Spectroscopic Assignments of the Excited $B$-Mesons

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(Dated: April 3, 2019)

Excited $B$-mesons have been observed by the D0, CDF, LHCb and CMS experiments. We use the predictions of the relativized quark model to make quark model spectroscopic assignments for these states. We identify the $B_{1}^{*}(5747)$ and $B_{1}(5721)$ as the $B_{2}^{*}[1^{+}P_{2}]$ and $B_{1}[1P_{1}]$ states and the $B_{2}^{*}(5840)$ and $B_{2}^{*}(5830)$ as the $B_{2}^{*}[1^{+}P_{2}]$ and $B_{2}^{*}[1P_{1}]$ states. More information is needed to identify the $B_{1}(5970)$ and $B_{1}(5840)$ states and we suggest a number of measurements to make this identification: the determination of their $J^{P}$ quantum numbers and either confirming or ruling out their decays to the $B\pi$ final state. With the current information available we believe it most likely that the $B_{1}(5970)$ is the $B^{*}[2^{3}S_{1}]$ state, with the $B_{1}(5840)$ needing confirmation.

PACS numbers:

I. INTRODUCTION

Over the past several years a large number of new hadron states have been observed by various collider experiments [1–3]. While the so-called exotic states not conforming to quark model states have received the bulk of the attention [2, 3], states that appear to be conventional quark model states can provide a useful test of the continued utility of the quark model [7, 8]. Over the last decade the D0 [10, 11], CDF [12–14], LHCb [15, 16] and CMS [17] hadron collider experiments have observed a number of excited bottom and bottom-strange mesons. We summarize the properties of these states in Table I where we quote the Particle Data Group (PDG) values [18] averaged over the different charge states. At the same time, there have been numerous theoretical calculations of the properties of these states [8, 19–34]. In this brief note we will compare the predictions of a particular quark model [7, 8] to the measured properties of the recently observed excited bottom mesons. We will not describe the model or calculations in any detail as these can be found in previous publications [7, 9].

We begin in Section II with a very brief outline of the quark model and decay model we are using to make our predictions. It turns out that the new excited states fall into natural groupings so we will examine each of these groupings in turn and discuss their spectroscopic assignments. In these sections we include two sets of decay results. The first simply reproduces the results of Ref. [8] which uses the predicted masses in the calculations. In the second set of results we recalculate the decay widths using the measured masses to properly take into account the phase space. In Section III we summarize our results and the suggested measurements that can be used to further discriminate between spectroscopic assignments, in particular for the $B_{1}(5970)$ and $B_{1}(5840)$ states.

TABLE I: Summary of the observed excited $B$-meson properties. Unless the charge state is explicitly labelled, the values are Particle Data Group values [18] averaged over the different charge states.

| State          | $J^{P}$ | Mass (MeV) | Width (MeV) |
|----------------|---------|------------|-------------|
| $B_{1}(5721)$  | $1^{+}$ | 5726.0 ± 1.2 | 28.5 ± 3.0  |
| $B_{2}^{*}(5747)$ | $2^{+}$ | 5738.4 ± 0.5 | 23.8 ± 1.6  |
| $B_{1}(5840)$  |          | 5860.8 ± 8.1 | 143.8 ± 34.6|
| $B_{1}(5970)$  |          | 5967.5 ± 3.5 | 76.0 ± 10.3 |
| $B_{2}^{*}(5830)$ | $1^{+}$ | 5828.63 ± 0.27 | 0.5 ± 0.4   |
| $B_{2}^{*}(5840)$ | $2^{+}$ | 5839.85 ± 0.17 | 1.47 ± 0.33 |
| $B_{2}^{*}(5747)$ | $0^{+}$ | 5726.0 ± 1.2 | 28.5 ± 3.0  |

II. BOTTOM MESONS: COMPARISON BETWEEN THEORY AND EXPERIMENT

A. A Brief Sketch of the Quark Model

In a previous publication we presented the results of a comprehensive calculation of bottom meson properties [8]. We will start by comparing those results to the measured properties of the observed excited bottom mesons to associate them with specific quark model states. Given that the quark model mass predictions do not exactly correspond with the observed masses we will recompute their decay partial widths using the measured masses as input to see how this alters the results.

For our predictions, we use the relativized quark model [7, 8]. It incorporates the colour Coulomb plus linear confining potential with a running strong coupling constant and relativistic corrections. The details of this model can be found in Ref. [7] and [8, 19, 33, 39] to which we refer the interested reader. The parameters of the model, including the constituent quark masses, are given in Ref. [7]. This model has been reasonably successful in describing most known mesons although in recent years

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an increasing number of states have been observed that
do not fit into this picture and as such are often referred
to as “exotics”[2,3]. An important limitation of this model is that it is restricted
to the $q\bar{q}$ sector of the Fock space and does not take into account higher-order
components that can be described by coupled channel effects[40,42]. As a
consequence of neglecting these effects and the crudeness of the relativization procedure we do not expect the mass predictions to be accurate to better than
$\sim 10-20$ MeV.

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 $^3P_1-^1P_1$ and
$^3D_2-^1D_2$ pairs, can mix via the spin orbit interaction or some other mechanism such as mixing via coupled channels. Consequently, for example, the physical $J=1$ $P$-wave states are linear combinations of $^3P_1$ and $^1P_1$:

\[
P_1 = ^1P_1 \cos \theta_{nP} + ^3P_1 \sin \theta_{nP}
\]

\[
P'_1 = -^1P_1 \sin \theta_{nP} + ^3P_1 \cos \theta_{nP}
\]

(1)

where $P \equiv L = 1$ designates the relative orbital angular momentum of the $q\bar{q}$ pair and the subscript $J = 1$ is the total angular momentum including the spin of the $q\bar{q}$ pair, which is equal to $L$, with analogous expressions for other values of $L$. $\theta_{nL}$ is found by diagonalizing the mass matrix for the antisymmetric piece of the spin-orbit interaction (which arises for unequal mass quarks and antiquarks) in the basis of eigenvectors of the $|jm;ls\rangle$ sectors[7]. The resulting mixing angles for each sector are given in the caption of the corresponding table (Tables II, III, and IV). In the heavy quark limit (HQL) in which the heavy quark mass $m_Q \rightarrow \infty$, the states can be described by the total angular momentum of the light quark, $j_q$, which couples to the spin of the heavy quark. In this limit the state that is mainly spin singlet has $j_q = l + \frac{1}{2}$ while the state that is mainly spin triplet has $j_q = l - \frac{1}{2}$ and is labelled with a prime[43]. For $L \neq 0$ this results in two doublets. The members of the $j_q = l + \frac{1}{2}$ doublet have relatively narrow widths while the members of the $j_q = l - \frac{1}{2}$ doublet are relatively broad. In the HQL, $\theta_J = \tan^{-1} \left( \sqrt{\frac{L}{J+1}} \right)$[42]. We note that the definition of the mixing angles is fraught with ambiguities and one should be extremely careful comparing predictions from different papers[44].

We calculate decay widths using the $^3P_0$ quark pair creation model[43,49]. The details of the $^3P_0$ quark pair creation model along with our conventions are summarized in Ref. [9] with the specifics applied to bottom mesons given in Ref. [9]. The parameters used in our calculation, $\gamma$, the pair creation parameter and $\beta$, a universal oscillator parameter for the light mesons, were found from fits to light meson decays[49,51]. The predicted widths are fairly insensitive to the precise values used for $\beta$ provided $\gamma$ is appropriately rescaled. However $\gamma$ can vary as much as 30% and still give reasonable global fits of light meson decay widths[49,51]. This can result in factors of two variations to predicted widths, both smaller or larger.

The radiative transition widths were calculated using the expressions from Refs. [52,54], which are reproduced in Ref. [8].

The predicted masses, mixing angles and widths for the the $B(1P)$, $B_1(1P)$, $B(2S)$ and $B(1D)$ multiplets are given in Tables II, III, IV and V, respectively. The masses and widths in column 3, labelled QM, were obtained using the predicted masses from Ref. [8] for both the initial state and for the heavy decay product[8] and the column labelled Expt shows the widths recalculated using the measured masses. For the $B_1$ widths we use the calculated mixing angle of $\theta_{1P} = 30.28^\circ$ for the $b\bar{q}[1P]$ states[8].

| State         | Property     | Value (MeV) | (QM) | (Expt) |
|---------------|--------------|-------------|------|--------|
| $B^*_1[1^3P_2]$ | Mass         | 5797        | 5738.4 |
| $\Gamma(B^*_1 \rightarrow B\gamma)(ub, db)$ | 0.4, 0.1 | 0.4, 0.1 |
| $\Gamma(B^*_1 \rightarrow B\pi)$ | 6.2 | 4.6 |
| $\Gamma(B^*_1 \rightarrow B^*\pi)$ | 5.0 | 4.3 |
| Total Width (ub, db) | 11.7, 11.4 | 9.3, 9.0 |
| $B_1[1^3P_1]$ | Mass         | 5777        | 5726.0 |
| $\Gamma(B_1 \rightarrow B\gamma)(ub, db)$ | 0.37, 0.11, 0.1 | 0.03 |
| $\Gamma(B_1 \rightarrow B\gamma)(ub, db)$ | 0.1, 0.03 | 0.3, 0.08 |
| $\Gamma(B_1 \rightarrow B^*\pi)$ | 7 | 6.4 |
| Total Width (ub, db) | 7.3, 6.9 | 6.8, 6.6 |
| $B'_1[1^1P_0]$ | Mass         | 5784        | 5725.5 |
| $\Gamma(B'_1 \rightarrow B^*\pi)$ | 163 | 160 |
| Total Width | 163 | 160 |
| $B^*_0[1^3P_0]$ | Mass | 5756 | 5697.4 |
| $\Gamma(B^*_0 \rightarrow B\pi)$ | 154 | 148 |
| Total Width | 154 | 148 |

The excited $B$-mesons fall into natural groupings. The $B^*_1(5747)$ and $B_1(5721)$ mesons appear to be consistent with the $B^*_2(1^3P_2)$ and $B_1(1P_1)$ states and the $B^*_2(5840)$ and $B_{2s}(5830)$ mesons with the $B^*_2(1^3P_2)$ and $B_2(1P_1)$ states. This has been previously noted in the literature. Quark model assignments for the $B_2(5840)$ and $B_{2s}(5970)$ states are not so obviously apparent. We will therefore consider each of these pairs of states in turn.
The pseudoscalar emission model) is in better agreement

![image](https://via.placeholder.com/150)

... one of the earliest calculations of these widths.

| State      | Property | Value (MeV) (QM) (Expt) |
|------------|----------|--------------------------|
| B_{s2}^{*}[1^3P_2] | Mass | 5876 5839.4  |
|            | $\Gamma(B_{s2}^{*} \to B_s^*\gamma)$ | 0.11 0.10  |
|            | $\Gamma(B_{s2}^{*} \to BK)$ | 0.66 0.57  |
|            | $\Gamma(B_{s2}^{*} \to B^*K)$ | 0.008 0.05  |
|            | Total Width | 0.78 0.72  |
| B_{s1}[1P_1] | Mass | 5857 5828.63  |
|            | $\Gamma(B_{s1} \to B_s\gamma)$ | 0.07 0.05  |
|            | $\Gamma(B_{s1} \to B_s^*\gamma)$ | 0.04 0.06  |
|            | $\Gamma(B_{s1} \to B^*K)$ | - 0.34  |
|            | Total Width | 0.11 0.45  |
| B_{s1}'[1P_1'] | Mass | 5861 5824.84  |
|            | $\Gamma(B_{s1}' \to B_s\gamma)$ | 0.05 0.07  |
|            | $\Gamma(B_{s1}' \to B_s^*\gamma)$ | 0.06 0.04  |
|            | $\Gamma(B_{s1}' \to B^*K)$ | - 77.3  |
|            | Total Width | 0.11 77.4  |
| B_{s0}^{*}[1^3P_0] | Mass | 5831 5794.84  |
|            | $\Gamma(B_{s0}^* \to BK)$ | 138 128  |
|            | Total Width | 138 128  |

**B. The B_{s2}^*(5747) and B_{1}(5721) States**

The B_{s2}^*(5747) and B_{1}(5721) are both relatively narrow states. Their measured J^P quantum numbers are those of the j_q = 3/2 doublet of a heavy-light meson in the heavy quark limit. Their masses and widths are also roughly consistent with the quark model predictions for these states shown in Table II, although the predicted masses are both about 50 MeV higher than observed and the predicted widths are smaller than observed. The high mass prediction has been observed in other heavy-light systems such as charm mesons so given this pattern it is reasonable to identify the B_{s2}^*(5747) and B_{1}(5721) as the 1^3P_2 and 1P_1 B mesons and deem the inconsistency in masses as a weakness of the model. The predicted widths are roughly a factor of two smaller than the observed widths. As pointed out above, this is within the predictive power of the quark pair creation model. The important prediction is that the j_q = 3/2 P-wave doublet, consisting of the 1^3P_2 and 1P_1 B states, is predicted to be narrow and the j_q = 1/2 doublet, consisting of the 1P_0 and 1^3P_0 states, is predicted to be broad. Interestingly, one of the earliest calculations of these widths using the flux-tube breaking model (and another using the pseudoscalar emission model) is in better agreement with the measured widths.

We recalculated the widths using the measured B_{s2}^* and B_{1} masses, which are shown in column 4 of Table II. The B_{s2} and B_{1} masses were obtained by subtracting the predicted B_{s2} - B_{1} and B_{s0} - B_{1} mass differences from the measured B_{s2} mass. Not surprisingly, there is no qualitative difference from the results using the predicted masses although the widths are slightly smaller due to the reduced phase space. We also recalculated the widths for the 1P_1 states using the HQL mixing angle of $\theta_1 = 35.3^\circ$ and although the narrow B_{1} width changes slightly it does not alter our conclusion.

A further test of this assignment is the predicted versus measured ratio of partial widths to B^*\pi and B\pi final states. The PDG average for the ratio is $18$:

$$\frac{\Gamma(B_{s2}^* \to B^*\pi^-)}{\Gamma(B_{s2}^* \to B^+\pi^-)} = 0.82 \pm 0.28. \tag{2}$$

This is compared to the predicted ratio: using the predicted B_{s2} mass as input we obtain $\Gamma(B_{s2}^* \to B^*\pi)/\Gamma(B_{s2}^* \to B\pi) = 0.81$ and using the measured B_{s2} mass as input we obtain $\Gamma(B_{s2}^* \to B^*\pi)/\Gamma(B_{s2}^* \to B\pi) = 0.93$. Both values are consistent with the measured value.

**C. The B_{s2}^*(5840) and B_{s1}(5830) States**

These states follow a similar pattern to the P-wave B-mesons of the previous subsection. The B_{s2} and B_{s1} states have properties consistent with the j_q = 3/2 P-wave B_{0} doublet. The predicted masses are roughly 30-40 MeV higher than the observed masses and the predicted decay widths are consistent with the measured widths. It is worth pointing out that for these states the radiative widths make a significant contribution to the total width. Using the observed masses to calculate the widths does

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**TABLE III: Summary of Quark model predictions for the B_{1}[1P] meson properties.** $\theta_1 = 39.12^\circ$ for the bs[1P] states.

| State      | Property | Value (MeV) (QM) (Expt) |
|------------|----------|--------------------------|
| B_{s2}^{*}[1^3P_2] | Mass | 5876 5839.4  |
|            | $\Gamma(B_{s2}^{*} \to B_{s}^{*}\gamma)$ | 0.11 0.10  |
|            | $\Gamma(B_{s2}^{*} \to BK)$ | 0.66 0.57  |
|            | $\Gamma(B_{s2}^{*} \to B^{*}K)$ | 0.008 0.05  |
|            | Total Width | 0.78 0.72  |
| B_{s1}[1P_1] | Mass | 5857 5828.63  |
|            | $\Gamma(B_{s1} \to B_{s}\gamma)$ | 0.07 0.05  |
|            | $\Gamma(B_{s1} \to B_{s}^{*}\gamma)$ | 0.04 0.06  |
|            | $\Gamma(B_{s1} \to B^{*}K)$ | - 0.34  |
|            | Total Width | 0.11 0.45  |
| B_{s1}'[1P_1'] | Mass | 5861 5824.84  |
|            | $\Gamma(B_{s1}' \to B_{s}\gamma)$ | 0.05 0.07  |
|            | $\Gamma(B_{s1}' \to B_{s}^{*}\gamma)$ | 0.06 0.04  |
|            | $\Gamma(B_{s1}' \to B^{*}K)$ | - 77.3  |
|            | Total Width | 0.11 77.4  |
| B_{s0}^{*}[1^3P_0] | Mass | 5831 5794.84  |
|            | $\Gamma(B_{s0}^{*} \to BK)$ | 138 128  |
|            | Total Width | 138 128  |

**TABLE IV: Summary of Quark model predictions for the B[2S] meson properties.** See the caption to Table III for further details.

| State      | Property | Value (MeV) (QM) (Expt) |
|------------|----------|--------------------------|
| B[2S_{1}] | Mass | 5933 5967.5  |
|            | $\Gamma(B^{*}(2S) \to B\pi)$ | 36 39  |
|            | $\Gamma(B^{*}(2S) \to B^*\pi)$ | 68 80  |
|            | $\Gamma(B^{*}(2S) \to B\eta)$ | 2 4  |
|            | $\Gamma(B^{*}(2S) \to B^*\eta)$ | 0.4 6  |
|            | $\Gamma(B^{*}(2S) \to B\eta\pi)$ | 2 8  |
|            | $\Gamma(B^{*}(2S) \to B^*\eta\pi)$ | - 8  |
| Total Width | 108 146  |
| B[2S_{0}] | Mass | 5904 5860.8  |
|            | $\Gamma(B(2S) \to B^*\pi)$ | 95 96  |
| Total Width | 95 96  |
The predicted ratio is 0.012 using the predicted mass as input is in good agreement with experiment giving further support to the identification of the $B_{s2}^*(5840)$ as the $B_{s2}^*(1^{3}P_{2})$ state.

For the $B_{s1}$ state, we note that using the HQL mixing angle of $\theta_{1P} = 35.3^{\circ}$, $\Gamma(B_{s1} \to B^{*}K)$ is reduced from 0.34 MeV to 0.02 MeV and the total width is dominated by the radiative transitions. Nevertheless, given the large experimental uncertainty on the total width, the width in the HQL is also consistent with experiment. Given how close the predicted mixing angle is to the HQL value, a more precise measurement of the width would be an interesting constraint on the $^{3}P_{1} \to ^{1}P_{1}$ mixing angle.

### D. The $B_{J}(5970)$ and $B_{J}(5840)$ States

The identification of the $B_{J}(5970)$ and $B_{J}(5840)$ states is less obvious. LHCb has suggested that these states can be identified with the $2^{1}S_{0}$ and $2^{1}S_{0}$ bottom states, respectively [13]. However, we note that the PDG has omitted the $B_{J}(5840)$ from the summary tables, so the experimental situation should be regarded as inconclusive. With this caveat, we explore the spectroscopic possibilities for these states.

The QM predicts the $2^{1}S_{1} - 2^{1}P_{0}$ mass splitting to be 29 MeV versus the measured mass splitting of 107 MeV. The predicted splitting is consistent with the expectation that the $2^{1}S_{1} - 2^{1}P_{0}$ splitting be smaller than the $1^{3}S_{1} - 1^{3}P_{0}$ mass splitting which is measured to be 45 MeV. So the $B_{J}(5970)$ and $B_{J}(5840)$ mass splitting is a red flag that their identification with the $2^{1}S_{1}$ and $2^{1}S_{0}$ states is questionable.

We start by associating the $B_{J}(5970)$ with the $2^{1}S_{1}$ bottom meson. The predicted mass is about 35 MeV below the measured mass. This is within the predictive reliability of the model, although it should be noted that the predicted bottom masses are typically above the experimental values not below. The total width is calculated to be 108 MeV using the predicted $2^{1}S_{1}$ mass, versus the measured width of 76.0 $\pm$ 10.3 MeV. Again, these values are consistent within the predictive power of the model. If we recalculate the total width using the measured mass as input we obtain a total width of 146 MeV, again acceptable although at the limits of acceptability. With this assignment we consider whether the $B_{J}(5840)$ can be identified with the $2^{1}P_{0}$ $B$-meson. The predicted $2^{1}S_{0}$ $B$-meson mass is 43 MeV above the measured mass and the predicted total width using the predicted mass as input is 95 MeV versus the measured value of 143.8 $\pm$ 34.6 MeV. Recalculating the width using the measured mass as input only changes the value of the width slightly, to 96 MeV. In both cases the mass and width are consistent with the $2^{1}S_{0}$ $B$-meson state within the predictive power of the model and the experimental uncertainties, especially for the total width. However, as pointed out above, the mass splitting between the $B_{J}(5970)$ and $B_{J}(5840)$ is a red flag that something is amiss. Further, both states have been seen to decay to $B^{*}\pi$ and "possibly seen" decaying to $B\pi$. The latter final state, if confirmed, would disallow the $2^{1}S_{0}$ identification of the $B_{J}(5840)$ as the decay $B[2^{1}S_{0}] \to B\pi$ is forbidden. Either confirming this decay or ruling it out would clarify the situation. Measuring the ratio $\Gamma(B_{J} \to B\pi)/\Gamma(B_{J} \to B^{*}\pi)$, which is predicted to be $\sim 0.5$ for the $B[2^{1}S_{1}]$ state, would help confirm the identity of these states.

Because the $B_{J}(5970) - B_{J}(5840)$ mass splitting is inconsistent with both the predicted and expected $2^{1}S_{1} - 2^{1}S_{0}$ mass splittings, let us consider a second scenario where we identify the $B_{J}(5840)$ as the $B[2^{1}S_{1}]$. Using its mass of 5860.8 MeV we obtain a total width of 95 MeV, which is consistent, within experimental uncer-

### Table V: Summary of Quark model predictions for the $B_{[1D]}$ meson properties. $\theta_{1D} = 39.69^{\circ}$ for the $bq[1D]$ states [8]. See the caption to Table III for further details.

| State          | Property      | Value (MeV) | (QM) | (Expt) |
|----------------|---------------|-------------|------|--------|
| $B_{1}^{*}[1^{3}D_{1}]$ Mass | 6110 | 5967.5 |       |        |
| $\Gamma(B_{1}^{*} \to B\pi)$ | 60  | 55  |       |        |
| $\Gamma(B_{1}^{*} \to B^{*}\pi)$ | 30  | 27  |       |        |
| $\Gamma(B_{1}^{*} \to B\eta)$ | 10  | 5   |       |        |
| $\Gamma(B_{1}^{*} \to B^{*}\eta)$ | 4   | 2   |       |        |
| $\Gamma(B_{1}^{*} \to B(1P_{0})\pi)$ | 63  | 43  |       |        |
| $\Gamma(B_{1}^{*} \to B_{s}K)$ | 19  | 7   |       |        |
| $\Gamma(B_{1}^{*} \to B_{s}^{*}K)$ | 7   | 2   |       |        |
| $\Gamma(B_{1}^{*} \to B\rho)$ | 2   | -   |       |        |
| Total Width    | 197  | 140 |       |        |
| $B_{2}[1^{1}D_{2}]$ Mass | 6095 | 5967.5 |       |        |
| $\Gamma(B_{2} \to B^{*}\pi)$ | 20  | 9.4 |       |        |
| $\Gamma(B_{2} \to B\rho)$ | 1.6 | -   |       |        |
| Total Width    | 23  | 10  |       |        |
| $B_{2}^{*}[1^{3}D_{2}]$ Mass | 6124 | 5967.5 |       |        |
| $\Gamma(B_{2}^{*} \to B^{*}\pi)$ | 96  | 87  |       |        |
| $\Gamma(B_{2}^{*} \to B^{*}\eta)$ | 14  | 5.5 |       |        |
| $\Gamma(B_{2}^{*} \to B^{*}(1P_{2})\pi)$ | 74  | 47  |       |        |
| $\Gamma(B_{2}^{*} \to B_{s}K)$ | 27  | 5   |       |        |
| Total Width    | 213 | 145 |       |        |
| $B_{3}^{*}[1^{3}D_{3}]$ Mass | 6106 | 5967.5 |       |        |
| $\Gamma(B_{3}^{*} \to B\pi)$ | 14  | 6   |       |        |
| $\Gamma(B_{3}^{*} \to B^{*}\pi)$ | 14  | 6   |       |        |
| Total Width    | 31  | 13  |       |        |
tainties, with the $B_J(5840)$ width. If we identify the $B_J(5840)$ with the $B[2^3S_1]$, then what is the $B_J(5970)$ state? The states nearest in mass to 5968 MeV are the 1D states. Their properties are summarized in Table V. The first thing to note is that the predicted 1D masses are $\sim 150$ MeV higher than the $B_J(5970)$ mass. Let us set this aside for a moment. The four 1D states are grouped into a $j_q = 3/2$ doublet comprised of the $1^3D_1$ and $1^3D_2$ states and a $j_q = 5/2$ doublet comprised of the $1^3D_2$ and $1^3D_3$ states. The $j_q = 5/2$ states are narrow with their widths inconsistent with the $B_J(5970)$ width, even taking into account both experimental and theoretical uncertainties. Thus, if we identify the $B_J(5970)$ with a 1D state it must be either the $1^3D_1$ or $1^3D_2$ state. Although the predicted widths are almost a factor of two, with the $1^3D_2$ state being forbidden to decay to $B\pi$. A final possibility that should be pointed out is that the $B_J(5970)$ is the $2^3S_1$ state but that the $B_J(5840)$ is not confirmed and the $2^3S_0$ state has yet to be observed.

From the discussion above, it is clear that confirming or ruling out the decays of the $B_J(5970)$ and $B_J(5840)$ states to $B\pi$ is crucial to making spectroscopic assignments for these states. If the $B_J(5840)$ is confirmed to decay to $B\pi$ it would rule out the $2^3S_0$ assignment while if the decay to $B\pi$ can be ruled out with some confidence, it would support that assignment. The latter case makes a strong case for identifying the $B_J(5840)$ and $B_J(5970)$ as the $B(2^3S_0)$ and $B(2^3S_1)$ states respectively. If the $B_J(5840)$ is confirmed to decay to $B\pi$, this assignment is no longer viable and the $B_J(5840)$ would be identified as the $B(2^3S_1)$. This opens up the possibility that the $B_J(5970)$ is a 1D state, either the $1^3D_1$ if its decay to $B\pi$ is confirmed, or the $1^3D_2$ otherwise. In any of these scenarios, determining the $J^P$ quantum numbers is a crucial piece of the puzzle.

III. SUMMARY AND CONCLUSIONS

In this paper we reviewed the possible spectroscopic assignments for the recently observed excited $B$ and $B_s$ mesons. As pointed out by others, the properties of the $B_J(5747)$ and $B_1(5721)$ are consistent with those of the $B_2$ and $B_1$ quark model states. Likewise the properties of the $B_{s2}^*(5840)$ and $B_{s1}(5830)$ are consistent with those of $B_{s2}$ and $B_{s1}$ states. The identification of the $B_J(5970)$ and $B_J(5840)$ states is problematic and needs further information: the $J^P$ quantum numbers, confirmation of the $B_J(5840)$ and confirmation of the $B\pi$ decay mode for both states. With the current information the most likely conclusion is that the $B_J(5970)$ is associated with the $B(2^3S_1)$ state and the $B(2^3S_0)$ has yet to be observed. If the $B_J(5840)$ is confirmed to decay to $B\pi$ it can be identified as the $B(2^3S_0)$ state. If it does decay to $B\pi$, it could be identified as the $B(2^3S_1)$ with the $B(2^3S_0)$ not yet observed and the $B_J(5970)$ identified as a 1D state, either the $1^3D_1$ or $1^3D_2$ depending on whether or not it is confirmed to decay to $B\pi$. We consider the latter explanation unlikely as we believe the $B_J(5970)$ mass to be inconsistent with a 1D state.

Acknowledgments

This research was supported in part by the Natural Sciences and Engineering Research Council of Canada under grant number SAPIN-2016-00041.

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