ spin-dependent corrections to the static interquark potential – in particular flavor-dependence is introduced via logarithmic dependence on quark mass. This can have strong effects on the open-flavor spectrum and can shift the nominal scalar meson mass down by roughly 100 MeV. This paper also examined relativistic effects (due to light quark spinors) on radiative transitions, and found large shifts.

Alternative relativistic (or “relativized”) models also appeared in the late 2000s. For example, Matsuki et al., who used scalar and vector interaction kernels in a Dirac equation with a Foldy-Wouthuysen reduction of the heavy quark portion of the interaction[22]. Related work by Ebert et al. appeared at about this time as well[23]. These authors used relativistic kinetic energies and vector, chromomagnetic, and scalar Dirac structures in the interaction kernels to obtain the $D$, $D_s$, $B$, and $B_s$ spectra. Finally, Devlani and Rai made an $O(p^6)$ reduction of the quark kinetic energy and supplemented this with a Cornell central potential and the Breit spin-dependent interaction[24]. Unfortunately, the authors appeared to have employed an unregulated delta function in the latter interaction, which is not acceptable in quantum mechan-
Radiative problems (evidently this problem was not discovered because the spectrum was obtained with a simple variational calculation). The first two of these papers did not examine radiative or strong transitions; radiative transitions were computed in the latter.

More recently, the chiral quark model has been revisited for the strong decays of open flavor mesons [28]. This work employed SHO mesonic wavefunctions with a fixed Gaussian width. Two additional papers have computed $B$ and $D$ meson spectra with the Godfrey-Isgur model [26, 27]. They have also calculated strong decays using a very similar method to that presented here; the main difference is that the latter group incorporated a quark form factor in the $^3P_0$ vertex to suppress high energy decay modes and used SHO mesonic wavefunctions with a single Gaussian width. A similar computation of the $B$ and $D$ spectra was made with a model with relativistic quark kinetic energy and an interaction with a running coupling and smeared delta functions [28]. Decays were not considered. Finally, Liu et al. have made a Foldy-Wouthuysen reduction of the instantaneous approximation to the Bethe-Salpeter equation and obtained the $D_s$, $B_s$, $B$, and $B_s$ spectra [29].

Shortly after this work appeared, a computation that used the model of Ref. [11] was submitted to the arXiv [30]. The authors computed $B$ and $B_s$ spectra and strong decays with the $^3P_0$ model using full mesonic wavefunctions. A factor of $m_s/m_u$ was applied to the $^3P_0$ coupling to suppress strange quark production. This factor can be justified by considering the quark pair production interaction to be proportional to $\int \bar{\psi}\psi$, however this is a model assumption, and we must resort to experiment to decide the issue.

III. RADIATIVE TRANSITIONS

A. E1 Transitions

Radiative transitions could play an important role in the discovery and identification of $B$ and $B_s$ states. They are sensitive to the internal structure of states, in particular to $^3L_L - ^1L_L$ mixing for states with $J = L$. In this section we calculate the electric dipole (E1) and magnetic dipole (M1) radiative widths. The partial width for an E1 radiative transition between states in the nonrelativistic quark model is given by [31].
\[ \Gamma(n^{2S+1}L,J \rightarrow n'^{2S'+1}L',J' + \gamma) = \frac{4}{3} \langle e_q \rangle^2 \alpha k^3 C_{fJ} \delta_{SS'} \delta_{LL'} | \langle n'^{2S'+1}L'| r | n^{2S+1}L,J \rangle |^2 \]  \\

where

\[ \langle e_q \rangle = \frac{m_b e_q - m_q e_u}{m_q + m_b} \]  \\

where \( q = u,d,s \), we use the quark masses \( m_u = m_d = 0.220 \text{ GeV}, m_s = 0.419 \text{ GeV} \) and \( m_b = 4.977 \text{ GeV} \), \( e_u = +2/3 \) and \( e_d = e_s = e_b = -1/3 \) are the quark charges in units of \( |e| \), \( \alpha \) is the fine-structure constant, \( k \) is the photon’s energy, and \( C_{fJ} \) is given by

\[ C_{fJ} = \max(L, L') (2J' + 1) \left\{ \begin{array}{ccc} L' & J' & S \\ J & L & 1 \end{array} \right\}^2 \]  \\

where \( \{ \ldots \} \) is a 6-\( j \) symbol. The matrix elements \( \langle n'^{2S'+1}L'| r | n^{2S+1}L,J \rangle \) are given in Tables IV-XXXV where applicable and were evaluated using the wavefunctions given by the relativized quark model [6]. Relativistic corrections are implicitly included in these E1 transitions through Siegert’s theorem [32-34] by including spin-dependent interactions in the Hamiltonian used to calculate the meson masses and wavefunctions. The E1 radiative widths are given in Tables IV-XXXV where applicable.

### B. M1 Transitions

Radiative transitions which flip spin are described by magnetic dipole (M1) transitions. The rates for magnetic dipole transitions between \( S \)-wave heavy-light bound states are given in the nonrelativistic approximation by [35-36].

\[ \Gamma(n^{2S+1}L,J \rightarrow n'^{2S'+1}L',J' + \gamma) = \alpha k^3 (2J' + 1) \delta_{SS'} \frac{e_q}{m_q} \langle f | j_0 \left( \frac{m_b}{m_q + m_b} kr \right) | i \rangle + \frac{e_b}{m_b} \langle f | j_0 \left( \frac{m_q}{m_q + m_b} kr \right) | i \rangle \]  \\

where \( e_q \), the quark charges, and \( m_q \), the quark masses, were given above, \( L = 0 \) for \( S \) waves and \( j_0(x) \) is the spherical Bessel function.

The M1 widths and overlap integrals are given in Tables IV-XXXV where applicable. Transitions in which the principle quantum number changes are referred to as hindered transitions, which are not allowed in the nonrelativistic limit due to the orthogonality of the wavefunctions. M1 transitions, especially hindered transitions, are notorious for their sensitivity to relativistic corrections [37]. In our calculations the wavefunction orthogonality is broken by including a smeared hyperfine interaction directly in the Hamiltonian so that the \( ^2S_1 \) and \( ^1S_0 \) states have slightly different wavefunctions. Ebert et al. are more rigorous in how they include relativistic corrections [38] but to improve the \( J/\psi \rightarrow \eta_c \gamma \) result they modify the confining potential by making it a linear combination of Lorentz vector and Lorentz scalar pieces.

The E1 and M1 radiative widths are given in Tables IV-XXXV when they are large enough that they might be observed. The predicted masses given in Tables I-II are used for all states under the assumption that predicted masses are expected to be shifted by comparable amounts from their measured masses leaving the phase space to remain approximately correct.
TABLE III: Light meson masses and effective harmonic oscillator parameters, $\beta_{eff}$, used in the calculation of strong decay widths. The experimental values of the masses are taken from the Particle Data Group (PDG) [45]. The input value of the $\pi$ mass is the weighted average of the experimental values of the $\pi^0$ and $\pi^\pm$ masses, and similarly for the input values of the $K$ and $K^*$ masses. All $\beta_{eff}$ values are taken to be 0.4 GeV for the light mesons.

| Meson State | $M_{input}$ (MeV) | $M_{exp}$ [45] (MeV) | $\beta_{eff}$ (GeV) |
|-------------|-------------------|----------------------|---------------------|
| $\pi$ $1^3S_0$ | 138.8877 | 134.8766 $\pm$ 0.0006 ($\pi^0$), 139.57018 $\pm$ 0.00035 ($\pi^\pm$) | 0.4 |
| $\eta$ $1^3S_0$ | 547.862 | 547.862 $\pm$ 0.018 | 0.4 |
| $\eta'$ $1^3S_0$ | 957.78 | 957.78 $\pm$ 0.06 | 0.4 |
| $\rho$ $1^3S_1$ | 775.26 | 775.26 $\pm$ 0.25 | 0.4 |
| $\omega$ $1^3S_1$ | 782.65 | 782.65 $\pm$ 0.12 | 0.4 |
| $\phi$ $1^3S_1$ | 1019.461 | 1019.461 $\pm$ 0.019 | 0.4 |
| $K$ $1^3S_0$ | 494.888 | 497.614 $\pm$ 0.024 ($K^0$), 493.677 $\pm$ 0.016 ($K^\pm$) | 0.4 |
| $K^*$ $1^3S_1$ | 894.36 | 895.81 $\pm$ 0.19 ($K^{*0}$), 891.66 $\pm$ 0.26 ($K^{*\pm}$) | 0.4 |

$m_s = 0.419$ GeV and $m_d = 0.220$ GeV. Finally, we use “relativistic phase space” as described in Ref. [42, 44]. We use the calculated bottom and bottom-strange meson masses listed in Tables I-II. For the light mesons we used the measured masses listed in Table III. Details regarding the notation and conventions used in the $^3P_0$ model calculations are given in the appendix of [46].

Typical values of the parameters $\beta_{eff}$ and $\gamma$ are found from fits to light meson decays [21, 42, 47]. The predicted widths are fairly insensitive to the precise values used for $\beta_{eff}$ provided $\gamma$ is appropriately rescaled. However $\gamma$ can vary as much as 30% and still give reasonable overall fits of light meson decay widths [21, 47]. This can result in factor of two changes to predicted widths, both smaller or larger. In our calculations of $D$ and $D_s$ meson strong decay widths from [48] and [49], we used a value of $\gamma = 0.4$, which has also been found to give a good description of strong decays of charmonium [21, 43]. We adopt the same value of $\gamma = 0.4$ in our calculations of $B$ and $B_s$ meson strong decays. The resulting partial widths are listed in Tables IV-XXXV. We include more complete sets of decays in a supplementary file that includes decays not included in the paper because we felt that their BR’s were too small to likely be observed. To make our results as comprehensive as possible the supplementary file also includes tables of strong decays for the $5S$, $4P$, $3D$, $2F$ and $2G$ states.
TABLE IV: Partial widths and branching ratios for strong and electromagnetic decays of the 1S and 2S B mesons. The initial state’s mass is given in MeV and is listed below the state’s name in column 1. Column 4 gives the matrix element, \( \mathcal{M} \), or strong amplitude appropriate to the particular decay. For radiative transitions the E1 or M1 matrix elements are \( \langle f | r | i \rangle \) (GeV\(^{-1}\)) and \( \langle f | j_0(kr \frac{m_q}{m_b + m_q}) | i \rangle \) respectively; these matrix elements were obtained using the wavefunctions of the GI model \([\text{ref}].\) For strong decays, the non-zero partial wave amplitudes are given in units of GeV\(^{-1/2}\). We only show radiative transitions that are likely to be observed and likewise generally do not show strong decay modes which have BR < 0.1%, although they are included in calculating the total width. Details of the calculations are given in the text.

| Initial state | Final state | \( M_f \) (MeV) | \( \mathcal{M} \) | Width (ub, db) (MeV) | B.R. (ub, db) (%) |
|---------------|-------------|-----------------|----------------|---------------------|-----------------|
| \( B^* \) \( B \gamma \) | 5312 | \( \langle 1^1 S_0 | j_0(kr \frac{m_q}{m_b + m_q}) | 1^3 S_1 \rangle = 0.9946, 0.9971 \) | 0.00431, 0.00123 | 100 |
| 5371 Total | | | 0.00431, 0.00123 | 100 |
| \( B(2^3 S_1) \) \( B \gamma \) | 5312 | \( \langle 1^1 S_0 | j_0(kr \frac{m_q}{m_b + m_q}) | 2^1 S_1 \rangle = 0.2404, 0.06506 \) | 0.260, 0.0674 | 0.24, 0.063 |
| 5933 \( B(1^3 P_2) \gamma \) | 5797 | \( \langle 1^3 P_2 | r | 2^1 S_1 \rangle = -2.445 \) | 0.0308, 0.00878 | 0.029, 0.0082 |
| \( B(1^3 P_1) \gamma \) | 5777 | \( \langle 1^3 P_1 | r | 2^1 S_1 \rangle = -2.126 \) | 0.00532 , 0.00152 | 0.0049 , 0.0014 |
| \( B(1P_0) \gamma \) | 5756 | \( \langle 1^3 P_0 | r | 2^1 S_1 \rangle = -1.927 \) | 0.0137, 0.00390 | 0.013, 0.0036 |
| \( B \pi \) | 5731 | \( \langle 1^1 S_1 | j_0(kr \frac{m_q}{m_b + m_q}) | 2^1 S_0 \rangle = 0.1093, -0.6636 \) | 0.108, 0.0250 | 0.11, 0.026 |
| \( B \eta \) | 5904 | \( \langle 1^1 S_1 | j_0(kr \frac{m_q}{m_b + m_q}) | 2^1 S_0 \rangle = -2.346 \) | 0.0311, 0.00887 | 0.033, 0.0094 |
| \( B(1P_1) \gamma \) | 5777 | \( \langle 1^1 S_1 | j_0(kr \frac{m_q}{m_b + m_q}) | 2^1 S_0 \rangle = -2.346 \) | 0.00901 , 0.00257 | 0.0095 , 0.0027 |
| \( B \pi \) | 5784 | \( \langle 1^3 P_1 | r | 2^1 S_0 \rangle = -0.256 \) | 94.6 | \( \sim 100 \) |
| Total | | | 94.7, 94.6 | 100 |
TABLE V: Partial widths and branching ratios for strong and electromagnetic decays of the 3S B mesons. See the caption to Table [IV] for further explanations.

| Initial | Final          | \( M_f \) | \( \mathcal{M} \) | Width (\( ub, db \)) | B.R. (\( ub, db \)) |
|---------|----------------|-----------|----------------|------------------------|-------------------|
| state   | state          | (MeV)     | (MeV)          | (\( \% \))               | (\( \% \))          |
| \( B(3^3S_1) \) | \( B\gamma \) | 5312      | \( 1^2S_0|j_0(kr\frac{m_b}{m_q+m_b})|3^3S_1| = 0.1282, 0.02989 \) | 0.319, 0.0822 | 0.23, 0.058 |
| 6355    | \( B(2^1S_0)\gamma \) | 5904      | \( 2^1S_0|j_0(kr\frac{m_b}{m_q+m_b})|3^3S_1| = 0.2666, 0.05527 \) | 0.129, 0.0333 | 0.092, 0.024 |
|         | \( B(1^3P_2)\gamma \) | 5797      | \( 1^3P_2|r|3^3S_1| = 0.3747 \) | 0.0450, 0.0128 | 0.032, 0.0091 |
|         | \( B(2^1P_2)\gamma \) | 6213      | \( 2^1P_2|r|3^3S_1| = -3.603 \) | 0.0757, 0.0216 | 0.054, 0.015 |
|         | \( B(2P_1)\gamma \) | 6197      | \( 2^1P_1|r|3^3S_1| = -3.202 \) | 0.0140, 0.00398 | 0.0099, 0.0028 |
|         | \( B(2P_1)\gamma \) | 6228      | \( 2^1P_1|r|3^3S_1| = -3.202 \) | 0.0186, 0.00531 | 0.013, 0.0038 |
|         | \( B(2P_0)\gamma \) | 6213      | \( 2^3P_0|r|3^3S_1| = -2.932 \) | 0.0100, 0.00286 | 0.0071, 0.0020 |

\[ B_{\pi} \]
\[ 1^1P_1 = 0.0232 \] 3.09 2.2
\[ B_{\rho} \]
\[ 3^P_1 = -0.0316 \] 3.38 2.4
\[ B_{\eta'} \]
\[ 1^1P_1 = -0.0195 \] 0.775 0.6
\[ B_{\omega} \]
\[ 3^P_1 = -0.0192 \] 1.24 0.9
\[ B^*_{\pi} \]
\[ 3^P_1 = -0.0314 \] 4.33 3.1
\[ B^*_{\rho} \]
\[ 1^1P_1 = -0.0223, 2^3P_1 = 0.0998 \] 29.7 21.2
\[ B^*_{\eta'} \]
\[ 3^P_1 = 0.0245 \] 0.646 0.4
\[ B^*_{\omega} \]
\[ 3^P_1 = -0.0133, 5^3P_1 = 0.0596 \] 10.5 7.4
\[ B(3^3S_0)_{\pi} \]
\[ 1^1P_1 = 0.0888 \] 8.32 5.9
\[ B(3^3S_0)_{\pi} \]
\[ 3^P_1 = -0.132 \] 16.3 11.6
\[ B(1P_1)\pi \]
\[ 3^S_1 = -0.00141 i, 2^D_1 = 0.119 i \] 24.0 17.0
\[ B(3P_1)\pi \]
\[ 3^S_1 = 0.00757 i, 3^D_1 = 0.00797 i \] 0.201 0.1
\[ B(1P_1)\eta \]
\[ 3^S_1 = -0.0516 i, 3^D_1 = 0.000519 i \] 1.35 1.0
\[ B(3P_2)\pi \]
\[ 5^D_1 = -0.132 i \] 27.6 19.6
\[ B_{sK} \]
\[ 1^1P_1 = -0.0151 \] 0.850 0.6
\[ B_{sK'} \]
\[ 3^P_1 = -0.0430 \] 3.05 2.2
\[ B^*_{sK} \]
\[ 3^P_1 = 0.0313 \] 3.22 2.3
\[ B^*_{sK'} \]
\[ 3^P_1 = -0.0101, 5^3P_1 = 0.0453 \] 1.35 1.0
| Total   | \( B(3^3S_0) \) | 6355 | 140.4 140.8 100 |

\[ B^*_{\pi} \]
\[ 3^P_0 = 0.0512 \] 8.40 5.6
\[ B_{\omega} \]
\[ 3^P_0 = 0.0308 \] 3.00 2.0
\[ B^*_{\pi} \]
\[ 3^P_0 = -0.0314 \] 4.19 2.8
\[ B^*_{\rho} \]
\[ 3^P_0 = -0.113 \] 33.7 22.4
\[ B^*_{\eta'} \]
\[ 3^P_0 = 0.00647 \] 0.151 0.1
\[ B^*_{\omega} \]
\[ 3^P_0 = -0.0669 \] 11.7 7.8
\[ B(2^3S_1)\pi \]
\[ 3^P_0 = -0.166 \] 23.2 15.4
\[ B(1^3P_0)\eta \]
\[ 1^1S_0 = -0.0467 i \] 1.27 0.8
\[ B(1^3P_2)\pi \]
\[ 5^D_0 = -0.187 i \] 51.7 34.3
\[ B_{sK} \]
\[ 3^P_0 = 0.0499 \] 3.37 2.2
\[ B_{sK'} \]
\[ 3^P_0 = 0.0462 \] 6.67 4.4
\[ B_{(1^3P_0)K} \]
\[ 1^1S_0 = -0.103 i \] 2.80 1.9
| Total   | \( B(3^3S_0) \) | 6355 | 150.6 150.8 100 |
TABLE VI: Partial widths and branching ratios for strong and electromagnetic decays of the $4^3S_1$ $B$ meson. See the caption to Table IV for further explanations.

| Initial state | Final state | $M_f$ (MeV) | $\mathcal{M}$ | Width (ub, db) (MeV) | B.R. (ub, db) (%) |
|---------------|-------------|-------------|---------------|---------------------|-----------------|
| $B(4^3S_1)$  | $B\gamma$ | 5312        | $|\langle 1^1 S_0 | j_0(kr\frac{m_u-m_d}{m_u+m_d})|4^3S_1 \rangle = 0.08966, 0.01881|$ | 0.345, 0.0886 | 0.24, 0.062 |
| $B(2^1 S_0)\gamma$ | 5904 | $(2^1 S_0 | j_0(kr\frac{m_u-m_d}{m_u+m_d})|4^3S_1 \rangle = 0.1566, 0.02310$ | 0.231, 0.0588 | 0.16, 0.041 |
| $B(3^3 S_0)\gamma$ | 6335 | $(3^3 S_0 | j_0(kr\frac{m_u-m_d}{m_u+m_d})|4^3S_1 \rangle = 0.2751, 0.05201$ | 0.0770, 0.0197 | 0.054, 0.014 |
| $B\pi$ | $^1 P_1 = 0.00820$ | 0.532 | 0.4 |
| $B^*\pi$ | $^3 P_1 = -0.00949$ | 0.665 | 0.5 |
| $B'^{\gamma}$ | $^1 P_1 = -0.00365, ^3 P_1 = 0.0159$ | 1.65 | 1.2 |
| $B'^{\eta'}$ | $^3 P_1 = 0.00522$ | 0.146 | 0.1 |
| $B'^{\omega}$ | $^1 P_1 = -0.00212, ^3 P_1 = 0.00950$ | 0.584 | 0.4 |
| $B(2^1 S_0)\pi$ | $^3 P_1 = -0.0724$ | 4.18 | 2.9 |
| $B(2^1 S_0)\rho$ | $^3 P_1 = -0.0638$ | 0.901 | 0.6 |
| $B(2^1 S_0)\omega$ | $^3 P_1 = -0.0316$ | 2.90 | 2.0 |
| $B(2^3 S_0)\pi$ | $^3 P_1 = 0.0129$ | 0.354 | 0.2 |
| $B(2^3 S_0)\rho$ | $^3 P_1 = 0.0662$ | 3.11 | 2.2 |
| $B(2^3 S_0)\omega$ | $^3 P_1 = -0.0984$ | 6.11 | 4.3 |
| $B(1^3 P_0)\rho$ | $^3 S_1 = -0.0111 i$ | 0.310 | 0.2 |
| $B(1^3 P_0)\pi$ | $^3 S_1 = -1.40 \times 10^{-5} i, ^3 D_1 = 0.0132 i$ | 0.699 | 0.5 |
| $B(1^3 P_0)\eta$ | $^3 S_1 = 0.00152 i, ^3 D_1 = 0.0313 i, ^5 D_1 = -0.0543 i$ | 9.11 | 6.4 |
| $B(1^3 P_0)\omega$ | $^3 S_1 = 0.000742 i, ^3 D_1 = -0.00764 i$ | 0.198 | 0.1 |
| $B(1^3 P_1)\rho$ | $^3 S_1 = 0.000723 i, ^3 D_1 = 0.0181 i, ^5 D_1 = -0.0313 i$ | 2.97 | 2.1 |
| $B(1^3 P_1)\pi$ | $^3 S_1 = -0.00505 i, ^3 D_1 = 0.00166 i, ^5 D_1 = -0.0053 i$ | 0.228 | 0.2 |
| $B(1^3 P_1)\eta$ | $^3 S_1 = -0.00721 i, ^3 D_1 = -0.000505 i$ | 0.172 | 0.1 |
| $B(1^3 P_1)\omega$ | $^5 D_1 = -0.0128 i$ | 0.639 | 0.4 |
| $B(1^3 P_1)\rho$ | $^3 D_1 = -0.0170 i, ^5 D_1 = -0.0219 i, ^7 D_1 = 0.104 i$ | 24.4 | 17.1 |
| $B(1^3 P_1)\pi$ | $^5 D_1 = 0.0109 i$ | 0.382 | 0.3 |
| $B(1^3 P_1)\omega$ | $^5 D_1 = -0.00972 i, ^7 D_1 = -0.0125 i, ^7 D_1 = 0.0594 i$ | 7.79 | 5.4 |
| $B(2^3 P_0)\pi$ | $^3 S_1 = -0.00162 i, ^3 D_1 = 0.110 i$ | 16.0 | 11.2 |
| $B(2^3 P_0)\eta$ | $^3 S_1 = 0.0192 i, ^3 D_1 = 0.00504 i$ | 0.465 | 0.3 |
| $B(2^3 P_0)\omega$ | $^5 D_1 = -0.116 i$ | 16.9 | 11.8 |
| $B(1^3 D_2)\rho$ | $^5 P_1 = -0.00264, ^5 F_1 = -0.0820$ | 12.7 | 8.9 |
| $B(1^3 D_2)\pi$ | $^5 P_1 = 0.0161, ^5 F_1 = -0.000409$ | 0.153 | 0.1 |
| $B(1^3 D_2)\eta$ | $^7 F_1 = 0.0836$ | 12.7 | 8.9 |
| $B(1^3 D_2)\omega$ | $^5 P_1 = 0.00109, ^5 F_1 = 0.0225$ | 0.158 | 0.1 |
| $B'^{\gamma}$ | $^3 P_1 = 0.00658$ | 0.271 | 0.2 |
| $B'^{K}$ | $^3 P_1 = 0.0481$ | 4.02 | 2.8 |
| $B_1(2^1 S_0)K$ | $^3 S_1 = -0.000496 i, ^3 D_1 = -0.0282 i$ | 2.29 | 1.6 |
| $B_1(2^3 S_0)K$ | $^3 S_1 = -0.0122 i, ^3 D_1 = 0.00265 i$ | 0.446 | 0.3 |
| $B_1(1^3 P_0)K$ | $^5 D_1 = 0.0344 i$ | 3.23 | 2.3 |
| Total | | | 142.9, 142.4 | 100 |
TABLE VII: Partial widths and branching ratios for strong and electromagnetic decays of the $4^1 S_0$ $B$ meson. See the caption to Table IV for further explanations.

| Initial state   | Final state | $M_f$ (MeV) | $\mathcal{M}$ | Width $(ub, \, db)$ (MeV) | B.R. $(ub, \, db)$ (%) |
|-----------------|-------------|-------------|---------------|--------------------------|------------------------|
| $B(4^1 S_0)$ $B^* \gamma$ | $5371$ | $\langle 1^3 S_1 | j_0 (kr \frac{m_q + m_b}{m_q + m_b}) | 4^1 S_0 \rangle = 0.03513, -0.01534$ | $0.141, 0.0333$ | $0.10, 0.024$ |
| $6689$ $B(2^3 S_1) \gamma$ | $5933$ | $\langle 2^3 S_1 | j_0 (kr \frac{m_q + m_b}{m_q + m_b}) | 4^1 S_0 \rangle = 0.09121, -0.02470$ | $0.204, 0.0493$ | $0.15, 0.035$ |
| $B(3^3 S_1) \gamma$ | $6355$ | $\langle 3^3 S_1 | j_0 (kr \frac{m_q + m_b}{m_q + m_b}) | 4^1 S_0 \rangle = 0.1852, -0.04902$ | $0.0801, 0.0193$ | $0.057, 0.014$ |
| $B\rho$ | $3P_0 = 0.00728$ | | | $2.31$ | $0.11$ |
| $B^*\pi$ | $3P_0 = -0.00899$ | | | $2.2$ | $0.11$ |
| $B^*\rho$ | $3P_0 = -0.00899$ | | | $2.2$ | $0.11$ |
| $B^*\eta'$ | $3P_0 = 0.00691$ | | | $2.2$ | $0.11$ |
| $B^*\omega$ | $3P_0 = -0.0110$ | | | $2.2$ | $0.11$ |
| $B(2^1 S_0)\rho$ | $3P_0 = 0.0648$ | | | $2.2$ | $0.11$ |
| $B(2^1 S_0)\pi$ | $3P_0 = -0.0353$ | | | $2.2$ | $0.11$ |
| $B(2^1 S_1)\eta$ | $3P_0 = 0.0205$ | | | $2.2$ | $0.11$ |
| $B(3^1 S_0)\pi$ | $3P_0 = 0.123$ | | | $2.2$ | $0.11$ |
| $B(1^1 P_0)\eta$ | $^1S_0 = -0.00649 i$ | | | $2.2$ | $0.11$ |
| $B(1^1 P_1)\rho$ | $^1S_0 = -0.000986 i, \, ^5D_0 = 0.0798 i$ | | | $2.2$ | $0.11$ |
| $B(1^1 P_1)\omega$ | $^1S_0 = -0.00330 i, \, ^5D_0 = 0.0457 i$ | | | $2.2$ | $0.11$ |
| $B(1^3 P_0)\pi$ | $^5D_0 = 0.117 i$ | | | $2.2$ | $0.11$ |
| $B(1^3 P_0)\rho$ | $^5D_0 = -0.0942 i$ | | | $2.2$ | $0.11$ |
| $B(1^3 P_0)\eta$ | $^5D_0 = 0.0192 i$ | | | $2.2$ | $0.11$ |
| $B(1^3 P_2)\omega$ | $^5D_0 = -0.0534 i$ | $5^3S_0 = 0.0174 i$ | | $2.2$ | $0.11$ |
| $B(1^3 P_2)\pi$ | $^5D_0 = -0.167 i$ | | | $2.2$ | $0.11$ |
| $B(1^3 D_1)\eta$ | $3P_0 = 0.163$ | | | $2.2$ | $0.11$ |
| $B(1^3 D_3)\pi$ | $7P_0 = 0.126$ | | | $2.2$ | $0.11$ |
| $B(1^3 F_1)\pi$ | $^9G_0 = -0.0166 i$ | | | $2.2$ | $0.11$ |
| $B^* K$ | $3P_0 = 0.00876$ | | | $2.2$ | $0.11$ |
| $B_s (2^3 S_1) K$ | $3P_0 = 0.0658$ | | | $2.2$ | $0.11$ |
| $B_s (1^1 P_0) K$ | $1^3S_0 = -0.0110 i$ | | | $2.2$ | $0.11$ |
| $B_s (1^3 P_2) K$ | $^5D_0 = 0.0531 i$ | | | $2.2$ | $0.11$ |
| **Total** | | | | $140.0, 139.7$ | $100$ |
TABLE VIII: Partial widths and branching ratios for strong and electromagnetic decays of the $1P$ and $2P$ $B$ mesons. See the caption to Table IV for further explanations.

| Initial state | Final state | $M_f$ (MeV) | $\mathcal{M}$ | Width (ub, db) | B.R. (ub, db) |
|---------------|-------------|-------------|--------------|---------------|--------------|
| $B(1^3P_0)$  | $B^*\gamma$ | 5371        | $\langle 1^3S_1 | r^1P_0 \rangle = 2.234$ | 0.325, 0.0927 | 0.21, 0.060 |
| 5756          | $B\pi$     | $^3S_0 = -0.390$ i | 154         | ~ 100         |
|               | Total       |             |              | 154           | 100          |
| $B(1^1P_1)$  | $B\gamma$  | 5312        | $\langle 1^3S_0 | r^1P_1 \rangle = 2.110$ | 0.373, 0.106  | 5.1, 1.5    |
| 5777          | $B^*\gamma$| 5371        | $\langle 1^3S_1 | r^3P_1 \rangle = 2.249$ | 0.0975, 0.0278 | 1.3, 0.40   |
|               | $B^*\pi$   | $^3S_1 = 0.0419$ i, $^3D_1 = 0.0792$ i | 6.80       | 93.6, 98.1 |
|               | Total       |             |              | 7.27, 6.93    | 100          |
| $B(1^3P_2)$  | $B^*\gamma$| 5371        | $\langle 1^3S_1 | r^3P_2 \rangle = 2.258$ | 0.300, 0.0855 | 0.18, 0.053 |
| 5797          | $B\pi$     | $^1D_2 = -0.0721$ i | 6.23        | 53.2, 54.7 |
|               | $B^*\pi$   | $^3D_2 = 0.0736$ i | 5.04       | 43.0, 44.2 |
|               | Total       |             |              | 163           | 100          |
| $B(2^3P_0)$  | $B^*\gamma$| 5371        | $\langle 1^3S_1 | r^2P_0 \rangle = -0.3303$ | 0.0667, 0.0190 | 0.036, 0.010 |
| 6213          | $B(2^3S_1)\gamma$ | 5933     | $\langle 2^3S_1 | r^2P_0 \rangle = 3.453$ | 0.309, 0.0881 | 0.17, 0.047 |
| $B(1^3D_1)\gamma$ | 6110     | $\langle 1^3D_1 | r^2P_0 \rangle = -2.441$ | 0.0161, 0.00459 | 0.0086, 0.0025 |
| $B\pi$       | $^1S_0 = -0.0720$ i | 19.5      | 10.5        |
| $B^*\rho$    | $^1S_0 = 0.138$ i, $^5D_0 = -0.0867$ i | 36.8    | 19.8        |
| $B^*\omega$  | $^1S_0 = 0.0832$ i, $^5D_0 = -0.0455$ i | 11.8   | 6.3         |
| $B(2^1S_0)\pi$ | $^1S_0 = -0.181$ i | 16.0    | 8.6         |
| $B(1^1P_1)\pi$ | $^3P_0 = 0.307$ | 93.2    | 50.0        |
| $B(1^3P_0)\pi$ | $^3P_0 = -0.0179$ | 0.308  | 0.2         |
| $B^*K$       | $^1S_0 = 0.0572$ i | 8.61   | 4.6         |
|               | Total       |             |              | 186.6, 186.3  | 100          |
| $B(2^1P_1)$  | $B^*\gamma$ | 5371        | $\langle 1^3S_1 | r^2P_1 \rangle = -0.2030$ | 0.00681, 0.00194 | 0.0036, 0.0010 |
| 6197          | $B(2^3S_0)\gamma$ | 5904     | $\langle 2^3S_0 | r^2P_1 \rangle = 3.134$ | 0.208, 0.0594 | 0.11, 0.032 |
| $B(2^3S_1)\gamma$ | 5933     | $\langle 2^3S_1 | r^2P_1 \rangle = 3.361$ | 0.0705, 0.0201 | 0.038, 0.011 |
| $B(1^3D_2)\gamma$ | 6095     | $\langle 1^3D_2 | r^2P_1 \rangle = -2.507, \langle 1^1D_2 | r^2P_1 \rangle = -2.506$ | 0.0148, 0.00422 | 0.0079, 0.0022 |
| $B^*\rho$    | $^3S_1 = -0.138$ i, $^3D_1 = -0.0269$ i | 36.9    | 19.7        |
| $B^*\omega$  | $^3S_1 = -0.0842$ i, $^3D_1 = -0.0148$ i | 13.2   | 7.0         |
| $B^*\pi$     | $^3S_1 = 0.00459$ i, $^3D_1 = -0.131$ i | 55.7   | 29.7        |
| $B^*\eta$    | $^3S_1 = 0.169$ i, $^3D_1 = 0.0401$ i, $^5D_1 = -0.0311$ i | 37.2   | 19.8        |
| $B^*\omega$  | $^3S_1 = 0.020026$ i, $^3D_1 = -0.0499$ i | 6.25   | 3.3         |
| $B^*\pi$     | $^3S_1 = 0.102$ i, $^3D_1 = 0.0202$ i, $^5D_1 = -0.0157$ i | 12.3   | 6.6         |
| $B(2^3S_1)\pi$ | $^3S_1 = 0.0144$ i, $^3D_1 = 0.0420$ i | 0.681  | 0.4         |
| $B(1^1P_0)\pi$ | $^1P_1 = -0.0484$ | 2.36   | 1.3         |
| $B(1^3P_1)\pi$ | $^3P_1 = -0.0807$ | 5.98   | 3.2         |
| $B(1^3P_0)\pi$ | $^3P_1 = -0.0356$ | 1.12   | 0.6         |
| $B(1^3P_2)\pi$ | $^5P_1 = -0.0574, ^5P_1 = -0.0499$ | 4.82   | 2.6         |
| $B^*K$       | $^3S_1 = -0.00258$ i, $^3D_1 = -0.0717$ i | 10.9   | 5.8         |
|               | Total       |             |              | 187.6, 187.4  | 100          |
| Initial state | Final state | \( M_f \) (MeV) | \( M \) | Width (ub, \( db \)) | B.R. (ub, \( db \)) |
|---------------|-------------|----------------|----------|---------------------|--------------------|
| \( B(2P')_\gamma \) | \( B^* \gamma \) | 5371 | \( \langle 1^3 S_1 | r | 2^3 P_1 \rangle = -0.2030 \) | 0.0189, 0.00538 | 0.0094, 0.0027 |
| \( B(2^3 S_0)_\gamma \) | 5904 | \( \langle 2^1 S_0 | r | 2^1 P_1 \rangle = 3.134 \) | 0.111, 0.0316 | 0.055, 0.016 |
| \( B(2^3 S_1)_\gamma \) | 5933 | \( \langle 2^1 S_1 | r | 2^1 P_1 \rangle = 3.361 \) | 0.243, 0.0692 | 0.12, 0.034 |
| \( B(1^3 D_1)_\gamma \) | 6110 | \( \langle 1^3 D_1 | r | 2^3 P_1 \rangle = -2.270 \) | 0.00368, 0.00105 | 0.0018, 0.00052 |
| \( B(1D'\_2)_\gamma \) | 6124 | \( \langle 1^3 D_2 | r | 2^3 P_1 \rangle = -2.507, \langle 1^1 D_2 | r | 2^3 P_1 \rangle = 2.506 \) | 0.0139, 0.00396 | 0.0069, 0.0020 |
| \( B(2^3 S_1)_\pi \) | | \( 3^3 S_1 = -0.0461 \, i, \, 3^3 D_1 = 0.0788 \, i \) | 18.1 | 9.0 |
| \( B(1^3 P_0)_\pi \) | | \( 3^1 P_1 = 0.0257 \) | 0.760 | 0.4 |
| \( B(1^3 P_1)_\pi \) | | \( 3^1 P_1 = -0.125 \) | 16.4 | 8.1 |
| \( B(1^3 P_2)_\pi \) | | \( 3^3 P_1 = 0.0483 \) | 2.38 | 1.2 |
| \( B(2^3 S_1)_\pi \) | | \( 3^3 S_1 = 0.0684 \, i, \, 3^3 D_1 = -0.00456 \, i \) | 17.4 | 8.6 |
| Total | | | 202.1, 201.8 | 100 |
| \( B(2^3 P_2)_\pi \) | | \( \langle 2^3 S_1 | r | 2^3 P_2 \rangle = 3.156 \) | 0.258, 0.0736 | 0.13, 0.037 |
| \( B(1^3 D_3)_\gamma \) | 6106 | \( \langle 1^3 D_3 | r | 2^3 P_2 \rangle = -2.544 \) | 0.0165, 0.00472 | 0.0083, 0.0024 |
| \( B(2^3 S_0)_\eta \) | | \( 1^3 P_1 = 0.00983 \, i, \, 5^3 S_2 = -0.234 \, i, \, 5^3 D_2 = -0.0496 \, i \) | 79.8 | 40.1 |
| \( B(1^3 P_0)_\eta \) | | \( 3^3 P_1 = -0.0394 \, i \) | 29.0 | 14.6 |
| Total | | | 199.2, 199.0 | 100 |
TABLE X: Partial widths and branching ratios for strong decays of the $3^3P_0$ $B$ meson. See the caption to Table IV for further explanations.

| Initial state | Final state | $\mathcal{M}$ | Width (MeV) | B.R. (%) |
|---------------|-------------|----------------|-------------|----------|
| $B(3^3P_0)$  | $B\pi$      | $^1S_0 = -0.0192 \, i$ | 2.49        | 1.5      |
| 6576          | $B\eta'$    | $^1S_0 = 0.0124 \, i$ | 0.707       | 0.4      |
| $B^*\rho$     | $^3S_0 = 0.0164 \, i, \, ^3D_0 = 0.0234 \, i$ | 4.04         | 2.4        |
| $B^*\omega$   | $^1S_0 = 0.00966 \, i, \, ^3D_0 = 0.0145 \, i$ | 1.50         | 0.9        |
| $B(2^1S_0)\pi$ | $^1S_0 = -0.0667 \, i$ | 10.1         | 6.0        |
| $B(2^1S_0)\eta$ | $^1S_0 = 0.0279 \, i$ | 1.07         | 0.6        |
| $B(3^1S_0)\pi$ | $^1S_0 = -0.130 \, i$ | 4.70         | 2.8        |
| $B(1^3P_0)\rho$ | $^3P_0 = 0.0473$ | 2.50         | 1.5        |
| $B(1^3P_0)\omega$ | $^3P_0 = 0.0262$ | 0.702        | 0.4        |
| $B(1^1P_1)\pi$ | $^3P_0 = 0.0248$ | 1.90         | 1.1        |
| $B(1^1P_1)\rho$ | $^3P_0 = 0.0752$ | 4.55         | 2.7        |
| $B(1^1P_1)\eta$ | $^3P_0 = -0.0335$ | 2.63         | 1.6        |
| $B(1^1P_1)\omega$ | $^3P_0 = 0.0378$ | 0.960        | 0.6        |
| $B(2^1P_1)\pi$ | $^3P_0 = -0.00824$ | 0.207        | 0.1        |
| $B(2^1P_1)\rho$ | $^3P_0 = 0.0576$ | 2.25         | 1.4        |
| $B(1^1P_1)\eta$ | $^3P_0 = 0.00857$ | 0.168        | 0.1        |
| $B(1^1P_1)\omega$ | $^3P_0 = 0.0264$ | 0.359        | 0.2        |
| $B(2^1P_1)\pi$ | $^3P_0 = 0.231$ | 40.2         | 24.1       |
| $B(2^1P_1)\pi$ | $^3P_0 = -0.0257$ | 0.416        | 0.2        |
| $B(1^1D_2)\pi$ | $^3D_0 = 0.189 \, i$ | 43.0         | 25.8       |
| $B(1^1D_2)\pi$ | $^5D_0 = -0.0260 \, i$ | 0.722        | 0.4        |
| $B_sK$        | $^1S_0 = 0.0151 \, i$ | 1.28         | 0.8        |
| $B_s^K*$      | $^1S_0 = 0.00336 \, i, \, ^5D_0 = 0.0479 \, i$ | 8.23         | 4.9        |
| $B_s(2^1S_0)K$ | $^1S_0 = 0.108 \, i$ | 12.2         | 7.3        |
| $B_s(1^1P_1)K$ | $^3P_0 = -0.0938$ | 17.0         | 10.2       |
| $B_s(1^1P_1)'K$ | $^3P_0 = 0.0383$ | 2.79         | 1.7        |
| Total         |              |               | 166.8       | 100      |
TABLE XI: Partial widths and branching ratios for strong decays of the $3P_1$ B meson. See the caption to Table IV for further explanations.

| Initial state | Final state | $\mathcal{M}$ | Width (MeV) | B.R. (%) |
|---------------|-------------|----------------|-------------|----------|
| $B(3P_1)$    | $B\rho$    | $^3S_1 = -0.0154 i, ^3D_1 = 0.000314 i$ | 1.26 | 1.4 |
|              | $B\omega$  | $^3S_1 = -0.00924 i, ^3D_1 = 0.000372 i$ | 0.453 | 0.5 |
|              | $B^*\pi$   | $^3S_1 = 0.00147 i, ^3D_1 = -0.0287 i$ | 5.01 | 5.4 |
|              | $B^*\rho$  | $^3S_1 = 0.0185 i, ^3D_1 = -0.013 i, ^5D_1 = 0.0107 i$ | 2.99 | 3.2 |
|              | $B^*\eta$  | $^3S_1 = 8.17 \times 10^{-5} i, ^3D_1 = -0.00482 i$ | 0.128 | 0.1 |
|              | $B^*\eta'$ | $^3S_1 = -0.000739 i, ^3D_1 = 0.0153 i$ | 0.886 | 1.0 |
|              | $B^*\omega$| $^3S_1 = 0.0109 i, ^3D_1 = -0.00807 i, ^5D_1 = 0.00663 i$ | 1.09 | 1.2 |
|              | $B(2^3S_1)\pi$ | $^3S_1 = 0.00403 i, ^3D_1 = -0.0959 i$ | 18.2 | 19.5 |
|              | $B(2^3S_1)\eta$ | $^3S_1 = -0.00350 i, ^3D_1 = -0.0276 i$ | 0.777 | 0.8 |
|              | $B(2^3S_1)\pi$ | $^3S_1 = 0.0125 i, ^3D_1 = 0.0227 i$ | 0.119 | 0.1 |
|              | $B(1^3P_0)\pi$ | $^1P_1 = -0.00789$ | 0.193 | 0.2 |
|              | $B(1^3P_0)\rho$ | $^3P_1 = 0.0210$ | 0.365 | 0.4 |
|              | $B(1^3P_0)\eta$ | $^3P_1 = 0.00817$ | 0.157 | 0.2 |
|              | $B(1^3P_0)\pi$ | $^3P_1 = 0.00836$ | 0.164 | 0.2 |
|              | $B(1^1P_1)\eta$ | $^3P_1 = 0.00842$ | 0.118 | 0.1 |
|              | $B(1^3P_2)\pi$ | $^5P_1 = -0.0446, ^5F_1 = 0.105$ | 31.4 | 33.6 |
|              | $B(1^3P_2)\eta$ | $^5P_1 = 0.00789, ^5F_1 = 0.0305$ | 2.03 | 2.2 |
|              | $B(1^3P_0)\pi$ | $^1P_1 = -0.0451$ | 1.25 | 1.3 |
|              | $B(2^3P_2)\pi$ | $^3P_1 = -0.0633$ | 2.70 | 2.9 |
|              | $B(2^3P_2)\eta$ | $^3P_1 = -0.0294$ | 0.486 | 0.5 |
|              | $B(2^3P_0)\pi$ | $^5P_1 = -0.0468, ^5F_1 = -0.0512$ | 2.96 | 3.2 |
|              | $B(1^3D_1)\pi$ | $^3S_1 = -0.00109 i, ^3D_1 = -0.0179 i$ | 0.335 | 0.4 |
|              | $B(1^1D_2)\pi$ | $^5D_1 = -0.0558 i$ | 3.47 | 3.7 |
|              | $B(1^3D_2)\pi$ | $^5D_1 = -0.0149 i$ | 0.218 | 0.2 |
|              | $B(1^3D_3)\pi$ | $^7D_1 = -0.0465 i, ^7G_1 = -0.0365 i$ | 3.72 | 4.0 |
|              | $B_sK^*$  | $^3S_1 = -0.00885 i, ^3D_1 = 0.00829 i$ | 0.581 | 0.6 |
|              | $B_s^*K^*$ | $^3S_1 = -0.00882 i, ^3D_1 = 0.0137 i$ | 0.935 | 1.0 |
|              | $B_s(2^3S_1)K$ | $^3S_1 = -0.00994 i, ^3D_1 = -0.0298 i$ | 0.670 | 0.7 |
|              | $B_s(1^3P_0)K$ | $^1P_1 = 0.0237$ | 1.12 | 1.2 |
|              | $B_s(1^3P_1)K$ | $^3P_1 = 0.0267$ | 1.28 | 1.4 |
|              | $B_s(1^3P_1)K$ | $^5P_1 = 0.0202, ^5F_1 = 0.0352$ | 2.74 | 2.9 |
|               | Total      |                | 93.4 | 100 |
TABLE XII: Partial widths and branching ratios for strong decays of the $3P_1^0$ $B$ meson. See the caption to Table [IV] for further explanations.

| Initial state | Final state | $\mathcal{M}$ | Width (MeV) | B.R. (%) |
|---------------|-------------|---------------|-------------|---------|
| $B(3P_1^0)$ | $B\rho$ | $3S_1 = -0.00553$ i, $3D_1 = 0.00242$ i | 0.204 | 0.1 |
| | $B^*\pi$ | $3S_1 = -0.0187$ i, $3D_1 = 0.00187$ i | 2.23 | 1.3 |
| | $B^*\rho$ | $3S_1 = -0.00976$ i, $3D_1 = 0.00456$ i, $5D_1 = 0.0106$ i | 1.15 | 0.7 |
| | $B^*\eta'$ | $3S_1 = 0.0131$ i, $3D_1 = 0.00114$ i | 0.707 | 0.4 |
| | $B^*\omega$ | $3S_1 = -0.00582$ i, $3D_1 = 0.00299$ i, $5D_1 = 0.00682$ i | 0.447 | 0.2 |
| | $B(2^3S_1)\pi$ | $3S_1 = -0.0659$ i, $3D_1 = -0.00616$ i | 9.40 | 5.4 |
| | $B(2^3S_1)\eta$ | $3S_1 = 0.0383$ i, $3D_1 = -0.00224$ i | 1.81 | 1.0 |
| | $B(3^3S_1)\pi$ | $3S_1 = -0.142$ i, $3D_1 = 0.00193$ i | 5.05 | 2.9 |
| | $B(1^3P_0)\rho$ | $3P_1 = 0.0400$ | 1.99 | 1.1 |
| | $B(1^3P_0)\omega$ | $3P_1 = 0.0226$ | 0.589 | 0.3 |
| | $B(1P_1)\pi$ | $3P_1 = -0.0120$ | 0.458 | 0.3 |
| | $B(1P_1)\rho$ | $1P_1 = -0.00515$, $3P_1 = -0.0429$, $5P_1 = 0.0369$, $5F_1 = -0.00939$ | 3.17 | 1.8 |
| | $B(1P_1)\eta$ | $3P_1 = 0.0109$ | 0.286 | 0.2 |
| | $B(1P_1)\omega$ | $1P_1 = -0.00276$, $3P_1 = -0.0229$, $5P_1 = 0.0197$, $5F_1 = -0.00384$ | 0.790 | 0.4 |
| | $B(1P_2)\pi$ | $3P_1 = -0.00982$ | 0.300 | 0.2 |
| | $B(1P_2)\rho$ | $1P_1 = 0.0396$, $3P_1 = 0.0509$, $5P_1 = 0.00286$, $5F_1 = -0.00076$ | 3.53 | 2.0 |
| | $B(1P_2)\eta$ | $3P_1 = 0.00905$ | 0.193 | 0.1 |
| | $B(1P_2)\omega$ | $1P_1 = 0.0204$, $3P_1 = 0.0262$, $5P_1 = 0.00146$, $5F_1 = -0.00137$ | 0.797 | 0.4 |
| | $B(2^3P_2)\pi$ | $5P_1 = 0.0273$, $5F_1 = 0.00756$ | 2.43 | 1.4 |
| | $B(2^3P_2)\rho$ | $3P_1 = 0.0145$, $5P_1 = 0.0658$, $5F_1 = 0.00873$, $7F_1 = -0.00309$ | 2.69 | 1.5 |
| | $B(2^3P_2)\eta$ | $5P_1 = -0.00323$, $5F_1 = 0.00235$ | 2.37 | 1.4 |
| | $B(2^3P_2)\omega$ | $3P_1 = 0.00589$, $5P_1 = 0.0267$, $5F_1 = 0.000157$, $7F_1 = 0.000556$ | 0.298 | 0.2 |
| | $B(2^3P_2)\eta$ | $3P_1 = -0.0229$ | 0.379 | 0.2 |
| | $B(2^3P_2)\pi$ | $3P_1 = -0.0960$ | 7.26 | 4.2 |
| | $B(2^3P_2)\rho$ | $3P_1 = -0.0399$ | 1.06 | 0.6 |
| | $B(2^3P_2)\omega$ | $3P_1 = 0.212$, $5F_1 = -0.0392$ | 32.6 | 18.6 |
| | $B(1^3D_1)_3\pi$ | $3S_1 = 0.000422$ i, $3D_1 = 0.0204$ i | 0.492 | 0.3 |
| | $B(1^3D_1)_5\pi$ | $5D_1 = -0.0918$ i | 10.5 | 6.0 |
| | $B(1^3D_1)_5\rho$ | $5D_1 = -0.0222$ i | 0.549 | 0.3 |
| | $B(1^3D_2)_7\pi$ | $7D_1 = 0.178$ i, $7G_1 = -0.00288$ i | 37.9 | 21.7 |
| | $B_1K^*$ | $3S_1 = -0.00477$ i, $3D_1 = -0.0198$ i | 1.75 | 1.0 |
| | $B_1K^*$ | $3S_1 = 0.0168$ i, $3D_1 = 0.00116$ i | 1.47 | 0.8 |
| | $B_1K^*$ | $3S_1 = -0.00367$ i, $3D_1 = 0.0159$ i, $5D_1 = 0.0326$ i | 4.87 | 2.8 |
| | $B_1(2^3S_1)K$ | $3S_1 = 0.128$ i, $3D_1 = -0.00291$ i | 14.8 | 8.5 |
| | $B_1(1^3P_0)K$ | $1P_1 = -0.0118$ | 0.302 | 0.2 |
| | $B_1(1P_1)K$ | $3P_1 = 0.0384$ | 2.96 | 1.7 |
| | $B_1(1P_2)K$ | $3P_1 = 0.0208$ | 0.854 | 0.5 |
| | $B_1(2^3P_2)K$ | $5P_1 = -0.0923$, $5F_1 = 0.00290$ | 15.9 | 9.1 |
| Total | | | 174.8 | 100 |
TABLE XIII: Partial widths and branching ratios for strong decays of the $3^3P_2$ B meson. See the caption to Table IV for further explanations.

| Initial state | Final state | $\mathcal{M}$ | Width (MeV) | B.R. (%) |
|---------------|-------------|---------------|-------------|----------|
| $B(3^3P_2)$  | $B\pi$      | $^1D_2 = 0.0194 \ i$ | 2.52       | 2.9      |
| 6570          | $B\eta$     | $^1D_2 = 0.00563 \ i$ | 0.194      | 0.2      |
|               | $B\eta'$    | $^1D_2 = -0.00459 \ i$ | 0.0961     | 0.1      |
|               | $B^*\pi$    | $^3D_2 = -0.0241 \ i$ | 3.60       | 4.1      |
|               | $B^*\rho$   | $^1D_2 = -0.00218 \ i, ^5S_2 = -0.0239 \ i, ^5D_2 = 0.00576 \ i$ | 2.99       | 3.4      |
|               | $B^*\eta$   | $^3D_2 = -0.00548 \ i$ | 0.169      | 0.2      |
|               | $B^*\eta'$  | $^3D_2 = 0.00974 \ i$ | 0.371      | 0.4      |
|               | $B^*\omega$ | $^1D_2 = -0.00146 \ i, ^5S_2 = -0.0143 \ i, ^5D_2 = 0.00387 \ i$ | 1.08       | 1.2      |
|               | $B(2^1S_0)\pi$ | $^1D_2 = 0.0515 \ i$ | 5.89       | 6.7      |
|               | $B(2^3S_0)\pi$ | $^1D_2 = 0.0223 \ i$ | 0.662      | 0.8      |
|               | $B(2^3S_1)\eta$ | $^3D_2 = -0.00696 \ i$ | 9.92       | 11.3     |
|               | $B(2^3S_1)\pi$ | $^3D_2 = -0.0238 \ i$ | 0.625      | 0.7      |
|               | $B(3^3S_0)\pi$ | $^1D_2 = -0.0238 \ i$ | 0.148      | 0.2      |
|               | $B(3^3S_1)\pi$ | $^3D_2 = 0.0226 \ i$ | 0.107      | 0.1      |
|               | $B(1^3P_0)\rho$ | $^3P_2 = 0.0417 \ i$ | 1.79       | 2.0      |
|               | $B(1^3P_0)\omega$ | $^3P_2 = 0.0227 \ i$ | 0.481      | 0.5      |
|               | $B(1^3P_1)\pi$ | $^3P_2 = 0.00463, ^3F_2 = -0.0650$ | 13.0       | 14.8     |
|               | $B(1^3P_1)\rho$ | $^3P_2 = 0.000502, ^3F_2 = 0.00184, ^5P_2 = -0.0339, ^5F_2 = -0.00260$ | 0.800      | 0.9      |
|               | $B(1^3P_1)\eta$ | $^3P_2 = -0.00362, ^3F_2 = -0.0218$ | 1.12       | 1.3      |
|               | $B(1^3P_1)\omega$ | $^3P_2 = 0.000221, ^3F_2 = 0.000497, ^5P_2 = -0.0158, ^5F_2 = -0.000703$ | 0.133      | 0.2      |
|               | $B(1^3P_2)\pi$ | $^3P_2 = -0.0104, ^3F_2 = -0.00408$ | 0.376      | 0.4      |
|               | $B(1^3P_2)\rho$ | $^3P_2 = 0.0432, ^3F_2 = 4.97 \times 10^{-5}, ^5P_2 = -0.000832, ^5F_2 = -7.03 \times 10^{-5}$ | 1.01       | 1.2      |
|               | $B(1^3P_2)\eta$ | $^3P_2 = 0.0104, ^3F_2 = -0.00123$ | 0.248      | 0.3      |
|               | $B(1^3P_2)\pi$ | $^3P_2 = -0.00928, ^3F_2 = 0.0620$ | 11.5       | 13.1     |
|               | $B(3^3P_1)\pi$ | $^5P_2 = 0.0108, ^5F_2 = 0.0197$ | 1.08       | 1.2      |
|               | $B(2^1P_1)\pi$ | $^3P_2 = 0.0258, ^3F_2 = 0.0479$ | 2.15       | 2.4      |
|               | $B(2^1P_1)\rho$ | $^3P_2 = -0.0534, ^3F_2 = 0.00170$ | 1.74       | 2.0      |
|               | $B(2^1P_2)\pi$ | $^5P_2 = -0.0745, ^5F_2 = -0.0366$ | 4.58       | 5.2      |
|               | $B(1^3D_3)\pi$ | $^3D_2 = 0.0135 \ i$ | 0.202      | 0.2      |
|               | $B(1^3D_2)\pi$ | $^5S_2 = 0.000404 \ i, ^5D_2 = 0.0303 \ i, ^5G_2 = 0.0308 \ i$ | 2.19       | 2.5      |
|               | $B(1^3D_2)\rho$ | $^5S_2 = -0.000462 \ i, ^5D_2 = -0.0204 \ i, ^5G_2 = 0.000290 \ i$ | 0.433      | 0.5      |
|               | $B(1^3D_3)\pi$ | $^7D_2 = -0.0672 \ i, ^7G_2 = -0.0233 \ i$ | 5.70       | 6.5      |
|               | $B_1K^*$     | $^3D_2 = -0.0143 \ i$ | 0.835      | 1.0      |
|               | $B_2'K^*$    | $^3D_2 = 0.00704 \ i$ | 0.251      | 0.3      |
|               | $B_2K$       | $^3D_2 = 0.00704 \ i$ | 0.251      | 0.3      |
|               | $B_2'K^*$    | $^1D_2 = -0.00850 \ i, ^5S_2 = -0.00852 \ i, ^5D_2 = 0.0225 \ i$ | 2.28       | 2.6      |
|               | $B_2(2^1S_0)K$ | $^1D_2 = 0.0292 \ i$ | 0.849      | 1.0      |
|               | $B_2(2^3S_1)K$ | $^3D_2 = -0.0277 \ i$ | 0.601      | 0.7      |
|               | $B_2(1^3P_1)K$ | $^3P_2 = -0.00675, ^3F_2 = -0.0267$ | 1.43       | 1.6      |
|               | $B_2(1^3P_2)K$ | $^3P_2 = 0.0313, ^3F_2 = 0.00250$ | 1.83       | 2.1      |
|               | $B_2(1^3P_2)K$ | $^5P_2 = 0.0302, ^5F_2 = 0.0232$ | 2.54       | 2.9      |
|               | **Total**    |               | **87.7**   | **100**  |
TABLE XIV: Partial widths and branching ratios for strong and electromagnetic decays of the $1D B$ mesons. See the caption to Table [IV] for further explanations.

| Initial state | Final state | $M_f$ (MeV) | $\mathcal{M}$ | Width (ub, db) | B.R. (ub, db) |
|---------------|-------------|-------------|---------------|----------------|---------------|
| $B(1^3D_1)$  | $B(1^3P_0)\gamma$ | 5756 | $(1^3P_0 | r | 1^3D_1) = 2.951$ | 0.297, 0.0847 | 0.15, 0.043 |
| 6110          | $B(1P_1)\gamma$ | 5777 | $(1^3P_1 | r | 1^3D_1) = 3.089$ | 0.0522, 0.0149 | 0.026, 0.0076 |
|               | $B(1P_1')\gamma$ | 5784 | $(1^3P_1 | r | 1^3D_1) = 3.089$ | 0.144, 0.0411 | 0.073, 0.021 |
|               | $B(1^3P_2)\gamma$ | 5797 | $(1^3P_2 | r | 1^3D_1) = 3.295$ | 0.0130, 0.00371 | 0.0066, 0.0019 |
| $B\pi$       | $^3P_1 = 0.140$ | 59.5 | 30.3 |
|               | $^3P_1 = -0.0548$ | 2.30 | 1.2 |
|               | $^1P_1 = 0.0647$ | 9.59 | 4.9 |
|               | $^3P_1 = -0.0264$ | 0.440 | 0.2 |
|               | $^3P_1 = 0.107$ | 30.2 | 15.4 |
|               | $^3P_1 = 0.0463$ | 3.96 | 2.0 |
|               | $^3P_0 = -0.0341$ | 0.215 | 0.1 |
|               | $^3S_1 = -0.330 i, ^3D_1 = -0.0381 i$ | 63.0 | 32.0 |
|               | $^3S_1 = -0.0278 i, ^3D_1 = 0.00191 i$ | 0.425 | 0.2 |
|               | $^3D_1 = -0.0355 i$ | 0.632 | 0.3 |
|               | $^1P_1 = 0.0997$ | 18.7 | 9.5 |
|               | $^3P_1 = 0.0695$ | 7.21 | 3.7 |
| Total         |                   | 196.7, 196.3 | 100 |

| $B(1D_2)$    | $B(1P_1)\gamma$ | 5777 | $(1^3P_1 | r | 1^3D_2) = 3.095, (1^1P_1 | r | 1^3D_2) = 3.163$ | 0.397, 0.113 | 1.7, 0.49 |
| 6095          | $B(1P_1')\gamma$ | 5784 | $(1^3P_1 | r | 1^3D_2) = 3.095, (1^1P_1 | r | 1^3D_2) = 3.163$ | 0.00267, 0.000761 | 0.012, 0.0033 |
|               | $B(1^3P_2)\gamma$ | 5797 | $(1^3P_2 | r | 1^3D_2) = 3.324$ | 0.0422, 0.0120 | 0.18, 0.052 |
|               | $^3P_2 = -0.0597, ^3F_2 = -8.03 \times 10^{-5}$ | 1.57 | 6.8 |
|               | $^3P_2 = 0.00228, ^3F_2 = -0.0889$ | 20.1 | 86.5, 87.7 |
|               | $^3P_2 = 0.00118, ^3F_2 = -0.0134$ | 0.316 | 1.4 |
|               | $^1D_2 = 0.0038 i$ | 0.0415 | 0.2 |
|               | $^3D_2 = 0.0254 i$ | 0.333 | 1.4 |
|               | $^3D_2 = 0.00778 i$ | 0.0300 | 0.1 |
|               | $^5S_2 = -0.0612 i, ^5D_2 = 0.0146 i, ^5G_2 = 0.00237 i$ | 0.115 | 0.5 |
|               | $^3P_2 = 0.00179, ^3F_2 = -0.0129$ | 0.237 | 1.0 |
| Total         |                   | 23.2, 22.9 | 100 |

| $B(1D_2')$   | $B(1P_1)\gamma$ | 5777 | $(1^3P_1 | r | 1^3D_2) = 3.095, (1^1P_1 | r | 1^3D_2) = 3.163$ | 0.0290, 0.00827 | 0.014, 0.0039 |
| 6124          | $B(1P_1')\gamma$ | 5784 | $(1^3P_1 | r | 1^3D_2) = 3.095, (1^1P_1 | r | 1^3D_2) = 3.163$ | 0.433, 0.123 | 0.20, 0.058 |
|               | $B(1^3P_2)\gamma$ | 5797 | $(1^3P_2 | r | 1^3D_2) = 3.324$ | 0.0805, 0.0230 | 0.038, 0.011 |
|               | $^3P_2 = -0.0250, ^3F_2 = 0.00442$ | 0.640 | 0.3 |
|               | $^3P_2 = 0.188, ^3F_2 = -4.40 \times 10^{-5}$ | 96.3 | 45.2 |
|               | $^3P_2 = 0.0848, ^3F_2 = -3.24 \times 10^{-5}$ | 14.1 | 6.6 |
|               | $^3P_2 = -0.0417, ^3F_2 = 1.45 \times 10^{-5}$ | 0.260 | 0.1 |
|               | $^3D_2 = 0.0348 i$ | 0.757 | 0.4 |
|               | $^5S_2 = -0.362 i, ^5D_2 = -0.0507 i, ^5G_2 = 2.94 \times 10^{-5} i$ | 73.8 | 34.6 |
|               | $^3P_2 = 0.130, ^3F_2 = -1.66 \times 10^{-5}$ | 26.8 | 12.6 |
| Total         |                   | 213.4, 213.0 | 100 |

| $B(1^3D_3)$  | $B(1^3P_2)\gamma$ | 5797 | $(1^3P_2 | r | 1^3D_3) = 3.346$ | 0.464, 0.132 | 1.5, 0.43 |
| 6106          | $B\pi$       | $^1F_1 = 0.0694$ | 14.4 | 46.4, 46.9 |
|               | $^1F_3 = 0.0140$ | 0.441 | 1.4 |
|               | $^3F_3 = -0.0737$ | 14.2 | 45.8, 46.3 |
|               | $^3F_3 = -0.0119$ | 0.257 | 0.8 |
|               | $^3D_3 = -0.0142 i, ^3G_3 = -0.00302 i$ | 0.117 | 0.4 |
|               | $^3D_3 = 0.0108 i, ^3G_3 = -0.000187 i$ | 0.0615 | 0.2 |
|               | $^5D_3 = 0.0307 i, ^5G_3 = 0.00189 i$ | 0.460 | 1.5 |
|               | $^3F_3 = 0.0140$ | 0.366 | 1.2 |
|               | $^3F_3 = -0.0116$ | 0.197 | 0.6 |
| Total         |                   | 31.0, 30.7 | 100 |
TABLE XV: Partial widths and branching ratios for strong decays of the $2^3D_1$ $B$ meson. See the caption to Table IV for further explanations.

| Initial state | Final state | $M$ | Width (MeV) | B.R. (%) |
|---------------|-------------|-----|-------------|---------|
| $B(2^3D_1)$  | $B\pi$     | $^1P_1 = 0.0400$ | 9.35 | 4.1 |
| 6475          | $B\eta$    | $^3P_1 = 0.00938$ | 0.465 | 0.2 |
|               | $B\eta'$   | $^3P_1 = -0.0205$ | 1.47 | 0.6 |
|               | $B^*\pi$   | $^3P_1 = 0.0266$ | 3.79 | 1.7 |
|               | $B^*\rho$  | $^1P_1 = -0.0149$, $^5P_1 = 0.00665$, $^5F_1 = 0.104$ | 44.2 | 19.5 |
|               | $B^*\omega$| $^3P_1 = -0.0207$ | 1.22 | 0.5 |
|               | $B(2^1S_0)\pi$ | $^1P_1 = 0.0685$ | 7.82 | 3.4 |
|               | $B(2^1S_0)\eta$ | $^1P_1 = 0.0316$ | 0.502 | 0.2 |
|               | $B(2^3S_1)\pi$ | $^3P_1 = 0.0542$ | 4.44 | 2.0 |
|               | $B(1P_1)\pi$ | $^3S_1 = -0.0507\ i$, $^3D_1 = 0.0822\ i$ | 22.6 | 10.0 |
|               | $B(1P_1)\eta$ | $^3S_1 = 0.0400\ i$, $^3D_1 = 0.0269\ i$ | 3.66 | 1.6 |
|               | $B(1P_1')\pi$ | $^3S_1 = -0.00302\ i$, $^3D_1 = -0.0296\ i$ | 2.10 | 0.9 |
|               | $B(1P_1')\eta$ | $^3S_1 = 0.00331\ i$, $^3D_1 = -0.0122\ i$ | 0.242 | 0.1 |
|               | $B(1^3P_2)\pi$ | $^5D_1 = 0.0875\ i$ | 17.6 | 7.8 |
|               | $B(1^3P_2)\eta$ | $^5D_1 = 0.0261\ i$ | 0.972 | 0.4 |
|               | $B(2P_1)\pi$ | $^3S_1 = -0.198\ i$, $^3D_1 = -0.0367\ i$ | 15.8 | 7.0 |
|               | $B(2P_1)\eta$ | $^5D_1 = 0.0323\ i$ | 0.354 | 0.2 |
|               | $B(1D_4)\pi$ | $^5P_1 = 0.242$, $^5F_1 = 0.0240$ | 44.4 | 19.6 |
|               | $B(1^3D_3)\pi$ | $^7F_1 = 0.0273$ | 0.529 | 0.2 |
|               | $B_sK$      | $^1P_1 = -0.0111$ | 0.582 | 0.2 |
|               | $B_sK^*$    | $^3P_1 = 0.0300$ | 2.78 | 1.2 |
|               | $B_s^*K$    | $^3P_1 = -0.0125$ | 0.663 | 0.3 |
|               | $B_s^*K^*$  | $^1P_1 = -0.0292$, $^5P_1 = 0.0131$, $^5F_1 = 0.0222$ | 3.73 | 1.6 |
|               | $B_s(1P_1)K$ | $^3S_1 = 0.128\ i$, $^3D_1 = 0.0319\ i$ | 21.2 | 9.4 |
|               | $B_s(1P_1')K$ | $^3S_1 = -0.0103\ i$, $^3D_1 = -0.0222\ i$ | 0.714 | 0.3 |
|               | $B_s(1^3P_2)K$ | $^5D_1 = 0.0322\ i$ | 1.12 | 0.5 |
|               | **Total**   |                   | 226.8 | 100 |
TABLE XVI: Partial widths and branching ratios for strong decays of the $2D_2$ $B$ meson. See the caption to Table IV for further explanations.

| Initial state | Final state | $M$ | Width (MeV) | B.R. (%) |
|---------------|-------------|-----|-------------|---------|
| $B(2D_2)$    | $B \rho$    | $^3P_2 = 0.00895, \; ^3F_2 = 0.0127$ | 1.04 | 1.0 |
| $B(2D_2)$    | $B \omega$  | $^3P_2 = 0.00618, \; ^3F_2 = 0.00730$ | 0.390 | 0.4 |
| $B^* \pi$    | $^3P_2 = 0.000507, \; ^3F_2 = 0.0628$ | 20.4 | 19.6 |
| $B^* \rho$   | $^3F_2 = -0.0228, \; ^3F_2 = -0.0519, \; ^5F_2 = 0.0119, \; ^5F_2 = 0.0477$ | 21.1 | 20.3 |
| $B^* \eta$   | $^3P_2 = 0.000429, \; ^3F_2 = 0.0287$ | 3.76 | 3.6 |
| $B^* \eta'$  | $^3P_2 = 0.000660, \; ^3F_2 = 0.0114$ | 0.329 | 0.3 |
| $B^* \omega$ | $^3P_2 = -0.0141, \; ^3F_2 = -0.0296, \; ^5F_2 = 0.00738, \; ^5F_2 = 0.0272$ | 6.92 | 6.7 |
| $B(2^3S_1)\pi$ | $^3P_2 = -0.000203, \; ^3F_2 = -0.0666$ | 6.13 | 5.9 |
| $B(1^3P_0)\pi$ | $^1D_2 = -0.0323 \; i$ | 2.50 | 2.4 |
| $B(1^3P_0)\eta$ | $^1D_2 = -0.0116 \; i$ | 0.209 | 0.2 |
| $B(1^1P_1)\pi$ | $^3D_2 = -0.0477 \; i$ | 5.14 | 5.0 |
| $B(1^1P_1)\eta$ | $^3D_2 = -0.0136 \; i$ | 0.257 | 0.2 |
| $B(1^1P_1')\pi$ | $^3D_2 = -0.0314 \; i$ | 2.19 | 2.1 |
| $B(1^1P_1')\eta$ | $^3D_2 = -0.00986 \; i$ | 0.129 | 0.1 |
| $B(1^3P_2)\pi$ | $^5S_2 = -0.000724 \; i, \; ^5D_2 = -0.0381 \; i, \; ^5G_2 = -0.0644 \; i$ | 12.0 | 11.5 |
| $B(1^3P_2)\eta$ | $^5S_2 = -0.00103 \; i, \; ^5D_2 = -0.00978 \; i, \; ^5G_2 = -0.00386 \; i$ | 0.137 | 0.1 |
| $B(2P_2)\pi$ | $^3D_2 = 0.0209 \; i$ | 0.137 | 0.1 |
| $B(1D_2)\pi$ | $^5F_2 = -0.0517, \; ^5F_2 = -0.0162$ | 1.92 | 1.8 |
| $B(1^3D_3)\pi$ | $^7P_2 = -0.0163, \; ^7F_2 = -0.0135, \; ^7H_2 = -0.00239$ | 0.279 | 0.3 |
| $B_5 K^*$ | $^3P_2 = 0.0473, \; ^3F_2 = 0.00319$ | 6.30 | 6.1 |
| $B^*_5 K$ | $^3P_2 = 0.000934, \; ^3F_2 = 0.0409$ | 6.77 | 6.5 |
| $B^*_5 K^*$ | $^3P_2 = -0.0399, \; ^3F_2 = -0.00893, \; ^5P_2 = 0.0222, \; ^5F_2 = 0.00824$ | 4.83 | 4.6 |
| $B_5 (1^3P_0) K$ | $^1D_2 = -0.0167 \; i$ | 0.341 | 0.3 |
| $B_5 (1P_1) K$ | $^3D_2 = -0.0186 \; i$ | 0.359 | 0.3 |
| $B_5 (1P_1') K$ | $^3D_2 = -0.0105 \; i$ | 0.112 | 0.1 |
| $B_5 (1^1P_1') K$ | $^5S_2 = -0.00227 \; i, \; ^5D_2 = -0.0113 \; i, \; ^5G_2 = -0.00240 \; i$ | 0.126 | 0.1 |
| Total | | 103.9 | 100 |
TABLE XVII: Partial widths and branching ratios for strong decays of the $2D'_2$ $B$ meson. See the caption to Table IV for further explanations.

| Initial state | Final state | $M$ | Width (MeV) | B.R. (%) |
|---------------|-------------|-----|-------------|---------|
| $B(2D'_2)$    | $B\rho$    | $^3P_2 = -0.00175, ~^3F_2 = -0.0603$ | 16.9 | 7.2 |
| 6486          | $B\omega$  | $^3P_2 = -0.000820, ~^3F_2 = -0.0347$ | 5.54 | 2.4 |
|               | $B^*\pi$   | $^3P_2 = 0.0523, ~^3F_2 = -0.00101$ | 15.0 | 6.4 |
|               | $B^*\rho$  | $^3P_2 = 0.0107, ~^3F_2 = 0.0450, ~^5P_2 = 0.00799, ~^5F_2 = 0.0632$ | 25.3 | 10.8 |
|               | $B^*\eta$  | $^3P_2 = 0.0115, ~^3F_2 = -0.000253$ | 0.645 | 0.3 |
|               | $B^*\eta'$ | $^3P_2 = -0.0307, ~^3F_2 = 1.74 \times 10^{-6}$ | 2.79 | 1.2 |
|               | $B^*\omega$| $^3P_2 = 0.00686, ~^3F_2 = 0.0257, ~^5P_2 = 0.00520, ~^5F_2 = 0.0362$ | 8.28 | 3.5 |
|               | $B(2^3S_1)\pi$ | $^3P_2 = 0.0914, ~^3F_2 = -0.000691$ | 13.1 | 5.6 |
|               | $B(1^3P_0)\pi$ | $^1D_2 = 0.0220 i$ | 1.27 | 0.5 |
|               | $B(1P_1)\pi$ | $^3D_2 = -0.0552 i$ | 7.56 | 3.2 |
|               | $B(1P_1)\eta$ | $^3D_2 = -0.0191 i$ | 0.605 | 0.2 |
|               | $B(1P'_1)\pi$ | $^3D_2 = -0.0329 i$ | 2.65 | 1.1 |
|               | $B(1P'_1)\eta$ | $^3D_2 = -0.0131 i$ | 0.274 | 0.1 |
|               | $B(1^3P_2)\pi$ | $^5S_2 = -0.0608 i, ~^5D_2 = 0.0983 i, ~^5G_2 = -0.000409 i$ | 31.5 | 13.4 |
|               | $B(1^3P_2)\eta$ | $^5S_2 = 0.0424 i, ~^5D_2 = 0.0322 i, ~^5G_2 = -5.20 \times 10^{-5} i$ | 4.26 | 1.8 |
|               | $B(2^1P_1)\pi$ | $^3D_2 = 0.0327 i$ | 0.451 | 0.2 |
|               | $B(2^1P_2)\pi$ | $^5S_2 = -0.206 i, ~^5D_2 = -0.0443 i, ~^5G_2 = 5.93 \times 10^{-5} i$ | 16.5 | 7.0 |
|               | $B(1D_2)\pi$ | $^5P_2 = -0.0612, ~^5F_2 = -0.0253$ | 3.49 | 1.5 |
|               | $B(1^3D_0)\pi$ | $^7P_2 = 0.248, ~^7F_2 = 0.0315, ~^7H_2 = -4.94 \times 10^{-5}$ | 46.9 | 19.9 |
|               | $B_1K^*$ | $^3P_2 = 0.00838, ~^3F_2 = -0.0187$ | 1.34 | 0.6 |
|               | $B'K$ | $^3P_2 = -0.0139, ~^3F_2 = -0.000261$ | 0.838 | 0.4 |
|               | $B'_1K^*$ | $^3P_2 = 0.0320, ~^3F_2 = 0.0105, ~^5P_2 = 0.0272, ~^5F_2 = 0.0148$ | 5.41 | 2.3 |
|               | $B_u(1^3F_0)K$ | $^1D_2 = 0.0140 i$ | 0.291 | 0.1 |
|               | $B_u(1P_1)K$ | $^3D_2 = -0.0276 i$ | 0.982 | 0.4 |
|               | $B_u(1P'_1)K$ | $^3D_2 = -0.0142 i$ | 0.255 | 0.1 |
|               | $B_u(1^3P_2)K$ | $^5S_2 = 0.134 i, ~^5D_2 = 0.0406 i, ~^5G_2 = -2.97 \times 10^{-5} i$ | 22.9 | 9.7 |
|               | Total | | 235.3 | 100 |
TABLE XVIII: Partial widths and branching ratios for strong decays of the $2^3D_3$ $B$ meson. See the caption to Table IV for further explanations.

| Initial state | Final state | $\mathcal{M}$ | Width (MeV) | B.R. (%) |
|---------------|-------------|----------------|-------------|---------|
| $B(2^3D_3)$   | $B\pi$      | $^1F_3 = -0.0266$ | 4.05        | 4.3     |
| 6460          | $B\rho$     | $^3F_3 = -0.0416$ | 7.57        | 8.1     |
|               | $B\eta$     | $^1F_3 = -0.0144$ | 1.06        | 1.1     |
|               | $B\eta'$    | $^3F_3 = -0.0100$ | 0.335       | 0.4     |
|               | $B\omega$   | $^3F_3 = -0.0239$ | 2.48        | 2.6     |
|               | $B^*\pi$    | $^3F_3 = 0.0392$  | 8.05        | 8.6     |
|               | $B^*\rho$   | $^1F_3 = -0.0218$, $^5P_3 = 0.0215$, $^5F_3 = 0.0479$ | 12.4        | 13.3    |
|               | $B^*\eta$   | $^3F_3 = 0.0194$  | 1.75        | 1.9     |
|               | $B^*\eta'$  | $^3F_3 = 0.00906$ | 0.217       | 0.2     |
|               | $B^*\omega$ | $^1F_3 = -0.0125$, $^5P_3 = 0.0139$, $^5F_3 = 0.0273$ | 4.17        | 4.5     |
|               | $B(2^1S_0)\pi$ | $^1F_3 = 0.0501$ | 3.97        | 4.2     |
|               | $B(2^1S_1)\pi$ | $^3F_3 = -0.0538$ | 4.14        | 4.4     |
|               | $B(1P_1)\pi$ | $^3D_3 = 0.0254 i$, $^3G_3 = 0.0503 i$ | 7.36        | 7.9     |
|               | $B(1P_1)\eta$ | $^3D_3 = 0.00838 i$, $^3G_3 = 0.00428 i$ | 0.129       | 0.1     |
|               | $B(1P_1')\pi$ | $^3D_3 = -0.0433 i$, $^3G_3 = 0.00306 i$ | 4.30        | 4.6     |
|               | $B(1P_1')\eta$ | $^3D_3 = -0.0149 i$, $^3G_3 = 0.000229 i$ | 0.311       | 0.3     |
|               | $B(1^1P_2)\pi$ | $^5D_3 = -0.0589 i$, $^5G_3 = -0.0402 i$ | 11.2        | 12.0    |
|               | $B(1^1P_2)\eta$ | $^5D_3 = -0.0170 i$, $^5G_3 = -0.00277 i$ | 0.388       | 0.4     |
|               | $B(2^1P_2)\pi$ | $^5D_3 = 0.0235 i$, $^5G_3 = 0.00149 i$ | 0.163       | 0.2     |
|               | $B(1D_2)\pi$ | $^5P_3 = 0.0124$, $^5F_3 = 0.0123$, $^5H_3 = 0.00252$ | 0.215       | 0.2     |
|               | $B(1D_2')\pi$ | $^5P_3 = -0.0156$, $^5F_3 = -0.0035$, $^5H_3 = 1.74 \times 10^{-5}$ | 0.148       | 0.2     |
|               | $B(1^1D_2)\pi$ | $^7P_3 = -0.0562$, $^7F_3 = -0.0200$, $^7H_3 = -0.00156$ | 2.32        | 2.5     |
|               | $B_sK$       | $^1F_3 = -0.0226$ | 2.35        | 2.5     |
|               | $B_sK^*$     | $^3F_3 = -0.0114$ | 0.380       | 0.4     |
|               | $B_s^*K$     | $^3F_3 = 0.0286$  | 3.38        | 3.6     |
|               | $B_s^*K^*$   | $^1F_3 = -0.00419$, $^5P_3 = 0.0644$, $^5F_3 = 0.00918$ | 9.65        | 10.3    |
|               | $B_s(1P_1')K$ | $^3D_3 = -0.0215 i$, $^3G_3 = -0.000268 i$ | 0.498       | 0.5     |
|               | $B_s(1^3P_2)K$ | $^5D_3 = -0.0202 i$, $^5G_3 = -0.00180 i$ | 0.400       | 0.4     |
|               | Total        |                | 93.5        | 100     |
TABLE XIX: Partial widths and branching ratios for strong and electromagnetic decays of the 1F B mesons. See the caption to Table [IV] for further explanations.

| Initial state | Final state | $M_f$ (MeV) | $M$ | Width (ub, db) (MeV) | B.R. (ub, db) (%) |
|---------------|-------------|-------------|-----|---------------------|------------------|
| $B(1^3F_2)$  | $B(1^3D_1)\gamma$ | 6110 | $|1^3D_1|1^3F_2\rangle = 3.833$ | 0.399, 0.114 | 0.20, 0.056 |
|              | $B(1^3D_2)\gamma$ | 6124 | $|1^3D_2|1^3F_2\rangle = 3.978$ | 0.0402, 0.0115 | 0.020, 0.0057 |
|              | $B(1^3D_3)\gamma$ | 6106 | $|1^3D_3|1^3F_2\rangle = 4.153$ | 0.00259, 0.000738 | 0.0013, 0.00036 |
|              | $B\pi$ | | $1D_2 = 0.0732i$ | 27.4 | 13.6 |
|              | $B\rho$ | | $3D_2 = -0.0642 i$ | 15.2 | 7.5 |
|              | $B\eta$ | | $1D_2 = 0.0335 i$ | 5.07 | 2.5 |
|              | $B\omega$ | | $1D_2 = 0.0202 i$ | 1.00 | 0.5 |
|              | $B\omega'$ | | $3D_2 = -0.0368 i$ | 4.97 | 2.5 |
|              | $B^*\pi$ | | $3D_2 = 0.0647 i$ | 19.5 | 9.6 |
|              | $B^*\rho$ | | $1D_2 = 0.0442 i$, $3D_2 = -0.0334 i$, $5G_2 = -0.0337 i$ | 13.2 | 6.5 |
|              | $B^*\eta$ | | $3D_2 = 0.0289 i$ | 3.35 | 1.7 |
|              | $B^*\omega$ | | $1D_2 = 0.0252 i$, $5D_2 = -0.0191 i$, $5G_2 = -0.0186 i$ | 4.18 | 2.1 |
|              | $B(2^1S_0)\pi$ | | $1D_2 = -0.047 i$ | 2.72 | 1.4 |
|              | $B(2^1S_1)\pi$ | | $3D_2 = -0.0359 i$ | 1.38 | 0.7 |
|              | $B(1P_1)\pi$ | | $3P_2 = 0.150$, $3F_2 = 0.0364$ | 44.9 | 22.2 |
|              | $B(1P_1)\eta$ | | $3P_2 = 0.0558$, $3F_2 = 0.00200$ | 2.73 | 1.4 |
|              | $B(1P_1)\eta$ | | $3P_2 = 0.0124$, $3F_2 = -0.0123$ | 0.560 | 0.3 |
|              | $B(1P_2)\pi$ | | $5P_2 = 0.0535$, $5F_2 = 0.0438$ | 8.41 | 4.2 |
|              | $B(1P_2)\eta$ | | $5P_2 = 0.0172$, $5F_2 = 0.00147$ | 0.209 | 0.1 |
|              | $B(2P_1)\pi$ | | $3P_2 = -0.0489$, $3F_2 = -0.00688$ | 0.348 | 0.2 |
|              | $B(1D_3)\pi$ | | $5S_2 = -0.260 i$, $5D_2 = -0.0410 i$, $5G_2 = -0.000956 i$ | 29.9 | 14.8 |
|              | $B_sK$ | | $1D_2 = 0.0451 i$ | 8.10 | 4.0 |
|              | $B_sK^*$ | | $3D_2 = -0.0163 i$ | 0.547 | 0.3 |
|              | $B^*_K$ | | $3D_2 = 0.0383 i$ | 5.19 | 2.6 |
|              | $B_s(1P_1)K$ | | $3P_2 = 0.0672$, $3F_2 = 0.000939$ | 2.48 | 1.2 |
|              | Total | | | 202.4, 202.0 | 100 |
| $B(1F_1)$  | $B(1D_2)\gamma$ | 6106 | $|1^3D_2|1^3F_1\rangle = 3.989$, $|1^3D_2|1^3F_1\rangle = 4.040$ | 0.427, 0.122 | 0.40, 0.12 |
|              | $B(1^3D_3)\gamma$ | 6106 | $|1^3D_3|1^3F_1\rangle = 4.184$ | 0.0207, 0.00590 | 0.020, 0.0056 |
|              | $B\rho$ | | $3D_3 = -0.0977 i$, $3G_3 = -0.00376 i$ | 34.1 | 32.4 |
|              | $B\omega$ | | $3D_3 = -0.0571 i$, $3G_3 = -0.00209 i$ | 11.0 | 10.4 |
|              | $B^*\pi$ | | $3D_3 = 0.000340 i$, $3G_3 = -0.0769 i$ | 26.2 | 24.8 |
|              | $B^*\rho$ | | $3D_3 = 0.0672 i$, $3G_3 = 0.0152 i$, $5D_3 = -0.0475 i$, $5G_3 = -0.0146 i$ | 20.7 | 19.6 |
|              | $B^*\eta$ | | $3D_3 = 8.06 \times 10^{-5} i$, $3G_3 = -0.0196 i$ | 1.46 | 1.4 |
|              | $B^*\omega$ | | $3D_3 = 0.0382 i$, $3G_3 = 0.00829 i$, $5D_3 = -0.0270 i$, $5G_3 = -0.00800 i$ | 6.56 | 6.2 |
|              | $B(1^3P_0)\pi$ | | $1F_3 = -0.0157$ | 0.453 | 0.4 |
|              | $B(1P_1)\pi$ | | $3F_3 = -0.0284$ | 1.38 | 1.3 |
|              | $B(1P_1)\eta$ | | $3F_3 = -0.0148$ | 0.369 | 0.4 |
|              | $B(1^3P_2)\pi$ | | $5P_3 = 7.60 \times 10^{-5}$, $5F_3 = -0.0226$, $5H_3 = -0.0103$ | 0.994 | 0.9 |
|              | $B_sK^*$ | | $3D_3 = -0.0196 i$, $3G_3 = -0.000142 i$ | 0.653 | 0.6 |
|              | $B^*_K$ | | $3D_3 = 0.0000478 i$, $3G_3 = -0.0178 i$ | 1.04 | 1.0 |
|              | Total | | | 105.6, 105.2 | 100 |
TABLE XX: Partial widths and branching ratios for strong and electromagnetic decays of the 1F $B$ mesons. See the caption to Table [IV](#) for further explanations.

| Initial state | Final state | $M_f$ (MeV) | $M$ (MeV) | Width (ub, db) | B.R. (ub, db) |
|---------------|-------------|-------------|-----------|---------------|---------------|
| $B(1F_1^0)$  | $B(1D_2)\gamma$ | 6095 | $\langle 1^3D_2|r|1^1F_3 \rangle = 3.989, \langle 1^1D_2|r|1^3F_3 \rangle = 4.040$ | 0.00229, 0.000652 | 0.0010, 0.00029 |
|               | $B(1D_1)\gamma$ | 6124 | $\langle 1^3D_2|r|1^1F_3 \rangle = 3.989, \langle 1^1D_2|r|1^3F_3 \rangle = 4.040$ | 0.457, 0.130 | 0.21, 0.059 |
|               | $B(1^3D_3)\gamma$ | 6106 | $\langle 1^3D_3|r|1^1F_3 \rangle = 4.184$ | 0.0408, 0.0116 | 0.018, 0.0052 |
| $B\rho$      | $3D_3 = -0.0143 i, 3G_3 = 0.0325 i$ | 4.78 | 2.2 |
| $B\omega$    | $3D_3 = -0.00823 i, 3G_3 = 0.0182 i$ | 1.49 | 0.7 |
| $B^*\pi$     | $3D_3 = 0.102 i, 3G_3 = 0.000694 i$ | 49.2 | 22.2 |
| $B^*\rho$    | $3D_3 = -0.0636 i, 3G_3 = -0.0178 i, 5D_3 = -0.0590 i, 5G_3 = -0.0226 i$ | 27.0 | 12.2 |
| $B^*\eta$    | $3D_3 = 0.0466 i, 3G_3 = 0.000207 i$ | 8.89 | 4.0 |
| $B^*\eta'$   | $3D_3 = 0.0189 i, 3G_3 = 1.27 \times 10^{-5} i$ | 0.636 | 0.3 |
| $B^*\omega$  | $3D_3 = -0.0363 i, 3G_3 = -0.00987 i, 5D_3 = -0.0337 i, 5G_3 = -0.0125 i$ | 8.65 | 3.9 |
| $B(2^3S_1)\pi$ | $3D_3 = -0.0637 i, 3G_3 = -0.000195 i$ | 4.51 | 2.0 |
| $B(1^3P_0)\pi$ | $3F_3 = 0.0119$ | 0.291 | 0.1 |
| $B(1^3P_1)\pi$ | $3F_3 = 0.0349$ | 2.35 | 1.1 |
| $B(1^3P_2)\pi$ | $3F_3 = 0.0150$ | 0.428 | 0.2 |
| $B(1^3P_0)\eta$ | $5P_3 = 0.172, 5F_3 = 0.0501, 5H_3 = 0.000184$ | 58.1 | 26.2 |
| $B(1^3P_1)\eta$ | $5P_3 = 0.0618, 5F_3 = 0.00218, 5H_3 = 1.32 \times 10^{-6}$ | 2.99 | 1.4 |
| $B(1^3P_2)\eta$ | $5P_3 = 0.0507, 5F_3 = 0.000786$ | 0.332 | 0.2 |
| $B(1^3D_3)\pi$ | $7S_3 = -0.283 i, 7D_3 = -0.0481 i, 7G_3 = -0.00142 i$ | 35.0 | 15.8 |
| $B^*\omega$  | $3D_3 = 0.00629 i, 3G_3 = 0.000192 i$ | 14.3 | 6.4 |
| $B^*\eta$    | $3D_3 = -0.0104 i, 3G_3 = -0.000452 i, 5D_3 = -0.00960 i, 5G_3 = -0.000572 i$ | 0.286 | 0.1 |
| Total         | $5P_3 = 0.0687, 5F_3 = 0.000880$ | 2.13 | 1.0 |
|               | 222.1, 221.8 | 100 |
| $B(1^3F_4)\pi$ | $1G_4 = 0.056 i$ | 15.5 | 14.0 |
| $B\rho$      | $3G_4 = 0.0212 i$ | 1.57 | 1.4 |
| $B\eta$      | $1G_4 = 0.0156 i$ | 1.06 | 1.0 |
| $B\omega$    | $3G_4 = 0.0118 i$ | 0.481 | 0.4 |
| $B^*\pi$     | $3G_4 = -0.0604 i$ | 16.3 | 14.8 |
| $B^*\rho$    | $1G_4 = 0.00803 i, 5D_4 = -0.132 i, 5G_4 = -0.0159 i$ | 51.9 | 47.1 |
| $B^*\eta$    | $3G_4 = -0.0157 i$ | 0.944 | 0.8 |
| $B^*\omega$  | $1G_4 = 0.00441 i, 5D_4 = -0.0750 i, 5G_4 = -0.00873 i$ | 16.5 | 15.0 |
| $B(1P_1)\pi$ | $3F_4 = 0.0184, 3H_4 = 0.00973$ | 0.758 | 0.7 |
| $B(1P_0^1)\pi$ | $3F_4 = -0.0208, 3H_4 = 0.000588$ | 0.740 | 0.7 |
| $B(1^3P_2)\pi$ | $5F_4 = -0.0374, 5H_4 = -0.00679$ | 2.38 | 2.2 |
| $B_0 K$      | $1G_4 = 0.0141 i$ | 0.752 | 0.7 |
| $B_0^* K$    | $3G_4 = -0.0143 i$ | 0.683 | 0.6 |
| Total         | 110.4, 110.0 | 100 |
TABLE XXI: Partial widths and branching ratios for strong decays of the 1G B mesons. In this table, we do not show strong decay modes which have BR < 0.5%, although they are included in calculating the total width. See the caption to Table IV for further explanations.

| Initial state | Final state | $\mathcal{M}$ | Width (MeV) | B.R. (%) |
|---------------|-------------|---------------|-------------|---------|
| $B(1^3G_3)$  | $B\pi$     | $F_3 = -0.0420$ | 12.7        | 6.9     |
|               | $B\rho$    | $F_3 = 0.0413$  | 10.2        | 5.6     |
|               | $B\eta$    | $F_3 = -0.0191$ | 2.42        | 1.3     |
|               | $B\eta'$   | $F_3 = -0.0171$ | 1.50        | 0.8     |
|               | $B\omega$  | $F_3 = 0.0238$  | 3.36        | 1.8     |
|               | $B'^\pi$   | $F_3 = -0.0396$ | 10.4        | 5.7     |
|               | $B'^\rho$  | $F_3 = -0.0286, 5F_3 = 0.0261, 5H_3 = 0.0453$ | 19.2 | 10.5 |
|               | $B'^\eta$  | $F_3 = -0.0178$ | 1.92        | 1.0     |
|               | $B'^\eta'$ | $F_3 = -0.0142$ | 0.908       | 0.5     |
|               | $B'^\omega$| $F_3 = -0.0165, 5F_3 = 0.0150, 5H_3 = 0.0256$ | 6.19 | 3.4 |
| $B(2^1S_0)\pi$| $1F_3 = 0.0427$ | 4.66        | 2.6     |
| $B(2^1S_1)\pi$| $3F_3 = 0.0358$ | 3.05        | 1.7     |
| $B(1P_1)\pi$  | $3D_3 = 0.0841, 3G_3 = 0.0290$ | 27.1 | 14.8 |
| $B(1P_1)\rho$ | $3D_3 = -0.0332 i, 3G_3 = -0.000956 i, 5D_3 = -0.0235 i, 5G_3 = -0.00253 i$ | 2.40 | 1.3 |
| $B(1P_1)\eta$   | $3D_3 = 0.0387 i, 3G_3 = 0.06068 i$ | 4.14 | 2.3 |
| $B(1P_1)\pi$  | $3D_3 = 0.0685 i, 3G_3 = -0.0158 i$ | 1.00 | 0.5 |
| $B(1P_1)\eta$ | $3D_3 = 0.0367 i, 3G_3 = 0.0387 i$ | 9.35 | 5.1 |
| $B(1P_2)\eta$  | $5D_3 = 0.168 i, 5G_3 = 0.00761 i$ | 0.896 | 0.5 |
| $B(2P_1)\pi$  | $3D_3 = -0.0619 i, 3G_3 = -0.00518 i$ | 3.65 | 2.0 |
| $B(1D_2)\pi$  | $7P_3 = 0.126, 5F_3 = 0.0410, 5H_3 = 0.00290$ | 25.2 | 13.8 |
| $B(1D_3)\pi$  | $7P_3 = 0.0298, 7F_3 = 0.0268, 7H_3 = 0.00470$ | 2.25 | 1.2 |
| $B(1F_3)\pi$  | $7S_3 = -0.202 i, 7D_3 = -0.0341 i, 7G_3 = -0.00108 i, 7I_3 = -1.12 \times 10^{-5} i$ | 14.5 | 7.9 |
| $B_sK$         | $F_3 = -0.0224$ | 3.02 | 1.6 |
| $B_s^*K$       | $F_3 = 0.0139$ | 0.891 | 0.5 |
| $B_s^*K$       | $F_3 = -0.0207$ | 2.36 | 1.3 |
| $B_s(1P_1)K$   | $3D_3 = 0.0505 i, 3G_3 = 0.00467 i$ | 5.82 | 3.2 |
| $B_s(1P_2)K$   | $5D_3 = 0.0217 i, 5G_3 = 0.00655 i$ | 1.10 | 0.6 |
| Total          |             | 183.2        | 100        |
| $B(1G_4)$      | $B\rho$    | $F_3 = 0.0626, 3H_4 = 0.00345$ | 22.1 | 23.1 |
|                | $B\omega$  | $F_3 = 0.0360, 3H_4 = 0.00195$ | 7.28 | 7.6 |
|                | $B'^\pi$   | $F_3 = -0.000117, 3H_4 = 0.0065$ | 23.2 | 24.2 |
|                | $B'^\rho$  | $F_3 = -0.0456, 3H_4 = -0.0213, 5F_4 = 0.0353, 5H_4 = 0.0208$ | 21.4 | 22.3 |
|                | $B'^\eta$  | $F_3 = -2.55 \times 10^{-5}, 3H_4 = 0.0182$ | 1.91 | 2.0 |
|                | $B'^\omega$| $F_3 = -0.0262, 3H_4 = -0.0120, 5F_4 = 0.0203, 5H_4 = 0.0118$ | 6.95 | 7.2 |
|                | $B(2^3S_1)\pi$ | $F_4 = -0.000228, 3H_4 = -0.0175$ | 0.660 | 0.7 |
|                | $B(1^4P_0)\pi$ | $G_4 = -0.0164 i, 3H_4 = -0.00175$ | 0.897 | 0.9 |
|                | $B(1^4P_1)\pi$ | $G_4 = -0.0249 i, 3H_4 = -0.00175$ | 1.97 | 2.1 |
|                | $B(1F_3)\rho$ | $G_4 = -4.31 \times 10^{-6} i, 5G_4 = 0.000319 i, 5D_4 = -0.0363 i, 5I_4 = -2.75 \times 10^{-6} i$ | 1.31 | 1.4 |
|                | $B(1F_3)\pi$ | $G_4 = -0.000758 i, 5I_4 = -2.75 \times 10^{-6} i$ | 0.835 | 0.9 |
|                | $B(1^3P_2)\rho$ | $G_4 = -0.0224 i, 3H_4 = -0.0166 i$ | 2.36 | 2.5 |
|                | $B_sK^*$   | $F_3 = 0.0195, 3H_4 = 0.000467$ | 1.62 | 1.7 |
|                | $B_s^*K$   | $F_3 = 5.85 \times 10^{-6}, 3H_4 = 0.0142$ | 1.06 | 1.1 |
|                | $B_sK^*$   | $F_3 = -0.0128, 3H_4 = -0.00245, 5F_4 = 0.00988, 5H_4 = 0.00239$ | 1.01 | 1.0 |
| Total          |             | 95.8         | 100        |
TABLE XXII: Partial widths and branching ratios for strong decays of the $1^G B$ mesons. In this table, we do not show strong decay modes which have BR < 0.5%, although they are included in calculating the total width. See the caption to Table IV for further explanations.

| Initial state | Final state | $\mathcal{M}$ | Width (MeV) | B.R. (%) |
|---------------|-------------|----------------|-------------|---------|
| $B(1G'_4)$   | $B\rho$    | $^3F_4 = 0.00695, ^3H_4 = -0.0355$ | 7.89 | 3.9 |
| 6628          | $B\omega$  | $^3F_4 = 0.00401, ^3H_4 = -0.0202$ | 2.53 | 1.2 |
|               | $B^*\pi$   | $^3F_4 = -0.0598, ^3H_4 = -0.000236$ | 23.9 | 11.8 |
|               | $B^*\rho$  | $^3F_4 = 0.0422, ^3H_4 = 0.0229, ^5F_4 = 0.0406, ^5H_4 = 0.0277$ | 25.7 | 12.7 |
|               | $B^*\eta$  | $^3F_4 = -0.0272, ^3H_4 = -8.44 \times 10^{-5}$ | 4.56 | 2.2 |
|               | $B^*\eta'$ | $^3F_4 = -0.0226, ^3H_4 = -3.42 \times 10^{-5}$ | 2.33 | 1.2 |
|               | $B^*\omega$| $^3F_4 = 0.0243, ^3H_4 = 0.0129, ^5F_4 = 0.0234, ^5H_4 = 0.0157$ | 8.40 | 4.1 |
|               | $(2^3 S_1)\pi$ | $^3F_4 = 0.0586, ^3H_4 = 0.000181$ | 8.27 | 4.1 |
|               | $(1P_1)\pi$ | $^3G_4 = -0.0288 i$ | 2.87 | 1.4 |
|               | $(1F_2)\pi$ | $^5D_4 = 0.0977 i, ^5G_4 = 0.0402 i, ^5I_4 = 0.000151 i$ | 37.1 | 18.3 |
|               | $(1^3 F_2)\rho$ | $^3G_4 = -0.000475 i, ^5D_4 = -0.0381 i, ^5G_4 = -0.00168 i, ^5I_4 = -3.66 \times 10^{-5} i$, $^7D_4 = -0.0199 i, ^7G_4 = -0.00192 i, ^7I_4 = -6.67 \times 10^{-5} i$ | 2.35 | 1.2 |
|               | $(2^3 F_2)\eta$ | $^5D_4 = 0.0461 i, ^5G_4 = 0.00816 i, ^5I_4 = 1.75 \times 10^{-5} i$ | 5.68 | 2.8 |
|               | $(2^3 D_3)\pi$ | $^5D_4 = -0.0691 i, ^5G_4 = -0.00692 i, ^5I_4 = -1.16 \times 10^{-5} i$ | 4.35 | 2.1 |
|               | $(2^3 D_3)\rho$ | $^7P_4 = 0.139, ^7F_4 = 0.0493, ^7G_4 = 0.00444, ^7J_4 = 8.90 \times 10^{-6}$ | 30.8 | 15.2 |
|               | $(1^3 F_2)\pi$ | $^9S_4 = -0.218 i, ^9D_4 = -0.0389 i, ^9G_4 = -0.00135 i, ^9I_4 = -1.79 \times 10^{-5} i$ | 16.9 | 8.3 |
|               | $B^*K$      | $^3F_4 = -0.0323, ^3H_4 = -7.37 \times 10^{-5}$ | 5.82 | 2.9 |
|               | $B^*K^*$    | $^3F_4 = 0.0134, ^3H_4 = 0.00313, ^5F_4 = 0.0129, ^5H_4 = 0.00380$ | 1.53 | 0.8 |
|               | $B_s(1^3 P_2)K$ | $^5D_4 = 0.0604 i, ^5G_4 = 0.00706 i, ^5I_4 = 1.00 \times 10^{-5} i$ | 8.03 | 4.0 |
|               | Total       |                | 203.2 | 100 |
| $B(1^3 G_5)$  | $B\pi$     | $^1H_5 = -0.0423$ | 12.3 | 12.1 |
| 6592          | $B\rho$    | $^3H_5 = -0.0237$ | 3.19 | 3.1 |
|               | $B\eta$    | $^3H_5 = -0.0133$ | 1.12 | 1.1 |
|               | $B\omega$  | $^3H_5 = -0.0134$ | 1.02 | 1.0 |
|               | $B^*\pi$   | $^3H_5 = 0.0461$ | 13.5 | 13.2 |
|               | $B^*\rho$  | $^1H_5 = -0.0111, ^5F_5 = 0.0881, ^5H_5 = 0.0207$ | 42.5 | 41.7 |
|               | $B^*\eta$  | $^3H_5 = 0.0140$ | 1.13 | 1.1 |
|               | $B^*\omega$| $^1H_5 = -0.00628, ^5F_5 = 0.0506, ^5H_5 = 0.0117$ | 13.9 | 13.6 |
|               | $(2^3 S_0)\pi$ | $^1H_5 = 0.0148$ | 0.515 | 0.5 |
|               | $(1P_1)\pi$ | $^3G_5 = 0.0174 i, ^3I_5 = 0.0143 i$ | 1.63 | 1.6 |
|               | $(1P'_1)\pi$ | $^3G_5 = -0.0224 i, ^3I_5 = 0.00823 i$ | 1.58 | 1.6 |
|               | $(1^3 D_3)\pi$ | $^5G_5 = -0.0341 i, ^5I_5 = -0.0102 i$ | 3.88 | 3.8 |
|               | $(1^3 D_3)\rho$ | $^3G_5 = 3.39 \times 10^{-5} i, ^5G_5 = 6.78 \times 10^{-5} i, ^7D_5 = -0.0271 i, ^7G_5 = -0.00376 i, ^7I_5 = -2.34 \times 10^{-6} i$ | 0.536 | 0.5 |
|               | $(1^3 D_3)\pi$ | $^7F_5 = -0.0217, ^7H_5 = -0.00390, ^7J_5 = -0.00293$ | 0.601 | 0.6 |
|               | $B_sK$      | $^1H_5 = -0.0103$ | 0.604 | 0.6 |
|               | $B_s^*K$    | $^3H_5 = 0.0110$ | 0.637 | 0.6 |
|               | $B_s^*K^*$  | $^1H_5 = -0.00131, ^5F_5 = 0.0253, ^5H_5 = 0.00243$ | 2.43 | 2.4 |
|               | Total       |                | 102.2 | 100 |
TABLE XXIII: Partial widths and branching ratios for strong and electromagnetic decays of the $1S$ and $2S B_s$ mesons. The initial state’s mass is given in MeV and is listed below the state’s name in column 1. Column 4 gives the matrix element, $\mathcal{M}$, or strong amplitude as appropriate to the particular decay. For radiative transitions the E1 or M1 matrix elements are $\langle f|r|i\rangle$ (GeV$^{-1}$) and $\langle f|J_0(kr\frac{m_b}{m_s+m_b})|i\rangle$ respectively; these matrix elements were obtained using the wavefunctions of the GI model [6]. For strong decays, the non-zero partial wave amplitudes are given in units of GeV$^{-1/2}$. We only show radiative transitions that are likely to be observed and likewise generally do not show strong decay modes which have BR < 0.1%, although they are included in calculating the total width. Details of the calculations are given in the text.

| Initial state | Final state | $M_f$ (MeV) | $\mathcal{M}$ | Width (MeV) | B.R. (%) |
|---------------|-------------|-------------|--------------|-------------|----------|
| $B_s^*$ | $B_s\gamma$ | 5394 | $\langle 1^1S_0|J_0(kr\frac{m_b}{m_s+m_b})|1^3S_1\rangle = 0.9953, 0.9971$ | 0.000313 | 100 |
| 5450 Total | | | | 0.000313 | 100 |
| $B_s(2^1S_1)$ | $B_s\gamma$ | 5394 | $\langle 1^1S_0|J_0(kr\frac{m_b}{m_s+m_b})|2^1S_1\rangle = 0.2079, 0.06476$ | 0.0142 | 0.012 |
| 6012 Total | | | | 0.00252 | 0.0028 |
| $B_s(1^3P_1)$ | $B_s\gamma$ | 5876 | $\langle 1^3P_1|r|2^1S_1\rangle = -2.344$ | 0.0808 | 0.076 |
| $B_s(1^1P_1)$ | $B_s\gamma$ | 5857 | $\langle 1^1P_1|r|2^3S_1\rangle = -2.098$ | 0.0028 | 0.0020 |
| $B_s(1^3P'_1)$ | $B_s\gamma$ | 5861 | $\langle 1^3P'_1|r|2^3S_1\rangle = -2.098$ | 0.0032 | 0.0028 |
| $B_s(1^3P_0)$ | $B_s\gamma$ | 5831 | $\langle 1^3P_0|r|2^3S_1\rangle = -1.916$ | 0.0025 | 0.0022 |
| $B_s(1^3P_1)$ | $B_s\gamma$ | 5857 | $\langle 1^3P_1|r|2^3S_0\rangle = -2.282$ | 0.0067 | 0.0089 |
| $B_s(1^3P'_1)$ | $B_s\gamma$ | 5861 | $\langle 1^3P'_1|r|2^3S_0\rangle = -2.282$ | 0.0040 | 0.0054 |
| $B_s(1^3P'_0)$ | $B_s\gamma$ | 5831 | $\langle 1^3P'_0|r|2^3S_0\rangle = -1.916$ | 0.0025 | 0.0022 |
| $B_s(1^1P_1)$ | $B_s\gamma$ | 5857 | $\langle 1^1P_1|r|2^3S_0\rangle = -2.098$ | 0.0032 | 0.0028 |
| $B_s(1^3P'_1)$ | $B_s\gamma$ | 5861 | $\langle 1^3P'_1|r|2^3S_0\rangle = -2.282$ | 0.0040 | 0.0054 |
| $B_s(1^3P'_0)$ | $B_s\gamma$ | 5831 | $\langle 1^3P'_0|r|2^3S_0\rangle = -1.916$ | 0.0025 | 0.0022 |
| $B_s(2^1S_1)$ | $B_s\gamma$ | 5450 | $\langle 1^3S_0|J_0(kr\frac{m_b}{m_s+m_b})|2^1S_0\rangle = 0.07796, -0.06457$ | 0.00323 | 0.0043 |
| 5984 Total | | | | 114.0 | 100 |
| $B_s(1^1P_1)$ | $B_s\gamma$ | 5831 | $\langle 1^3P_0|r|2^3S_0\rangle = -1.916$ | 0.0025 | 0.0022 |
| $B_s(1^3P'_1)$ | $B_s\gamma$ | 5861 | $\langle 1^3P'_1|r|2^3S_0\rangle = -2.282$ | 0.0040 | 0.0054 |
| $B_s(1^3P'_0)$ | $B_s\gamma$ | 5831 | $\langle 1^3P'_0|r|2^3S_0\rangle = -1.916$ | 0.0025 | 0.0022 |
| $B_s(2^1S_1)$ | $B_s\gamma$ | 5450 | $\langle 1^3S_0|J_0(kr\frac{m_b}{m_s+m_b})|2^1S_0\rangle = 0.07796, -0.06457$ | 0.00323 | 0.0043 |
| 5984 Total | | | | 114.0 | 100 |

For strong decays, the non-zero partial wave amplitudes are given in units of GeV$^{-1/2}$. We only show radiative transitions that are likely to be observed and likewise generally do not show strong decay modes which have BR < 0.1%, although they are included in calculating the total width. Details of the calculations are given in the text.
TABLE XXIV: Partial widths and branching ratios for strong and electromagnetic decays of the 3S_{1} B mesons. See the caption to Table [XXIII] for further explanations.

| Initial state | Final state | $M_f$ (MeV) | $\mathcal{M}$ | Width (MeV) | B.R. (%) |
|---------------|-------------|-------------|---------------|-------------|----------|
| $B_s(3^1S_1)$ | $B_s \gamma$ | 5394 | $(1^1S_1)_{J=0}(kr, \frac{m_b}{m_b+m_s})|3^1S_1\rangle = 0.1086, 0.02980$ | 0.0164 | 0.013 |
| 6429 | $B_s(2^1S_0)\gamma$ | 5984 | $(2^1S_0)_{J=0}(kr, \frac{m_b}{m_b+m_s})|3^1S_1\rangle = 0.2359, 0.05756$ | 0.00710 | 0.0055 |
| $B_s(1^3P_2)\gamma$ | | 5876 | $(1^3P_2)_{J=0}|3^1S_1\rangle = 0.3170$ | 0.00896 | 0.0069 |
| $B_s(2^3P_2)\gamma$ | | 6295 | $(2^3P_2)_{J=0}|3^3S_1\rangle = -3.493$ | 0.0174 | 0.013 |
| $B_s(2^1P_1)\gamma$ | | 6279 | $(2^1P_1)_{J=0}|3^3S_1\rangle = -3.196$ | 0.00357 | 0.0028 |
| $B_s(2^3P_1)\gamma$ | | 6296 | $(2^3P_1)_{J=0}|3^3S_1\rangle = -3.196$ | 0.00598 | 0.0046 |
| $B_s(2^3P_0)\gamma$ | | 6279 | $(2^3P_0)_{J=0}|3^3S_1\rangle = -2.973$ | 0.00347 | 0.0027 |
| $B^*K$ | | | $^1P_1 = 0.0379$ | 7.18 | 5.5 |
| $B^*K^*$ | | | $^3P_1 = -0.0413$ | 5.89 | 4.5 |
| $B^*K$ | | | $^3P_1 = -0.0444$ | 8.89 | 6.8 |
| $B^*K^*$ | | | $^1P_1 = -0.0314, ^3P_1 = 0.140$ | 58.2 | 44.8 |
| $B(2^1S_0)K$ | | | $^1P_1 = 0.0794$ | 3.21 | 2.5 |
| $B(1^3P_0)K$ | | | $^3S_1 = 0.00310 i, ^3D_1 = 0.114 i$ | 19.0 | 14.6 |
| $B(1^3P_2)K$ | | | $^3S_1 = -0.0425 i, ^3D_1 = 0.00757 i$ | 2.62 | 2.0 |
| $B(1^1P_1)K$ | | | $^3D_1 = -0.117 i$ | 18.2 | 14.0 |
| $B_\eta\gamma$ | | | $^3P_1 = -0.0276$ | 1.49 | 1.2 |
| $B_\phi\gamma$ | | | $^3P_1 = -0.0340$ | 1.06 | 0.8 |
| $B_\eta\gamma$ | | | $^3P_1 = -0.0124$ | 0.579 | 0.4 |
| $B_\eta'\gamma$ | | | $^3P_1 = 0.0305$ | 0.917 | 0.7 |
| $B_\eta'(1^3P_0)\eta$ | | | $^3S_1 = 0.0697 i, ^3D_1 = 0.000789 i$ | 2.29 | 1.8 |
| Total | | | | 129.8 | 100 |
| $B_s(3^1S_0)$ | $B_s^*\gamma$ | 5450 | $(1^1S_1)_{J=0}(kr, \frac{m_b}{m_b+m_s})|3^1S_0\rangle = 0.03084, -0.2852$ | 0.00261 | 0.0022 |
| 6410 | $B_s(2^1S_1)\gamma$ | 6012 | $(2^1S_1)_{J=0}(kr, \frac{m_b}{m_b+m_s})|3^1S_0\rangle = 0.1280, -0.05419$ | 0.00401 | 0.0033 |
| $B_s(1^3P_2)\gamma$ | | 5857 | $(1^3P_2)_{J=0}|3^1S_0\rangle = 0.2487$ | 0.00595 | 0.0049 |
| $B_s(1^3P_0)\gamma$ | | 5861 | $(1^3P_0)_{J=0}|3^1S_0\rangle = 0.2487$ | 0.00386 | 0.0032 |
| $B_s(2^3P_1)\gamma$ | | 6279 | $(2^3P_1)_{J=0}|3^3S_0\rangle = -3.418$ | 0.0190 | 0.016 |
| $B_s(2^3P_0)\gamma$ | | 6296 | $(2^3P_0)_{J=0}|3^3S_0\rangle = -3.418$ | 0.00538 | 0.0045 |
| $B^*K^*$ | | | $^3P_6 = 0.069$ | 15.4 | 12.8 |
| $B^*K$ | | | $^3P_6 = -0.0431$ | 8.07 | 6.7 |
| $B^*K^*$ | | | $^3P_6 = -0.158$ | 64.6 | 55.3 |
| $B(1^3P_0)K$ | $^1S_0 = -0.039 i$ | 2.23 | 1.8 |
| $B(1^3P_2)K$ | $^3D_0 = -0.15 i$ | 26.4 | 21.9 |
| $B_\eta\eta$ | | | $^3P_6 = -0.0222$ | 1.77 | 1.5 |
| $B_s(1^3P_0)\eta$ | | | $^1S_0 = 0.0619 i$ | 2.24 | 1.8 |
| Total | | | | 120.8 | 100 |
TABLE XXV: Partial widths and branching ratios for strong and electromagnetic decays of the $4^3S_1$ $B_s$ meson. See the caption to Table XXIII for further explanations.

| Initial state | Final state | $M_f$ (MeV) | $\mathcal{M}$ | Width (MeV) | B.R. (%) |
|---------------|-------------|-------------|---------------|-------------|---------|
| $B_s(4^3S_1)$ $B_s\gamma$ | 5394 | $(1^1S_0)j_0(kr^{\frac{m_{B_s}}{m_{B_s}+m_\pi}})|4^3S_1\rangle = 0.07398, 0.019775$ | 0.0168 | 0.016 |
| $B_s(4^3S_0)\gamma$ | 5984 | $(2^1S_0)j_0(kr^{\frac{m_{B_s}}{m_{B_s}+m_\eta}})|4^3S_1\rangle = 0.1338, 0.02237$ | 0.0116 | 0.011 |
| $B_s(4^3S_0)\gamma$ | 6410 | $(3^1S_0)j_0(kr^{\frac{m_{B_s}}{m_{B_s}+m_\eta'}})|4^3S_1\rangle = 0.2473, 0.04972$ | 0.00432 | 0.0042 |
| $BK$ | 4.18 | $P_1 = -0.0234$ | 4.18 | 4.0 |
| $B^* K$ | 1.50 | $P_1 = -0.00333, P_1 = 0.0149$ | 1.50 | 1.4 |
| $B(2^1S_0)K$ | 1.53 | $P_1 = 0.0224$ | 1.53 | 1.5 |
| $B(2^3S_1)K$ | 1.43 | $P_1 = -0.0224$ | 1.43 | 1.4 |
| $B(1^3P_0)K^*$ | 0.183 | $S_1 = 0.00876 i$ | 0.183 | 0.2 |
| $B(1^1P_1)K^*$ | 0.878 | $S_1 = 0.00660 i, D_1 = 0.0147 i$ | 0.878 | 0.8 |
| $B(1^3P_2)K^*$ | 14.1 | $S_1 = -2.25 \times 10^{-5} i, D_1 = 0.0405 i, D_1 = -0.0702 i$ | 14.1 | 13.6 |
| $B(2^1P_1)K^*$ | 0.265 | $S_1 = 0.00809 i, D_1 = 0.00786 i$ | 0.265 | 0.2 |
| $B(1^3P_2)K^*$ | 0.120 | $S_1 = 0.00618 i, D_1 = 0.00223 i, D_1 = 0.00387 i$ | 0.120 | 0.1 |
| $B(1^3D_2)K^*$ | 0.449 | $D_1 = 0.0107 i$ | 0.449 | 0.4 |
| $B(1^3P_2)K^*$ | 31.0 | $D_1 = -0.0203 i, D_1 = 0.0262 i, D_1 = 0.124 i$ | 31.0 | 29.9 |
| $B(2^1P_1)K$ | 8.10 | $S_1 = 0.00228 i, D_1 = 0.0936 i$ | 8.10 | 7.8 |
| $B(2^3P_1)K$ | 5.37 | $S_1 = 0.0881 i, D_1 = 0.00297 i$ | 5.37 | 5.2 |
| $B(2^1P_2)K$ | 5.71 | $D_1 = -0.0842 i$ | 5.71 | 5.5 |
| $B(1^3D_2)K$ | 0.319 | $P_1 = 0.0144$ | 0.319 | 0.3 |
| $B(1^3D_2)K$ | 8.94 | $D_1 = 0.00148, F_1 = -0.0736$ | 8.94 | 8.6 |
| $B(1^3D_2)K$ | 1.87 | $D_1 = 0.0306, F_1 = -0.000611$ | 1.87 | 1.8 |
| $B(1^3D_2)K$ | 0.70 | $F_1 = 0.0712$ | 0.70 | 7.7 |
| $B_s\eta'$ | 0.108 | $P_1 = -0.00428$ | 0.108 | 0.1 |
| $B_s \phi$ | 0.320 | $P_1 = 0.00760$ | 0.320 | 0.3 |
| $B_s \eta'$ | 0.209 | $P_1 = 0.00627$ | 0.209 | 0.2 |
| $B_s \phi$ | 0.667 | $P_1 = 0.00254, P_1 = 0.0114$ | 0.667 | 0.6 |
| $B_s(2^1S_0)\eta$ | 0.441 | $P_1 = 0.0139$ | 0.441 | 0.4 |
| $B_s(2^3S_0)\eta$ | 1.55 | $P_1 = -0.0274$ | 1.55 | 1.5 |
| $B_s(1^3P_1)\eta$ | 1.02 | $S_1 = 0.000559 i, D_1 = 0.0176 i$ | 1.02 | 1.0 |
| $B_s(1^3P_2)\eta$ | 0.419 | $S_1 = 0.0112 i, D_1 = -0.00161 i$ | 0.419 | 0.4 |
| $B_s(1^3D_2)\eta$ | 1.56 | $D_1 = -0.0223 i$ | 1.56 | 1.5 |
| Total | 103.7 | | 100 | |
TABLE XXVI: Partial widths and branching ratios for strong and electromagnetic decays of the $4^1 S_0$ $B_s$ meson. See the caption to Table [XXIII] for further explanations.

| Initial state | Final state | $M_f$ (MeV) | $M$ | Width (MeV) | B.R. (%) |
|---------------|-------------|-------------|-----|-------------|----------|
| $B_s(4^1 S_0)$ | $B_s^* \gamma$ | 6759        | 5450 | $\langle 1^1 S_1 | j_0 (k r \frac{m_{s^*}}{m_s + m_{s^*}}) | 1^1 S_0 \rangle = 0.02012, -0.01626$ | 0.00332  | 0.0039  |
|               | $B_s(2^3 S_1) \gamma$ | 6012        | 5861 | $\langle 2^3 S_1 | j_0 (k r \frac{m_{s^*}}{m_s + m_{s^*}}) | 4^1 S_0 \rangle = 0.06664, -0.02662$ | 0.00156  | 0.0018  |
| $B^* K$       | $3 P_0 = -0.0244$ | 4.45       | 5.3  |
| $B^* K^*$     | $3 P_0 = -0.0213$ | 2.85       | 3.4  |
| $B(2^3 S_1) K$| $3 P_0 = -0.0177$ | 0.851      | 1.0  |
| $B(1^3 P_0) K$| $1 S_0 = -0.007111 i$ | 0.208     | 0.2  |
| $B(1^3 P_1) K^*$| $1 S_0 = 0.002000 i, 3 D_0 = 0.0981 i$ | 6.62      | 7.8  |
| $B(1^3 P_1) K^*$| $1 S_0 = -0.0273 i, 5 D_0 = 0.00537 i$ | 14.4      | 17.0 |
| $B(1^3 P_2) K^*$| $3 P_0 = 0.00712$ | 0.411      | 0.5  |
| $B(2^3 P_0) K$| $3 P_0 = -0.00621$ | 0.257      | 0.3  |
| $B(2^3 P_2) K$| $3 P_0 = 0.00712$ | 0.261      | 0.3  |
| $B(1^3 D_0) K$| $3 P_0 = 0.00831$ | 0.329      | 0.4  |
| $B(1^3 D_1) K$| $3 P_0 = -0.0399$ | 3.10       | 3.7  |
| $B(1^3 D_2) K$| $3 P_0 = 0.0102 i$ | 0.352      | 0.4  |
| $B_s \phi$    | $3 P_0 = -0.0363 i$ | 3.97       | 4.7  |
| $B_s^* \eta$  | $3 P_0 = 0.0204$ | 0.238      | 0.3  |
| $B_s^* \eta^*$| $3 P_0 = -0.00621$ | 0.257      | 0.3  |
| $B_s(1^3 P_0)$| $1 S_0 = -0.058 i$ | 138        | $\sim 100$ |
| $B_s(1^3 P_1)$| $1 S_0 = 0.0583 i$ | 138        | $\sim 100$ |
| $B_s(1^3 P_2)$| $1 S_0 = 0.058 i$ | 138        | $\sim 100$ |

Total

84.7 100

TABLE XXVII: Partial widths and branching ratios for strong and electromagnetic decays of the $1^P B_s$ mesons. See the caption to Table [XXIII] for further explanations.

| Initial state | Final state | $M_f$ (MeV) | $M$ | Width (MeV) | B.R. (%) |
|---------------|-------------|-------------|-----|-------------|----------|
| $B_s(1^3 P_0)$ | $B_s \gamma$ | 5831        | 5450 | $\langle 1^1 S_1 | j_0 (1^3 P_0) | 1^1 S_0 \rangle = 2.051$ | 0.0760  | 0.055  |
| $B_s(1^3 P_1)$ | $B_s \gamma$ | 5857        | 5394 | $\langle 1^1 S_0 | j_0 (1^3 P_1) | 1^1 S_0 \rangle = 1.922$ | 0.0706  | 65.7   |
| $B_s(1^3 P_2)$ | $B_s \gamma$ | 5861        | 5394 | $\langle 1^1 S_0 | j_0 (1^3 P_2) | 1^1 S_0 \rangle = 2.058$ | 0.0369  | 34.3   |
| $B_s(1^3 P_1)$ | $B_s \gamma$ | 5861        | 5450 | $\langle 1^1 S_1 | j_0 (1^3 P_1) | 1^1 S_0 \rangle = 1.922$ | 0.0478  | 45.5   |
| $B_s(1^3 P_2)$ | $B_s \gamma$ | 5857        | 5450 | $\langle 1^1 S_1 | j_0 (1^3 P_2) | 1^1 S_0 \rangle = 2.058$ | 0.0573  | 54.5   |
| Total No strong decays |               |             |     |             |          |
| Total |               |             |     |             |          |

0.1075 100

0.1051 100

0.106 13.6

0.663 85.4

0.00799 1.0

0.777 100
TABLE XXVIII: Partial widths and branching ratios for strong and electromagnetic decays of the 2P $B_s$ mesons. See the caption to Table [XXVII] for further explanations.

| Initial state | Final state | $M_f$ (MeV) | $M$ | Width (MeV) | B.R. (%) |
|---------------|-------------|-------------|-----|-------------|---------|
| $B_s(2^3P_1)$ | $B_s^*\gamma$ | 5450        | $|^{1S_1}|r|^{2S_3}P_0| = -0.1862$ | 0.00581 | 0.0082 |
| 6279         | $B_s(2^3S_1)\gamma$ | 6012        | $|^{2S_1}|r|^{2S_3}P_0| = 3.225$  | 0.0668  | 0.094  |
| $B_s(1^3D_3)\gamma$ | 6182 | $|^{1D_3}|r|^{2S_3}P_0| = -2.424$ | 0.00387 | 0.0054 |
| $B_K$        | $^{1S_0} = -0.0908i$ |           |     | 31.0        | 43.6    |
| $B^*K$       | $^{1S_0} = 0.225i, ^2D_0 = -0.0283i$ |           |     | 36.5        | 51.4    |
| $B(1P_1)K$   | $^{3P_0} = 0.108$ |           |     | 2.85        | 4.0     |
| $B_s\eta$    | $^{1S_0} = -0.0152i$ |           |     | 0.686       | 1.0     |
|              | Total       | 71.0       |     | 100         |         |
| $B_s(2P_1')$ | $B_s(2^3S_0)\gamma$ | 5084        | $|^{2S_0}|r|^{2S_3}P_1| = 2.889$ | 0.0507  | 0.023  |
| 6279         | $B_s(2^3S_1)\gamma$ | 6012        | $|^{2S_1}|r|^{2S_3}P_1| = 3.120$ | 0.0186  | 0.0085 |
| $B_s(1D_2)\gamma$ | 6169 | $|^{1D_2}|r|^{2S_3}P_1| = -2.459, ^1D_2|r|^{2S_3}P_1| = -2.454$ | 0.00514 | 0.0024 |
| $B^*K$       | $^{3S_1} = -0.203i, ^3D_1 = -0.0270i$ |           |     | 72.4        | 33.1    |
| $B^*K$       | $^{3S_1} = 0.00394i, ^3D_1 = -0.162i$ |           |     | 86.5        | 39.6    |
| $B^*K^*$     | $^{3S_1} = 0.257i, ^3D_1 = 0.0170i, ^5D_1 = -0.0135i$ |           |     | 47.5        | 21.7    |
| $B(1^5P_1)K$ | $^{1P_1} = -0.0308$ |           |     | 0.461       | 0.2     |
| $B(1^3P_1)K$ | $^{3P_1} = -0.0299$ |           |     | 0.219       | 0.1     |
| $B_s\eta$    | $^{3S_1} = 0.000557i, ^5D_1 = 0.0666i$ |           |     | 11.3        | 5.2     |
|              | Total       | 218.4      |     | 100         |         |
| $B_s(2P_1')$ | $B_s\gamma$ | 5394        | $|^{1S_0}|r|^{2S_3}P_1| = 0.07821$ | 0.000385 | 0.00049 |
| 6296         | $B_s(2^3S_0)\gamma$ | 5084        | $|^{2S_0}|r|^{2S_3}P_1| = 2.889$ | 0.0252  | 0.032  |
| $B_s(2^3S_1)\gamma$ | 6012 | $|^{2S_1}|r|^{2S_3}P_1| = 3.120$ | 0.0523  | 0.066 |
| $B_s(1^3D_3)\gamma$ | 6182 | $|^{1D_3}|r|^{2S_3}P_1| = -2.265$ | 0.000944 | 0.0012 |
| $B_s(1D_2')\gamma$ | 6196 | $|^{1D_2}|r|^{2S_3}P_1| = -2.459, ^1D_2|r|^{2S_3}P_1| = -2.454$ | 0.00347 | 0.0044 |
| $B^*K$       | $^{3S_1} = -0.0706i, ^3D_1 = 0.0800i$ |           |     | 22.1        | 28.1    |
| $B^*K$       | $^{3S_1} = -0.0840i, ^3D_1 = -0.00687i$ |           |     | 24.3        | 30.9    |
| $B^*K^*$     | $^{3S_1} = -0.148i, ^5D_1 = -0.0232i, ^5D_1 = -0.0437i$ |           |     | 26.2        | 33.3    |
| $B(1^3P_0)K$ | $^{1P_0} = 0.0210$ |           |     | 0.279       | 0.4     |
| $B(1^3P_1)K$ | $^{3P_1} = 0.0763$ |           |     | 2.60        | 3.3     |
| $B(1^1P_1)K$ | $^{3P_1} = 0.0255$ |           |     | 0.243       | 0.3     |
| $B(1^3P_2)K$ | $^{5P_0} = 0.0798, ^5F_1 = -1.14 \times 10^{-5}$ |           |     | 1.14        | 1.4     |
| $B_s\eta$    | $^{3S_1} = -0.0245i, ^3D_1 = 0.00285i$ |           |     | 1.62        | 2.1     |
|              | Total       | 78.6       |     | 100         |         |
| $B_s(2^3P_3)$ | $B_s^*\gamma$ | 5450        | $|^{1S_1}|r|^{2S_3}P_2| = 0.09397$ | 0.00156 | 0.00063 |
| 6295         | $B_s(2^3S_1)\gamma$ | 6012        | $|^{2S_1}|r|^{2S_3}P_2| = 2.940$ | 0.0654  | 0.027  |
| $B_s(1^3D_3)\gamma$ | 6179 | $|^{1D_3}|r|^{2S_3}P_2| = -2.476$ | 0.00561 | 0.0023 |
| $B_K$        | $^{1D_2} = 0.0863i$ |           |     | 28.9        | 11.8    |
| $B^*K$       | $^{3D_2} = 0.0655i$ |           |     | 8.26        | 3.4     |
| $B^*K$       | $^{3D_2} = -0.120i$ |           |     | 49.0        | 19.9    |
| $B^*K^*$     | $^{3D_2} = 0.0130i, ^5S_2 = -0.372i, ^5D_2 = -0.0344i$ |           |     | 147         | 59.8    |
| $B(1^1P_1)K$ | $^{3P_2} = -0.0300, ^3F_2 = 0.000124$ |           |     | 0.323       | 0.1     |
| $B_s\eta$    | $^{1D_2} = -0.0413i$ |           |     | 5.28        | 2.2     |
| $B_s^*\eta$  | $^{3D_2} = 0.0516i$ |           |     | 7.10        | 2.9     |
|              | Total       | 246        |     | 100         |         |
TABLE XXIX: Partial widths and branching ratios for strong decays of the $3P B_s$ mesons. See the caption to Table XXIII for further explanations.

| Initial state | Final state | $\mathcal{M}$ | Width (MeV) | B.R. (%) |
|---------------|-------------|----------------|-------------|----------|
| $B_s(3^1P_0)$ | $BK$        | $^1S_0 = -0.0424 i$ | 12.4 | 24.3 |
|                | $B^*K^*$    | $^1S_0 = 0.0206 i, ^3D_1 = 0.0186 i$ | 3.88 | 7.6 |
|                | $B(2^1S_0)K$ | $^1S_0 = -0.0426 i$ | 3.72 | 7.3 |
|                | $B(1^D_2)K$ | $^5D_0 = 0.0852 i$ | 4.88 | 9.6 |
|                | $B_s\eta$  | $^1S_0 = -0.00629 i$ | 0.239 | 0.5 |
|                | $B_s\eta'$ | $^1S_0 = 0.0156 i$ | 1.08 | 2.1 |
|                | $B_s^*\phi$ | $^1S_0 = 0.00356 i, ^5D_0 = 0.0575 i$ | 11.1 | 21.8 |
|                | $B_s(2^1S_0)\eta$ | $^1S_0 = -0.0616 i$ | 4.72 | 9.3 |
|                | $B_s(1^P_1)\eta$ | $^3P_0 = 0.0590$ | 7.70 | 15.1 |
|                | $B_s(1^P_1')\eta$ | $^3P_0 = -0.0238$ | 1.23 | 2.4 |
|                | Total       |                | 51.0 | 100 |
| $B_s(3P_1)$    | $BK^*$      | $^3S_1 = -0.0116 i, ^3D_1 = -0.00437 i$ | 0.858 | 0.8 |
|                | $B^*K^*$    | $^3S_1 = 0.00257 i, ^3D_1 = -0.0502 i$ | 16.0 | 14.8 |
|                | $B^*K^*$    | $^3S_1 = 0.0222 i, ^3D_1 = -0.00758 i, ^5D_1 = 0.00613 i$ | 2.93 | 2.7 |
|                | $B(2^1S_1)K$ | $^3S_1 = 0.00148 i, ^3D_1 = -0.125 i$ | 28.3 | 26.1 |
|                | $B(1^D_2)K$ | $^5P_1 = 0.00162, ^5D_1 = 0.125$ | 43.9 | 40.6 |
|                | $B(1^D_2)K$ | $^3S_1 = -0.0517 i, ^3D_1 = -0.00518 i$ | 1.38 | 1.3 |
|                | $B(1^D_4)K$ | $^5D_1 = -0.0246 i$ | 0.399 | 0.4 |
|                | $B_s\phi$  | $^3S_1 = -0.0150 i, ^3D_1 = 0.0106 i$ | 1.34 | 1.2 |
|                | $B_s^*\eta'$ | $^3S_1 = -0.00851 i, ^3D_1 = 0.0228 i$ | 1.96 | 1.8 |
|                | $B_s^*\phi$ | $^3S_1 = 0.00463 i, ^3D_1 = -0.0322 i, ^5D_1 = 0.0244 i$ | 5.45 | 5.0 |
|                | $B_s(2^3S_1)\eta$ | $^3S_1 = 0.00558 i, ^3D_1 = 0.0346 i$ | 1.21 | 1.1 |
|                | $B_s(1^P_0)\eta$ | $^1P_1 = -0.0135$ | 0.431 | 0.4 |
|                | $B_s(1^P_1)\eta$ | $^3P_1 = -0.0163$ | 0.583 | 0.5 |
|                | $B_s(1^P_1')\eta$ | $^3P_1 = -0.00940$ | 0.190 | 0.2 |
|                | $B_s(1^P_2)\eta$ | $^5P_1 = -0.0132, ^5F_1 = -0.0373$ | 3.20 | 3.0 |
|                | Total       |                | 108.2 | 100 |
| Initial state | Final state | \( M \) | Width (MeV) | B.R. (%) |
|---------------|-------------|--------|------------|---------|
| \( B_s(3P_1^\prime) \) | \( BK^\prime \) | \( ^3S_1 = -0.00356 \, i, ^3D_1 = 0.0135 \, i \) | 1.12 | 2.4 |
| 6650 | \( B^*K \) | \( ^3S_1 = -0.0394 \, i, ^3D_1 = -0.00329 \, i \) | 10.1 | 21.2 |
|  | \( B^*K^\prime \) | \( ^3S_1 = -0.0119 \, i, ^3D_1 = 0.00163 \, i, ^5D_1 = 0.00391 \, i \) | 0.818 | 1.7 |
|  | \( B(2^3S_1)K \) | \( ^3S_1 = -0.0333 \, i, ^3D_1 = -0.00806 \, i \) | 2.25 | 4.7 |
|  | \( B(1P_1)K \) | \( ^3P_1 = -0.00599 \) | 0.110 | 0.2 |
|  | \( B(1^3P_2)K \) | \( ^5P_1 = 0.00180, ^5F_1 = 0.00833 \) | 0.213 | 0.4 |
|  | \( B(1^3D_1)K \) | \( ^3S_1 = -0.0026 \, i, ^3D_1 = 0.00827 \, i \) | 0.0483 | 0.1 |
|  | \( B(1D_2)K \) | \( ^5D_1 = -0.0500 \, i \) | 1.91 | 4.0 |
|  | \( B(1^3D_2)K \) | \( ^7D_1 = 0.0834 \, i, ^7G_1 = -0.000258 \, i \) | 4.71 | 9.9 |
|  | \( B_s^\phi \) | \( ^3S_1 = -0.00716 \, i, ^3D_1 = -0.0246 \, i \) | 2.72 | 5.7 |
|  | \( B_s^\eta \) | \( ^3S_1 = -0.00835 \, i, ^3D_1 = -2.47 \times 10^{-5} \, i \) | 0.394 | 0.8 |
|  | \( B_s^\eta^\prime \) | \( ^3S_1 = 0.0146 \, i, ^3D_1 = 0.00154 \, i \) | 0.856 | 1.8 |
|  | \( B_s^\phi^\prime \) | \( ^3S_1 = -0.00460 \, i, ^3D_1 = 0.0199 \, i, ^5D_1 = 0.0401 \, i \) | 7.03 | 14.7 |
|  | \( B_s(2^3S_1)\eta \) | \( ^3S_1 = -0.0749 \, i, ^3D_1 = 0.00256 \, i \) | 6.24 | 13.1 |
|  | \( B_s(1P_1)\eta \) | \( ^1P_1 = 0.00672 \) | 0.113 | 0.2 |
|  | \( B_s(3^1P_2)K \) | \( ^3S_1 = -0.0245 \, i, ^3D_1 = -0.0125 \, i \) | 0.357 | 0.7 |
|  | \( B_s(3^1P_2)\eta \) | \( ^5P_1 = 0.0584, ^5F_1 = -0.00263 \) | 7.36 | 15.4 |
| Total | | | 47.7 | 100 |

| Initial state | Final state | \( M \) | Width (MeV) | B.R. (%) |
|---------------|-------------|--------|------------|---------|
| \( B_s(3^1P_2) \) | \( BK \) | \( ^1D_2 = 0.0323 \, i \) | 7.29 | 6.8 |
| 6648 | \( BK^\prime \) | \( ^3D_2 = 0.0138 \, i \) | 1.10 | 1.0 |
|  | \( B^*K \) | \( ^3D_2 = -0.0406 \, i \) | 10.6 | 9.9 |
|  | \( B^*K^\prime \) | \( ^1D_2 = 0.000413 \, i, ^5S_2 = -0.0270 \, i, ^5D_2 = -0.00109 \, i \) | 3.74 | 3.5 |
|  | \( B(2^3S_0)K \) | \( ^1D_2 = 0.0752 \, i \) | 12.0 | 11.2 |
|  | \( B(2^3S_1)K \) | \( ^3D_2 = -0.0961 \, i \) | 17.6 | 16.5 |
|  | \( B(1P_1)K \) | \( ^3P_2 = 0.00261, ^3F_2 = -0.0829 \) | 21.1 | 19.8 |
|  | \( B(1^3P_2)K \) | \( ^5P_2 = -0.00256, ^5F_2 = 0.0772 \) | 17.4 | 16.3 |
|  | \( B(1D_2)K \) | \( ^5S_2 = 0.000314 \, i, ^5D_2 = 0.0168 \, i, ^7G_2 = 0.00404 \, i \) | 0.233 | 0.2 |
|  | \( B(1^3D_2)K \) | \( ^7D_2 = -0.0317 \, i, ^7G_2 = -0.00218 \, i \) | 0.665 | 0.6 |
|  | \( B_s^\eta \) | \( ^1D_2 = -0.00906 \, i \) | 0.372 | 0.3 |
|  | \( B_s^\phi \) | \( ^3D_2 = -0.0186 \, i \) | 1.42 | 1.3 |
|  | \( B_s^\eta^\prime \) | \( ^3D_2 = 0.0157 \, i \) | 0.965 | 0.9 |
|  | \( B_s^\phi^\prime \) | \( ^1D_2 = -0.0111 \, i, ^5S_2 = -0.0130 \, i, ^5D_2 = 0.0294 \, i \) | 3.99 | 3.7 |
|  | \( B_s(2^3S_0)\eta \) | \( ^1D_2 = -0.0287 \, i \) | 1.08 | 1.0 |
|  | \( B_s(2^3S_1)\eta \) | \( ^3D_2 = 0.0300 \, i \) | 0.985 | 0.9 |
|  | \( B_s(1P_1)\eta \) | \( ^3P_2 = 0.00403, ^3F_2 = 0.0283 \) | 1.86 | 1.7 |
|  | \( B_s(1^3P_2)\eta \) | \( ^3P_2 = -0.0185, ^3F_2 = -0.00253 \) | 0.782 | 0.7 |
| Total | | | 106.8 | 100 |
TABLE XXXI: Partial widths and branching ratios for strong and electromagnetic decays of the 1D $B_s$ mesons. See the caption to Table [XXXIII] for further explanations.

| Initial state | Final state | $M_f$ (MeV) | $M$ | Width (MeV) | B.R. (%) |
|---------------|-------------|-------------|-----|-------------|---------|
| $B_s(1^1D_1)$ | $B_s(1^3P_0)\gamma$ | 5831 | $(1^3P_0|\gamma|1^1D_1) = 2.805$ | 0.0747 | 0.41 |
| 6182 | $B_s(1^3P_1)\gamma$ | 5857 | $(1^3P_1|\gamma|1^1D_1) = 2.939$ | 0.0196 | 0.11 |
| | $B_s(1P'_1)\gamma$ | 5861 | $(1^3P_1|\gamma|1^1D_1) = 2.939$ | 0.0285 | 0.16 |
| | $B_s(1^3P_2)\gamma$ | 5876 | $(1^3P_2|\gamma|1^1D_1) = 3.113$ | 0.00307 | 0.0017 |
| $BK$ | | | $^1P_1 = 0.19$ | 108 | 59.0 |
| $B^*K$ | | | $^3P_1 = 0.144$ | 52.8 | 28.9 |
| $B_s\eta$ | | | $^1P_1 = -0.0832$ | 15.4 | 8.4 |
| $B_s^*\eta$ | | | $^3P_1 = -0.0589$ | 6.26 | 3.4 |
| Total | | | | 183.0 | 100 |
| $B_s(1D_2)$ | $B_s(1P_1)\gamma$ | 5857 | $(1^3P_1|\gamma|1^3D_2) = 2.940, (1^3P_1|\gamma|1^1D_2) = 2.994$ | 0.0959 | 0.58 |
| 6169 | $B_s(1P'_1)\gamma$ | 5861 | $(1^3P_1|\gamma|1^3D_2) = 2.940, (1^3P_1|\gamma|1^1D_2) = 2.994$ | 0.000368 | 0.0022 |
| | $B_s(1^3P_2)\gamma$ | 5876 | $(1^3P_2|\gamma|1^3D_2) = 3.127$ | 0.0102 | 0.062 |
| $B^*K$ | | | $^3P_2 = 0.00252, ^3F_2 = -0.0803$ | 15.9 | 97.1 |
| $B_s^*\eta$ | | | $^3P_2 = -0.000861, ^3F_2 = 0.0150$ | 0.387 | 2.4 |
| Total | | | | 16.4 | 100 |
| $B_s(1D'_2)$ | $B_s(1P_1)\gamma$ | 5857 | $(1^3P_1|\gamma|1^3D_2) = 2.940, (1^3P_1|\gamma|1^1D_2) = 2.994$ | 0.00107 | 0.00055 |
| 6196 | $B_s(1P'_1)\gamma$ | 5861 | $(1^3P_1|\gamma|1^3D_2) = 2.940, (1^3P_1|\gamma|1^1D_2) = 2.994$ | 0.112 | 0.058 |
| | $B_s(1^3P_2)\gamma$ | 5876 | $(1^3P_2|\gamma|1^3D_2) = 3.127$ | 0.0188 | 0.0097 |
| $B^*K$ | | | $^3P_2 = 0.254, ^3F_2 = 0.00193$ | 171 | 88.3 |
| $B_s^*\eta$ | | | $^3P_2 = -0.108, ^3F_2 = -0.000397$ | 22.3 | 11.5 |
| Total | | | | 194 | 100 |
| $B_s(1^3D_3)$ | $B_s(1^3P_2)\gamma$ | 5876 | $(1^3P_2|\gamma|1^3D_3) = 3.134$ | 0.109 | 0.41 |
| 6179 | $BK$ | | $^1F_3 = 0.0688$ | 14.0 | 53.0 |
| | $B^*K$ | | $^3F_3 = -0.0672$ | 11.4 | 43.1 |
| | $B_s\eta$ | | $^1F_3 = -0.0154$ | 0.522 | 2.0 |
| | $B_s^*\eta$ | | $^3F_3 = 0.0131$ | 0.305 | 1.1 |
| Total | | | | 26.4 | 100 |
V. MODEL SENSITIVITY

The results of Tables IV–XXXV are presented in terms of Godfrey-Isgur model masses and wavefunctions. Rather than double the number of tables by giving the analogous ARM results, we have chosen to represent model sensitivity graphically. For example, Fig. 3 is a scatter plot of Godfrey-Isgur versus ARM masses. A close correspondence is evident, although ARM masses tend to be lower than GI masses higher in the spectrum due to the different string tensions employed in the models.

![FIG. 3: Mass predictions for Godfrey-Isgur (GI) and ARM (Rel) models. Solid symbols are B states; open symbols are B_s states.](image)

The similarity of the mass predictions is also reflected in the high correlation of the predicted strong decay widths of the two models, shown in Fig. 4. An alternate measure of the model sensitivity is to calculate the relative difference of the predicted strong decay widths which we take to be the difference between the GI predictions and the ‘alternate model’ divided by the GI prediction. For the predictions of the alternate model, data were generated under a variety of conditions; specifically (i) full ARM predictions, (ii) ARM wavefunctions, (iii) ARM wavefunctions and quark masses, (iv) ARM wavefunctions and meson masses. For the purposes of illustration a representative set of decays were used to construct the frequency histogram of the relative difference of predicted strong decay widths shown in Fig. 5. One observes that the distribution is peaked at zero deviation, while the average deviation is 14%.

![FIG. 4: Selected Strong Decay Width Predictions for Godfrey-Isgur (GI) and AR (Rel) models.](image)

Radiative transitions can be very sensitive to model details. For example, the size of hindered M1 transitions depends crucially on assumed wavefunctions. Similarly, radiative transition rates for heavy-light mesons involve differences of light and heavy quark amplitudes, and these differences depend strongly on whether the light quark amplitude is considered in the nonrelativistic limit or not [11]. It is therefore perhaps not surprising that the GI and AR models deviate somewhat in their predicted E1 transition rates, as shown in Fig. 6. Fig. 7 shows the related frequency histogram, calculated as described above, and indicates that the GI E1 predictions tend to be approximately 50% larger than those of the AR model.

![FIG. 5: Relative deviation of strong decay predictions.](image)

We find these results reasonably reassuring. It appears that constituent quark models that have been tuned to a wide range of hadrons provide similar predictions for hadronic properties. Perhaps the most interesting deviation seen here is the systematically lighter predictions
of excited $B$ and $B_s$ states by the AR model with respect to the GI model. This is almost certainly due to the differing string tensions employed in the two models. Certainly, the ‘stiff’ string tension of the GI model is preferred by lattice Wilson loop computations and bottomonium spectroscopy. However, the smaller string tension of the ARM fits lighter mesons better. It will be interesting to see which is preferred in the description of heavy-light mesons.

### VI. CLASSIFICATION OF THE OBSERVED BOTTOM MESONS

The experimental knowledge of excited $B$ mesons is rather limited. However recent measurements by the LHCb collaboration [3] have demonstrated the potential to extend our knowledge of these states considerably. In the following section we will discuss the excited $B$ mesons we believe are most likely to be observed in the near future and how they might be observed. In this section we will summarize the existing situation, comment on spectroscopic assignments and suggest measurements.
TABLE XXXIII: Partial widths and branching ratios for strong decays of the $2D B_s$ mesons. See the caption to Table XXXIII for further explanations.

| Initial state | Final state | $\mathcal{M}$ | Width (MeV) | B.R. (%) |
|---------------|-------------|---------------|-------------|----------|
| $B_s(2D'_2)$ | $B K^*$     | $^3P_2 = -0.00218, ~^3F_2 = -0.0806$ | 30.7 | 13.8 |
| $B K^*$      | $^3P_2 = 0.0838, ~^3F_2 = 0.000655$ | 39.2 | 17.6 |
| $B^* K^*$    | $^3P_2 = 0.00911, ~^3F_2 = 0.0590, ~^5P_2 = 0.00895, ~^5F_2 = 0.0835$ | 43.9 | 19.7 |
| $B(2^3S_1) K$ | $^3P_2 = 0.163, ~^3F_2 = 0.000346$ | 32.6 | 14.6 |
| $B(1^3P_0) K$ | $^3D_2 = 0.0294 i$ | 2.16 | 1.0 |
| $B(1P_1) K$  | $^3D_2 = -0.0693 i$ | 11.2 | 5.0 |
| $B(1P_2) K$  | $^3D_2 = -0.0409 i$ | 3.83 | 1.7 |
| $B(1^3P_2) K$ | $^5S_2 = -0.0247 i, ~^5D_2 = 0.121 i, ~^5G_2 = 0.000351 i$ | 33.4 | 15.0 |
| $B_s \eta'$  | $^3P_2 = 0.0119, ~^3F_2 = -0.0201$ | 1.61 | 0.7 |
| $B_s \phi$   | $^3P_2 = -0.0457, ~^3F_2 = -2.25 \times 10^{-5}$ | 5.91 | 2.6 |
| $B_s(1^3P_0) \eta$ | $^3D_2 = 0.0387, ~^3F_2 = 0.00859, ~^5P_2 = 0.0337, ~^5F_2 = 0.0121$ | 6.26 | 2.8 |
| $B_s(1P_1) \eta$ | $^3D_2 = -0.0116 i$ | 0.236 | 0.1 |
| $B_s(1P_2) \eta$ | $^3D_2 = 0.0251 i$ | 0.977 | 0.4 |
| Total         | $^5S_2 = -0.0771 i, ~^5D_2 = -0.0373 i, ~^5G_2 = -3.67 \times 10^{-5} i$ | 10.3 | 4.6 |
| $B_s(2^1D_3)$ | $B K$       | $^1F_3 = -0.0339$ | 6.82 | 6.4 |
| $B K^*$      | $^3F_3 = -0.0582$ | 15.4 | 14.4 |
| $B^* K^*$    | $^3F_3 = 0.0523$ | 14.8 | 13.8 |
| $B^* K^*$    | $^1F_3 = -0.0300, ~^5P_3 = 0.0235, ~^5F_3 = 0.0657$ | 22.7 | 21.2 |
| $B(2^3S_1) K$ | $^1F_3 = 0.0294$ | 1.13 | 1.1 |
| $B(2^3S_2) K$ | $^3F_3 = -0.0252$ | 0.702 | 0.6 |
| $B(1P_1) K$  | $^3D_3 = 0.0321 i, ~^3G_3 = 0.0403 i$ | 5.87 | 5.5 |
| $B(1P_2) K$  | $^3D_3 = -0.0530 i, ~^3G_3 = 0.00252 i$ | 6.08 | 5.7 |
| $B(1^3P_2) K$ | $^5D_3 = -0.0727 i, ~^5G_3 = -0.0298 i$ | 12.7 | 11.9 |
| $B_s \eta'$  | $^1F_3 = 0.0219$ | 2.45 | 2.3 |
| $B_s \eta'$  | $^1F_3 = -0.0120$ | 0.467 | 0.4 |
| $B_s \phi$   | $^1F_3 = -0.0127$ | 0.440 | 0.4 |
| $B_s \eta$   | $^3F_3 = -0.0282$ | 3.86 | 3.4 |
| $B_s \eta'$  | $^3F_3 = 0.0105$ | 0.285 | 0.3 |
| $B_s \phi$   | $^1F_3 = -0.00330, ~^5P_3 = 0.0796, ~^5F_3 = 0.00724$ | 12.2 | 11.4 |
| $B_s(1P_1) \eta$ | $^3D_3 = -0.00758 i, ~^3G_3 = -0.00448 i$ | 0.110 | 0.1 |
| $B_s(1P_2) \eta$ | $^3D_3 = 0.0201 i, ~^3G_3 = 0.00380 i$ | 0.561 | 0.5 |
| Total         | $^5D_3 = 0.0210 i, ~^5G_3 = 0.00280 i$ | 0.572 | 0.5 |

that would improve our understanding of these states. A summary of the experimental status of the excited $B$ mesons is presented in Table XXXVI.

Starting with the $B$ mesons, four members of the $1P$ multiplet are expected to be seen around 5750 MeV, comprised of a doublet of two relatively narrow states and a doublet of two relatively broad states. The $B_1(5727)$ and $B_2(5739)$ with widths of 30 MeV and 24 MeV respectively (we quote recent results from LHCb [4], which have smaller errors than listed in the PDG [45]) have measured properties that are in qualitative agreement with our predictions. The GI model overestimates the $B_1$ and $B_2'$ masses by approximately 50 MeV. However the GI model also overestimates the $B$ and $B^*$ masses by a similar amount so it is reasonable to assume that the GI model in general overestimates $B$ masses by $\sim 50$ MeV. In contrast, the ARM mass predictions agree with experiment within approximately 10 MeV. However the GI model predicts a doublet of two relatively narrow states, the predicted widths are quite a bit smaller than the measured widths; 7 MeV vs 30 MeV for the $B_1$ and 12 MeV vs 24 MeV for the $B_2'$. In general we would not be surprised if our width predictions were off by a factor of 2 so would consider the $B_2'$ width prediction to be...
TABLE XXXIV: Partial widths and branching ratios for strong and electromagnetic decays of the 1F Bs mesons. See the caption to Table XXIII for further explanations.

| Initial state | Final state | \( M_f \) (MeV) | \( M \) | Width (MeV) | B.R. (%) |
|---------------|-------------|----------------|--------|-------------|---------|
| \( B_s(1^3F_2) \) | \( B_s(1^3D_1)\gamma \) | 6182 | (1\(^3\)D\(_1\)|r|1\(^3\)F\(_2\)) = 3.711 | 0.101 | 0.039 |
| \( B_s(1^3F_2) \) | \( B_s(1^3D_2)\gamma \) | 6196 | (1\(^3\)D\(_2\)|r|1\(^3\)F\(_2\)) = 3.835 | 0.00946 | 0.0037 |
| \( B_s(1^3D_1)\gamma \) | \( B_s(1^3D_2)\gamma \) | 6196 | (1\(^3\)D\(_2\)|r|1\(^3\)F\(_2\)) = 3.835 | 0.0100 | 0.0039 |
| \( BK \) | 1\(^1\)D\(_2\) = 0.107 i | 59.9 | 23.4 |
| \( BK^* \) | 3\(^1\)D\(_2\) = 0.0897 i | 29.8 | 11.6 |
| \( B^*K \) | 3\(^1\)D\(_2\) = 0.0951 i | 42.7 | 16.7 |
| \( B^*K^* \) | 1\(^1\)D\(_2\) = 0.059 i, 5\(^1\)D\(_2\) = 0.0447 i, 5\(^1\)G\(_2\) = 0.0370 i | 21.1 | 8.2 |
| \( B(2^1S_0)K \) | 1\(^1\)D\(_2\) = 0.0204 i | 0.297 | 0.1 |
| \( B(1^1P_1)K \) | 3\(^1\)P\(_2\) = 0.212, 3\(^1\)F\(_2\) = 0.0243 | 73.9 | 28.8 |
| \( B(1^3P_1)K \) | 3\(^3\)P\(_2\) = 0.0167, 3\(^3\)F\(_2\) = 0.00500 | 0.481 | 0.2 |
| \( B(1^3P_2)K \) | 5\(^3\)P\(_2\) = 0.0739, 5\(^3\)F\(_2\) = 0.0269 | 9.21 | 3.6 |
| \( B_s\eta \) | 1\(^1\)D\(_2\) = 0.0439 i | 8.49 | 3.3 |
| \( B_s\eta^* \) | 1\(^3\)D\(_2\) = 0.0215 i | 1.05 | 0.4 |
| \( B_s\eta^* \) | 3\(^1\)D\(_2\) = 0.0374 i | 5.51 | 2.2 |
| \( B_s(1^3P_2)\eta \) | 3\(^3\)P\(_2\) = 0.0640, 3\(^3\)F\(_2\) = 0.00144 | 3.12 | 1.2 |
| Total | &nbsp; | 256.3 | 100 |

| \( B_s(1^3F_3) \) | \( B_s(1^3D_2)\gamma \) | 6196 | (1\(^3\)D\(_2\)|r|1\(^3\)F\(_3\)) = 3.839, (1\(^3\)D\(_2\)|r|1\(^3\)F\(_3\)) = 3.878 | 0.105 | 0.076 |
| \( B(1^3P_1)K \) | &nbsp; | 0.00503 | 0.0036 |
| \( B(1^3P_2)K \) | &nbsp; | 7.11 \times 10^{-5}, 5\(^3\)F\(_3\) = -0.0119, 5\(^5\)H\(_3\) = 0.00248 | 0.192 | 0.1 |
| \( B_s\eta \) | &nbsp; | 0.000122 i, 3\(^3\)G\(_3\) = 0.0217 i | 1.74 | 1.3 |
| Total | &nbsp; | 138.4 | 100 |

| \( B_s(1^3F_3) \) | \( B_s(1^3D_3)\gamma \) | 6197 | (1\(^3\)D\(_2\)|r|1\(^3\)F\(_3\)) = 3.992 | 0.000446 | 0.00016 |
| \( B(1^3P_1)K \) | &nbsp; | 0.00989 | 0.0036 |
| \( B(1^3P_2)K \) | &nbsp; | 0.243, 3\(^3\)F\(_3\) = 0.0321, 5\(^3\)H\(_3\) = 6.03 \times 10^{-5} | 92.9 | 33.9 |
| \( B_s\eta \) | &nbsp; | 0.0066 i, 3\(^3\)G\(_3\) = 0.00211 i | 14.7 | 5.4 |
| \( B_s\eta^* \) | &nbsp; | 3\(^3\)D\(_3\) = 0.0183 i, 3\(^5\)G\(_3\) = 7.98 \times 10^{-6} i | 0.538 | 0.2 |
| \( B_s(1^3P_2)\eta \) | &nbsp; | 5\(^5\)P\(_3\) = 0.0679, 5\(^3\)F\(_3\) = 0.00154 | 3.04 | 1.1 |
| Total | &nbsp; | 274 | 100 |

| \( B_s(1^3F_3) \) | \( B_s(1^3D_3)\gamma \) | 6197 | (1\(^3\)D\(_3\)|r|1\(^3\)F\(_3\)) = 4.002 | 0.113 | 0.082 |
| \( B(1^3P_1)K \) | &nbsp; | 0.0702 i | 24.8 | 17.9 |
| \( B(1^3P_3)K \) | &nbsp; | 3\(^3\)G\(_4\) = 0.0252 i | 2.20 | 1.6 |
| \( B(1^3P_2)^* \) | &nbsp; | 3\(^3\)G\(_4\) = 0.0729 i | 24.1 | 17.4 |
| \( B^*K^* \) | 1\(^1\)G\(_4\) = 0.00834 i, 5\(^1\)D\(_4\) = 0.171 i, 5\(^1\)G\(_4\) = 0.0165 i | 84.2 | 60.8 |
| \( B(1^3P_3)K \) | &nbsp; | 3\(^3\)F\(_4\) = 0.0110, 3\(^3\)H\(_4\) = 0.00306 | 0.193 | 0.1 |
| \( B(1^3P_2)^* \) | &nbsp; | 3\(^3\)F\(_4\) = 0.00990, 3\(^5\)H\(_4\) = 0.00183 | 0.140 | 0.1 |
| \( B(1^3P_3)^* \) | &nbsp; | 5\(^3\)F\(_4\) = 0.0205, 5\(^3\)H\(_4\) = 0.00173 | 0.564 | 0.4 |
| \( B_s\eta \) | &nbsp; | 1\(^1\)G\(_4\) = 0.0173 i | 1.25 | 0.9 |
| \( B_s\eta^* \) | &nbsp; | 3\(^3\)G\(_4\) = 0.0172 i | 1.11 | 0.8 |
| Total | &nbsp; | 138.6 | 100 |
TABLE XXXV: Partial widths and branching ratios for strong decays of the $1G B_s$ mesons. In this table, we do not show strong decay modes which have BR < 0.5%, although they are included in calculating the total width. See the caption to Table XXXIII for further explanations.

| Initial state | Final state | $M$ | Width (MeV) | B.R. (%) |
|---------------|-------------|-----|-------------|---------|
| $B_s(1^3G_3)$ | $B K$       | $^1F_3 = -0.0662$ | 32.2 | 11.9 |
|               | $B K^*$     | $^3F_3 = 0.0656$  | 26.3 | 9.7  |
|               | $B^* K$     | $^3F_3 = -0.0630$ | 27.0 | 10.0 |
|               | $B^* K^*$   | $^1F_3 = -0.0450, ^5F_3 = 0.0410, ^5H_3 = 0.0666$ | 44.9 | 16.6 |
|               | $B(2^1S_0)K$ | $^1F_3 = 0.0446$  | 4.76 | 1.8  |
|               | $B(2^3S_1)K$ | $^3F_3 = 0.0351$  | 2.67 | 1.0  |
|               | $B(1P_1)K$  | $^3D_3 = 0.130 i, ^3G_3 = 0.0312 i$ | 60.4 | 22.4 |
|               | $B(1^3P_2)K$ | $^5D_3 = 0.0570 i, ^5G_3 = 0.0409 i$ | 15.8 | 5.8  |
|               | $B(1D_2)K$  | $^5P_3 = 0.175, ^5F_3 = 0.0165, ^5H_3 = 0.000413$ | 31.7 | 11.7 |
|               | $B(1^3D_4)K$ | $^7P_3 = 0.0403, ^7F_3 = 0.00952, ^7H_3 = 0.000533$ | 1.63 | 0.6  |
|               | $B_s\eta$   | $^1F_3 = 0.0254$  | 4.18 | 1.6  |
|               | $B_s\eta'$  | $^1F_3 = -0.0197$ | 1.91 | 0.7  |
|               | $B_s\phi$   | $^3F_3 = 0.0208$  | 1.96 | 0.7  |
|               | $B_s^*\eta$ | $^3F_3 = 0.0233$  | 3.26 | 1.2  |
|               | $B_s^*\phi$ | $^1F_3 = -0.0122, ^5F_3 = 0.0112, ^5H_3 = 0.00733$ | 1.28 | 0.5  |
|               | $B_s(1P_1)\eta$ | $^3D_3 = -0.0489 i, ^3G_3 = -0.00546 i$ | 6.22 | 2.3  |
|               | Total       |               | 269.7 | 100  |
| $B_s(1^1G_4)$ | $B K^*$     | $^3F_4 = 0.0988, ^3H_4 = 0.00519$ | 56.2 | 33.5 |
|               | $B^* K$     | $^3F_4 = -0.000169, ^3H_4 = 0.0863$ | 48.2 | 28.7 |
|               | $B^* K^*$   | $^3F_4 = -0.0709, ^3H_4 = -0.0307, ^5F_4 = 0.0549, ^5H_4 = 0.0299$ | 50.9 | 30.3 |
|               | $B(1P_1)K$  | $^3G_4 = -0.0263 i$ | 2.14 | 1.3  |
|               | $B(1^3P_2)K$ | $^5D_4 = -9.42 \times 10^{-5} i, ^5G_4 = -0.0225 i, ^5I_4 = -0.0122 i$ | 1.92 | 1.1  |
|               | $B_s\phi$   | $^3F_4 = 0.0282, ^3H_4 = 0.000613$ | 3.28 | 2.0  |
|               | $B_s^*\eta$ | $^3F_4 = 4.53 \times 10^{-6}, ^3H_4 = -0.0199$ | 2.24 | 1.3  |
|               | $B_s^*\phi$ | $^3F_4 = -0.0166, ^3H_4 = -0.00266, ^5F_4 = 0.0129, ^5H_4 = 0.00260$ | 1.58 | 0.9  |
|               | Total       |               | 168.2 | 100  |
| $B_s(1^3G_4)$ | $B K^*$     | $^3F_4 = 0.0111, ^3H_4 = -0.0539$ | 18.7 | 6.3  |
|               | $B^* K$     | $^3F_4 = -0.0948, ^3H_4 = -0.000248$ | 61.5 | 20.8 |
|               | $B^* K^*$   | $^3F_4 = 0.0658, ^3H_4 = 0.0333, ^5F_4 = 0.0635, ^5H_4 = 0.0405$ | 61.8 | 20.9 |
|               | $B(2^1S_0)K$ | $^3F_4 = 0.0580, ^3H_4 = 9.80 \times 10^{-5}$ | 7.44 | 2.5  |
|               | $B(1P_1)K$  | $^3G_4 = -0.0319 i$ | 3.46 | 1.2  |
|               | $B(1^3P_2)K$ | $^5D_4 = 0.153 i, ^5G_4 = 0.0426 i, ^5I_4 = 0.000107 i$ | 81.4 | 27.5 |
|               | $B(1^3D_4)K$ | $^7P_4 = 0.195, ^7F_4 = 0.0185, ^7H_4 = 0.000552$ | 37.6 | 12.7 |
|               | $B_s^*\eta$ | $^3F_4 = 0.0360, ^3H_4 = 7.45 \times 10^{-5}$ | 7.82 | 2.6  |
|               | $B_s^*\phi$ | $^3F_4 = -0.0254, ^3H_4 = -2.49 \times 10^{-5}$ | 2.84 | 1.0  |
|               | $B_s(1^3P_2)\eta$ | $^3F_4 = 0.0186, ^3H_4 = 0.00381, ^5F_4 = 0.0179, ^5H_4 = 0.00462$ | 2.77 | 0.9  |
|               | $B_s(1^3P_2)\phi$ | $^3D_4 = -0.0573 i, ^3G_4 = -0.00796 i, ^5I_4 = -1.11 \times 10^{-5} i$ | 8.25 | 2.8  |
|               | Total       |               | 295.5 | 100  |
| $B_s(1^3G_5)$ | $B K$       | $^1H_5 = -0.0615$ | 26.6 | 14.9 |
|               | $B K^*$     | $^3H_5 = -0.0356$ | 7.32 | 4.1  |
|               | $B^* K$     | $^3H_5 = 0.0655$ | 27.9 | 15.7 |
|               | $B^* K^*$   | $^1H_5 = -0.0160, ^5F_5 = 0.137, ^5H_5 = 0.0297$ | 103 | 57.9 |
|               | $B(1P_1)K$  | $^3G_5 = 0.0180 i, ^3I_5 = 0.0113 i$ | 1.40 | 0.8  |
|               | $B(1^3P_2)K$ | $^3G_5 = -0.0200 i, ^3I_5 = 0.000685 i$ | 1.23 | 0.7  |
|               | $B(1^3P_2)K$ | $^5G_5 = -0.0345 i, ^5I_5 = -0.00756 i$ | 3.68 | 2.1  |
|               | $B_s\eta$   | $^1H_5 = 0.0146$ | 1.32 | 0.7  |
|               | $B_s^*\eta$ | $^3H_5 = -0.0153$ | 1.33 | 0.7  |
|               | $B_s^*\phi$ | $^1H_5 = -0.00144, ^5F_5 = 0.0331, ^5H_5 = 0.00267$ | 3.90 | 2.2  |
|               | Total       |               | 178 | 100  |
acceptable also taking into account experimental error. However the discrepancy of the \( B_1 \) width prediction is most likely due to the sensitivity of the prediction to the \( ^3P_1 \rightarrow ^1P_1 \) mixing angle (\( \theta_{1P} \)). Even a small change in mixing angle would have a dramatic effect on the width prediction and in fact we could use this information to constrain \( \theta_{1P} \).

The \( B(5970) \) has been seen in the \( B\pi \) final state by the CDF collaboration with a mass of \( 5961 \pm 13 \) MeV for the \( B(5970)^0 \) and \( 5977 \pm 13 \) MeV for the \( B(5970)^0 \) with widths of \( 60 \pm 50 \) MeV and \( 70 \pm 42 \) MeV respectively [14]. The only \( B \) mesons that are close in mass to the \( B(5970) \) are the \( B^*(2^3S_1) \) and \( B(2^1S_0) \) states. However, the \( B(2^1S_0) \) cannot decay to a \( B\pi \) final state, leaving only the \( B^*(2^3S_1) \) as a possible candidate. The GI model predicts the mass of the \( B^*(2^3S_1) \) to be 5933 MeV although as previously noted we believe that the GI model overestimates \( B \) masses by approximately 50 MeV. The AR model predicts the mass of this state to be 5864 MeV. Thus the observed mass appears to be too large to be identified with the \( B^*(2^3S_1) \) state. However the predicted width for the \( B^*(2^3S_1) \) is 108 MeV which, given both the large experimental errors and theoretical uncertainties, is consistent with the measured widths. So while the \( B(5970) \) might be identified with the \( B^*(2^3S_1) \), given the large discrepancy between the predicted and observed mass we wait for further measurements of this state before making a conclusion.

Recently LHCb [4] reported the observation of new states, the \( B_1(5840) \) and the \( B_1(5960) \) with masses and widths of \( M(B_1(5840)) = 5857 \) MeV, \( \Gamma(B_1(5840)) = 175.9 \) MeV and \( M(B_1(5960)) = 5967 \) MeV, \( \Gamma(B_1(5960)) = 73 \) MeV where we have averaged the masses and widths for the two observed charge states and do not quote experimental errors as they are quite large and the extracted values are very model dependent. LHCb suggests these may be the \( B(2^1S_0) \) and \( B^*(2^3S_1) \) states. This can be compared to the predicted masses (from ARM) and widths for the two states of \( M = 5834 \) MeV and \( \Gamma = 95 \) MeV for the \( B(2^1S_0) \) and \( M = 5864 \) MeV and \( \Gamma = 108 \) MeV for the \( B^*(2^3S_1) \). The predicted properties of the \( B(2^1S_0) \) are consistent with those of \( B_1(5840) \) within experimental and theoretical uncertainties and while the predicted \( B^*(2^3S_1) \) width is consistent with that of the \( B_1(5960) \), the predicted mass is about 100 MeV too low. All things considered, these new states can be identified with the \( 2S \) \( B \) mesons but ideally more measurements are needed to support this conclusion. A final comment is that the properties of the \( B(5970) \) seen by CDF are consistent with the properties of the \( B_1(5960) \) seen by LHCb.

The two remaining excited bottom mesons that have been observed are the bottom-strange states: the \( B_{s1}(5830)^0 \) with \( M = 5828.78 \pm 0.35 \) MeV and \( \Gamma = 0.5 \pm 0.4 \) MeV and the \( B_{s2}^*(5840)^0 \) with \( M = 5839.83 \pm 0.19 \) MeV and \( \Gamma = 1.47 \pm 0.33 \) MeV [15]. Further, for the \( B_{s2}^* \), \( \Gamma(B^{++}K^-)/\Gamma(B^+K^-) = 0.093 \pm 0.018 \). We compare these to the properties of the \( B_{s1}(1P) \) with \( M = 5822 \) MeV and \( \Gamma = 0.11 \) MeV and the \( B_{s2}^*(1P_2) \) with \( M = 5836 \) MeV and \( \Gamma = 0.78 \) MeV where we quote the mass predictions of the AR model. The predicted masses are in good agreement with the measured masses and the predicted width of the \( B_{s1}^*(1P_2) \) is in acceptable agreement with the \( B_{s2}^*(5840)^0 \) measured width. However, as in the case of the \( B_1(5727) \) we again surmise that the discrepancy is due to the sensitivity of the \( B_{s1}(1P) \) width to the \( ^3P_1 \rightarrow ^1P_1 \) mixing angle. The \( B_{s1}(1P) \) is also close to the \( B^*K \) threshold so is very sensitive to phase space. As shown in Table [XXVII] there are no kinematically allowed strong decay modes for the \( B_{s1}(1P_1) \) and \( B_{s1}(1P_2) \) when using their predicted Godfrey-Isgur masses as input. However, using the measured mass for
the $B_{s1}(1P)$ state as input to the $^3P_0$ model calculations opens up the $B_s(1P_1) \rightarrow B^*K$ decay mode with a partial width of 0.331 MeV.

To summarize, the information on excited bottom mesons is limited. For both the bottom and bottom-strange mesons, two narrow states have been seen and their properties are consistent with those of the $1^3P_2$ and $1P_1$ quark model states. Two more states have been observed, most recently by the LHCb collaboration \[,\] but the experimental uncertainties are quite large so although these states may be the $B(2^3S_0)$ and $B^*(2^3S_1)$ states more data is needed to confirm these identifications. However, the recent LHCb results show the promise that LHCb holds in opening up new frontiers in bottom meson spectroscopy. In the next section we examine the $B$ meson landscape and suggest promising avenues for finding new excited bottom mesons.

**VII. EXPERIMENTAL SIGNATURES AND SEARCH STRATEGIES**

We expect that the excited $B$ mesons most likely to be observed in the near future are those that are relatively narrow and that have a large branching ratio (BR) to a simple final state such as $B\pi$, $B^*\pi$, $BK$, or $B^*K$. There has been great recent progress in finding excited charm mesons in the analogous $D\pi$ final states \[.\] In this section we examine Tables [IV][XXXV] to identify states that meet these criteria.

Starting with the $B$ and $B_s$ $1P$ multiplets the $1P_1$ and $1^3P_2$ states have already been seen. Their predicted properties are in reasonable agreement with the measured properties within the theoretical uncertainties. The hallmark of these states is that they have relatively small total widths with large BR’s to simple final states. We expect the total widths for the $j_q = 1/2$ doublet to be considerably larger but still not so large that an observable signal in a simple final state should be seen. Specifically, we calculate the total width for the $B(1^3P_0)$ to be 154 MeV decaying almost 100% of the time to $B\pi$ (with a small BR to $B^*\pi$), and $\Gamma(B(1P_1)) = 163$ MeV decaying almost 100% of the time to $B^*\pi$. Similarly we calculate $\Gamma(B_s(1^3P_0)) = 138$ MeV decaying predominantly to $BK$, and the $B_s(1P_1)$ is below $B^*K$ threshold so is expected to be quite narrow with its dominant BRs to $B_s\gamma$ and $B^*_s\gamma$. The ratio of these two BR’s would determine the $^3P_0 - 1P_1$ mixing angle. For these predicted total widths it should be possible to observe the missing $B$ and $B_s$ $1P$ states in the near future. The challenge will be disentangling overlapping states but this should be possible with sufficient statistics.

Next highest in mass are the $2S$ states. The $B(2^3S_1)$ is predicted to have a mass of 5864 MeV, and $\Gamma = 108$ MeV with $\text{BR}(B\pi) = 33\%$ and $\text{BR}(B^*\pi) = 63\%$. The properties of the $B(2^1S_0)$ are $M = 5834$ MeV, $\Gamma = 95$ MeV with $\text{BR}(B^*\pi) \approx 100\%$. In both cases we quote the ARM mass prediction. There is evidence that LHCb has seen these states but as discussed above more data is needed to confirm this. For the analogous bottom-strange states we find for the $B_s(2^3S_1)$ $M = 5948$ MeV, $\Gamma = 114$ MeV with $\text{BR}(BK) = 38.3\%$ and $\text{BR}(B^*K) = 58.4\%$, and for the $B_s(2^1S_0)$ $M = 5925$ MeV, $\Gamma = 76$ MeV with $\text{BR}(B^*K) \approx 100\%$. These states are relatively narrow with large BR’s to simple final states so it should be possible to observe them in the near future.

As we move to higher mass states the situation becomes more complicated. In general the mass multiplets are closer together with relatively small splittings within multiplets ($\mathcal{O}(10$ MeV)), and many of the states become broader due to the increased phase space resulting in many overlapping resonances. To disentangle this will require higher statistics to measure the spins. LHCb has demonstrated their ability to accomplish this with spin measurements in the charm meson sector. However, not all states are broad due to angular momentum suppression in decays so it should still be possible to find some of these excited states. In what follows we will focus on the states most likely to be found first.

The $1D$ multiplets are next highest in mass. They consist of a narrow doublet and a broad doublet. The narrow $B$ doublet consists of the $1D_2$ with total width 23 MeV with $\text{BR}(B^*\pi) = 87\%$ and the $1^3D_3$ with total width 31 MeV with $\text{BR}(B\pi) = 46\%$ and $\text{BR}(B^*\pi) = 46\%$. These two states should have strong signals in their dominant decay modes. However, because these two states are close in mass it will likely require an angular distribution analysis to distinguish the $1D_2$ from the $1^3D_3$ in the $B^*\pi$ final state. Nevertheless it should be possible to observe the two narrow $1D$ states. In contrast, for the two broad states, $1^3D_1$ and $1D_2$, despite the fact that the $1D_2$ is expected to have a large BR of 45% to $B^*\pi$ and the $1^3D_1$ of 30% to $B\pi$, because they are expected to have total widths of approximately 200 MeV it will likely be difficult to extract a strong signal. These observations equally apply to the $B_s(1D)$ states. The narrow $B_s(1D_2)$ and $B_s(1^3D_3)$ states have widths of 16 MeV and 26 MeV respectively. The $B_s(1D_2)$ has a BR $B^*K$ of 97% while the $B_s(1^3D_3)$ has BR’s to $BK$ of 53% and to $B^*K$ of 43%. In contrast, the broad $D_s(1^3D_1)$ has a width of 183 MeV with a BR to $BK$ of 59% and to $B^*K$ of 29% while the broad $B_s(1D_2)$ has a width of 194 MeV with BR to $BK$ of 88%. We conclude that the narrow states will produce strong signals although sitting in broad backgrounds so that measuring their spins and parities will be helpful in identifying them.

Next in mass are the $2P$ multiplets. All members of the nonstrange bottom $2P$ multiplet are relatively broad with $\Gamma \sim 200$ MeV which is significantly greater than the intra-multiplet mass splitting. The largest BR’s are mainly to more complicated final states, for example $\text{BR}(B(2^3P_0) \rightarrow B(1P_1)\pi) = 50\%$ and $\text{BR}(B(2^1P_1) \rightarrow B(1^3P_2)\pi) = 41\%$. The most promising possibility is to study the $B\pi$ final state which only the $B(2^3P_0)$ and $B(2^1P_2)$ can decay to with BR’s of 10.5% and 8.4% respectively. Because the expected widths are so much
larger than the splitting, distinguishing the states will require an angular momentum analysis to identify the two states. The $B(2P_1)$ and $B(2P_0)$ both decay to $B^{*}\pi$ with BR’s of 30% and 9% respectively. But again, because they are overlapping resonances more information would be needed to distinguish the two states, such as BR’s to other final states such as $B\rho$ and $B^*\rho$, although this would be difficult because the $B(2^3P_0)$ and $B(2^1P_2)$ also decay to $B^*\rho$ with BR’s of approximately 20% and 40% respectively. We conclude that only the $B(2^3P_0)$ and $B(2^1P_2)$ might be observed in the foreseeable future.

In contrast, the $2P$ $B_s$ mesons divide into two relatively narrow states, $B_{s}(2^3P_0)$ and $B_{s}(2^1P_1)$, and two relatively broad states, $B_{s}(2^3P_1)$ and $B_{s}(2^3P_2)$. The $B_{s}(2^3P_0)$ has a total width of 71 MeV and BR to $BK$ of 44% and the $B_{s}(2^3P_1)$ has a total width of 79 MeV with a BR of 31% to $B^*K$ and 28% to $BK^*$. In contrast, the $B_{s}(2^1P_1)$ has total width of 218 MeV and the $B_{s}(2^3P_2)$ has a total width of 246 MeV. Although the $B_{s}(2^3P_1)$ and $B_{s}(2^3P_2)$ overlap with the $B_{s}(2^3P_0)$ and $B_{s}(2^1P_1)$, and the $B_{s}(2^3P_1)$ has significant BR’s to $B^*K$ of 40% and to $BK^*$ of 33%, the $B_{s}(2^3P_2)$ to $BK$ of 12% and to $B^*K$ of 20%, it should be possible to extract a meaningful signal for the $B_{s}(2^3P_0)$ in the $BK$ final state and for the $B_{s}(2^3P_1)$ in the $B^*K$ final state.

The $3S$ and $1F$ multiplets are very close in mass, at approximately 6300 MeV, and overlap. The $B(3^3S_1)$ and $B(3^1S_0)$ have total widths of 140 and 151 MeV respectively with BR’s of $BR(3^3S_1 \to B\pi) = 2.2\%$, $BR(3^3S_1 \to B^*\pi) = 3.1\%$ and $BR(3^1S_0 \to B^*\pi) = 2.8\%$ so that the signals to observe these states are rather small. Both states have large BR to $B^*\rho$ of 21% and 22% respectively so these are potentially interesting but also more challenging; as the final state consists of three pions it would be necessary to perform a Dalitz plot analysis to reconstruct the intermediate $\rho$ meson. The narrow $B(1F)$ states are the $B(1F_3)$ with total width 106 MeV and $BR(B(1F) = 25\%)$, and the $B(1F_3)$ with total width 110 MeV and $BR(B(1F) = 15\%$ and $BR(B(1F) = 14\%$. So in fact the narrow $1F$ states might be more likely to be observed than the $3S$ states although it will be challenging. We also note that these states also have reasonable BR’s to $B^*\rho$ of 20% for the $B(1F_3)$ and 47% for the $B(1F_4)$.

The situation for the $B_s(3S)$ states is similar, although perhaps a bit more promising, with total widths of 130 MeV for the $B_s(3^3S_1)$ and 121 MeV for the $B_s(3^1S_0)$ with relatively small BR’s to the simple final states; $BR(B_s(3^3S_1 \to BK) = 5.5\%$, $BR(B_s(3^3S_1 \to B^*K) = 6.9\%$ and $BR(B_s(3^1S_0 \to B^*K) = 6.7\%$. The narrow $B_s(1F)$ states are the $B_s(1F_3)$ with total width 138 MeV and BR to $B^*K$ of 28% and the $B_s(1F_4)$ with total width of 139 MeV and BR to $BK$ of 18% and to $B^*K$ of 17%. Another prominent decay mode for these states is $BK^*$. So although there are numerous overlapping resonances, some of these states are narrow enough with a reasonable signal strength to a simple final state that if one can determine their spin it should be possible to observe them.

As we move higher in mass, more final states become kinematically allowed so that BR’s to simple states become smaller with some exceptions, which we note in what follows. We refer the interested reader to Tables 4 and 5 for more details.

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**TABLE XXXVI**: Summary of excited bottom mesons. Unless otherwise stated we quote values from the Particle Data Group [45].

| State       | $J^P$ | $B^{*}\pi$ Decays | Mass (MeV) | Width (MeV) | References |
|-------------|------|-------------------|-----------|-------------|------------|
| $B_1(5721)^+$ | $B^{*}\pi^+$ | 5726.8$^{+3.2}_{-1.0}$ | 49$^{+12}_{-9.3}$ | LHCb[4] |
| $B_1(5721)^0$ | $B^{*}\pi^-$ | 5724.9$^{+2.4}_{-2.4}$ | 23$^{+7}_{-4}$ | LHCb[4] |
| $B_1(5721)^-\pi^+$ | 5727.7$^{+3.4}_{-0.8}$ | 30$^{+15}_{-5.2}$ | LHCb[4] |
| $B_2^+(5747)^+$ | $B^{*}\pi^+$ | 5730$^{+5}_{-5}$ | 22$^{+7}_{-6}$ | LHCb[4] |
| $B_2^0(5747)^0$ | $B^{*}\pi^0, B^{*+\pi^-}$ | 5739.4$^{+0.3}_{-0.3}$ | 24.5$^{+1.5}_{-1.5}$ | LHCb[4] |
| $B(5970)^+$ | $B^{*}\pi^+$ | 5961$^{+13}_{-13}$ | 60$^{+30}_{-20}$ | LHCb[4] |
| $B(5970)^0$ | $B^{*}\pi^-$ | 5977$^{+13}_{-13}$ | 70$^{+30}_{-20}$ | LHCb[4] |
| $B_{s1}(5830)^0$ | $B^{*}\pi^-$ | 5828.7$^{+0.30}_{-0.30}$ | 0.5$^{+0.3}_{-0.3}$ | LHCb[4] |
| $B_{s2}(5830)^0$ | $B^{*}\pi^-$ | 5839.8$^{+0.19}_{-0.19}$ | 1.47$^{+0.33}_{-0.33}$ | LHCb[4] |

*aWe quote the results from the isobar analysis.
The $B(3P_1)$ and $B(3P_2)$ are relatively narrow with total widths of 93 MeV and 88 MeV respectively with the $B(3P_1)$ having BR($B^*\pi$) = 5.4% and the $B(3P_2)$ having BR($B\pi$) = 2.9% and BR($B^*\pi$) = 4%. The $B(2D_2)$ has a total width of 104 MeV with BR($B\pi$) = 19.6% and the $B(2D_3)$ has a total width of 94 MeV with BR($B\pi$) = 4.3% and BR($B^*\pi$) = 8.6%.

The $B_s(4S_1)$ has a total width of 104 MeV with BR to $B K$ and $B^* K$ of 2.9% and 4% respectively and the $B_s(4S_0)$ has a total width of 85 MeV with BR to $B^* K$ of 5.3%. The $B_s(3P)$ multiplet are all relatively narrow with large BR’s to simple final states. For example, most prominently, the $B_s(3P_0)$ has a total width of 51 MeV with BR to $B K$ of 24% and the $B_s(3P_1)$ has a total width of 48 MeV with BR to $B^* K$ of 21%. The final state we note is the $B_s(2D_2)$ with total width of 107 MeV and BR to $B K$ and $B^* K$ of 6.4% and 13.8% respectively.

Finally, we included the strong decay widths for the 1G multiplets as the $B(1G_4)$ and $B(1^3G_3)$ are relatively narrow, $\Gamma[B(1G_4)] = 96$ MeV and $\Gamma[B(1^3G_3)] = 102$ MeV, with large BR’s to simple final states; $\text{BR}[B(1G_4) \to B^*\pi] = 24.2\%$, $\text{BR}[B(1^3G_3) \to B\pi] = 12.1\%$ and $\text{BR}[B(1^3G_3) \to B^*\pi] = 13.2\%$. These states overlap with the $3P$ multiplet and are close in mass to the $2F$ states so that it will be necessary to determine their spins to identify them. It would be interesting to find these states as they are high spin analogous to Rydberg states of atomic physics. Their masses would give insights into the confining potential and their splittings on the nature of the spin dependent potentials. They would test our understanding of QCD in a region that has not been explored. In contrast, the $B_s(1G)$ states are broader, $\sim 200 - 300$ MeV, so are less likely to be easily found.

The important conclusion we wish to draw from these results is that there are numerous excited bottom mesons that are expected to be relatively narrow with significant BR’s to simple final states. With sufficient statistics it should be possible to observe many of these states and improve our knowledge of bottom spectroscopy. The challenge is that there is significant overlapping of these states so it will be necessary to perform an angular distribution analysis to determine the spins of the underlying states to disentangle the observed final states.

VIII. SUMMARY

The primary purpose of this paper is to calculate the properties of excited $B$ and $B_s$ mesons as a guide to help identify newly observed states. The masses were calculated using the relativized quark model of Godfrey and Isgur and an alternative relativistic quark model. Radiative transition widths were calculated using a nonrelativistic formalism and wavefunctions from the respective models. Strong decay widths were calculated with the $3P_2$ quark creation model coupled with harmonic oscillator wavefunctions that were tuned to reproduce the RMS radius of the relevant hadrons.

Our current experimental knowledge of bottom mesons is rather sparse, having only clearly identified the two narrow members of the $B$ and $B_s$ 1P multiplets. Two other excited states have also been observed and identified with the $B(2S)$ states but they have not been independently confirmed by a second experiment.

In the near future the LHCb experiment offers the possibility of significantly increasing our knowledge of excited bottom states. Numerous $B$ and $B_s$ states with moderate widths and with significant branching fractions to simple final states (such as $B\pi$, $B^*\pi$, $B K$, and $B^* K$) are expected. However, the spectrum consists of many overlapping states, thus measuring the spins of putative signals will be vital for the success of any $B$ spectroscopy program. With the high statistics expected in future LHC runs we are optimistic that this can be achieved and that our knowledge of the bottom meson spectrum will be significantly expanded.

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