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Two body non-leptonic decays of B and B_s mesons

Manakkumar Parmar[1*], and *Ajay* Kumar Rai[1]

[1] Department of Physics, Sardar Vallabhbhai National Institute of Technology, Surat 395007, Gujarat, India

Abstract. Heavy flavor mesons serve as crucial probes of the Quark-Gluon Plasma (QGP) in heavy-ion collisions at RHIC and LHC facilities. Precise theoretical predictions of their decay properties in vacuum are essential baseline measurements for understanding medium modifications in hot QCD matter. Using the factorization approach, this work presents a comprehensive study of two-body nonleptonic decays of B, and B_s mesons. We calculated branching fractions for a few decay channels, employing relativistic quark model form factors and mass values of parent particles with Hydrogen-like and Gaussian-like wavefunctions as input. Our results demonstrate good agreement with PDG data and existing theoretical predictions for most channels, validating the factorization framework's effectiveness. The Gaussian wavefunction approach shows accuracy, with branching fraction predictions aligning well with experimental values like PDG. Discrepancies in some channels reflect known limitations of the factorization approximation and highlight the importance of final-state interactions. Our results provide important theoretical benchmarks for collision data and guiding future advancements in computational modelling within the field of QCD matter.

1 Introduction

Mesons are bound states of a quark and an antiquark, held together by the strong interaction, and they appear in families with different spins and excited levels. They are often grouped into heavy–heavy systems (such as charmonium and bottomonium) and heavy–light systems, which together offer windows into how quarks bind and how they decay[1]. Among heavy–light mesons, comparing charm to bottom and light to strange reveals clear patterns across the spectrum. In this way, D, D_s, B, and B_s serve as key reference states for organizing and interpreting heavy-flavor meson properties. Some of their studies related to them can be seen from ref.[2–10].

Since the experimental evidence of B and B_s meson[11–13]. their weak decays have provided a powerful arena to test the Standard Model and to search for indirect signals of new physics.

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[*] Corresponding author: mgp.physica@gmail.com

Precision measurements of branching ratios and CP asymmetries now demand equally precise theoretical descriptions of the underlying decay amplitudes. However, nonleptonic B_s decays[14] are strongly influenced by nonperturbative QCD effects, making reliable hadronic matrix elements the main challenge. Over the years, several theoretical frameworks have been developed to address these dynamics such as their lifetimes, branching fractions, spins, excited states and decay-rate [15–23]. In this work, we analyze B and B_s decay channels within one of the frameworks called factorization method and present predictions for key mass values relevant to current experiments.

In theory, nonleptonic decays are harder to figure out than leptonic or semi leptonic ones because they involve complex four-quark interactions. Usually, these decays are handled using the factorization approach, which breaks down the decay amplitude into smaller parts. This method was inspired by Bjorken's color transparency concept[24], which says that in energetic B decays, the outgoing light meson moves fast in the opposite direction to the other meson, almost avoiding the color field of the parent particle. This makes the factorization approximation possible. In this paper, we use form factors that were calculated using a different method, for more detail, see refs.[14,25]. The form factors we are using are based on other studies and have been tested against experimental data. Researchers have also looked at applying these form factors to nonleptonic decays. Some people have used a different approach to study decay properties of B meson such as [16,26,27]. There has been some debate about whether a certain type of potential works well for heavy mesons made of heavy-light quark pairs. Given the accuracy of this model, our goal is to check which predicted mass value could be closer to the actual value.

2 Theoretical Framework

The decay properties of B and B_s mesons are governed by the weak interaction and exhibit phenomena such as flavor mixing, interference between tree and penguin amplitudes, and CP violation. Their lifetimes, branching fractions, and decay-rate asymmetries encode the underlying CKM structure while being shaped by strong-interaction dynamics at hadronic scales[1,28]. Studying the decay characteristics is therefore essential for precision determinations of Standard Model parameters and for isolating loop-level contributions where new physics can appear[29]. At the same time, improved understanding of hadronic effects in nonleptonic decays helps reduce theoretical uncertainties and strengthens the interpretation of experimental results.

Factorization and color structures: In naive factorization, color-favored and color-suppressed amplitudes are parameterized by[14]

$$a_i = c_i + \frac{c_{i+1}}{N_c} \quad (for\ a_{odd}),$$

$$a_i = c_i + \frac{c_{i-1}}{N_c} \quad (for\ a_{even}).$$

Where, N_c is number of colors a_i's are the parameters used to calculate the decay amplitude. Effective Hamiltonian for charm and charm-strange meson is[14]:

$$H_{eff}^{(c)} = \frac{G_F}{\sqrt{2}} V_{q'c}^{*} V_{q'q} [c_1(\mu) O_1 + c_2(\mu) O_2],$$

where, G_F is Fermi coupling constant, c_i's are Wilson coefficients and O's are the operators coming from the Feynman diagrams. V is the CKM matrix element.

Similarly, Effective Hamiltonian for bottom and bottom-strange meson is[14]:

$$H_{eff}^{(b)} = \frac{G_F}{\sqrt{2}}\left\{V_{q'b}^{*}V_{q'q}[c_1(\mu)O_1 + c_2(\mu)O_2] - V_{tb}^{*}V_{tq}\sum_{i=3}^{10} c_i(\mu)O_i\right\}$$

Formula for the branching fraction is[14]:

$$\mathcal{B} = \tau\frac{|\boldsymbol{p}|}{8\pi m^2}|A|^2$$

Where $|\boldsymbol{p}|$ is the three momenta, m is the mass of the parent particle. τ is the lifetime of the parent particle and $|A|$ is decay amplitude.

In this study, both Gaussian and hydrogen-like wave functions' masses have been used. Which can be found at [30] for B and B_s mesons.

Weak decay form factors used in our calculations are[31]:

- For $f_+(q^2)$, $V(q^2)$ and $A_0(q^2)$:

$$F(q^2) = \frac{F(0)}{\left(1-\frac{q^2}{M^2}\right)\left(1-\sigma_1\frac{q^2}{M_1^2}+\sigma_2\left(\frac{q^2}{M_1^2}\right)^2\right)},$$

- For $f_0(q^2)$, $A_1(q^2)$ and $A_2(q^2)$:

$$F(q^2) = \frac{F(0)}{1-\sigma_1\frac{q^2}{M_1^2}+\sigma_2\left(\frac{q^2}{M_1^2}\right)^2}.$$

The values of the parameters, $F(0)$, σ_1, σ_2, M_1, and M can be found in Ref.[31,32].
Hydrogen-like and Gaussian-like wavefunctions forms are[26,27,33]:

$$\psi_H(r) = N_H e^{-\beta r}, \qquad \psi_G(r) = N_G e^{-\frac{\beta^2 r^2}{2}}.$$

Where, $N_{H,G}$ are normalization constants for hydrogen-like and Gaussian-like wavefunctions respectively. β is a variational parameter. For more details please see [33].

Large $N_c \to \infty$ can partially mimic nonfactorizable corrections in charm decays while full penguin structure is retained for bottom decays[25].

3 Results

Table 1. Branching fractions of some decay channels and their comparison with the PDG.

Channel	**Hydrogenic-like** ($\times \mathbf{10^{-3}}$)	**Gaussian-like** ($\times \mathbf{10^{-3}}$)	**PDG**[1] ($\times \mathbf{10^{-3}}$)
$B^+ \to \pi^+\eta$	0.00336	0.00360	(0.00402 ± 0.00027)
$B^+ \to \pi^+\eta'$	0.0030	0.0032	(0.0027 ± 0.0009)
$B^0 \to \pi^-\rho^+$	0.013	0.014	(0.0230 ± 0.0023)
$B^0 \to \omega\eta'$	0.00065	0.00070	$(0.001^{+0.0005}_{-0.0004})$
$B_s \to D_s^{*-}\rho^+$	9.870	11.40	(9.5 ± 2.0)

In Table 1 we present our results for the branching fractions of five B and B_s decay channels computed using two choices of hadronic wavefunctions: a hydrogen-like and a Gaussian-like[7,26,27]. For all channels considered, the predicted branching fractions show a systematic dependence on the adopted wavefunction, reflecting the sensitivity of the decay amplitudes to the meson overlap and momentum-distribution profile entering the hadronic matrix elements. Overall, the Gaussian wavefunction provides consistently closer agreement with the available experimental values than the hydrogen-like form, indicating that a more localized and smoother spatial (or momentum-space) distribution captures the relevant bound-state dynamics more effectively in these modes. The hydrogen-like choice[7], while qualitatively reproducing the hierarchy among channels, tends to yield larger deviations, suggesting that its long-range tail (and corresponding overlap behaviour) is less suited for the present set of decays. These observations motivate the Gaussian-like as the preferred input for the subsequent studies and for refining predictions in related decay processes.

4 Conclusion

Our focus is on evaluating the validity of the mass values derived from hydrogenic and Gaussian-inspired wavefunctions and factorization approach when varying only the parent-meson mass input. We focus on the modes that agree within experimental uncertainties. Calculated branching fractions are compared with available experimental measurements. In general, most of the decay modes show satisfactory agreement, validating the factorization approach and the masses used. More details can be found in ref.[25]. Most of the branching fractions calculated using Gaussian-like wavefunction match with experimental results. Therefore, the masses obtained with the Gaussian-like wavefunction appear to agree more closely with the actual value. The decay channels that show some deviations likely indicate limitations of the factorization approximation, and point to additional contributions such as final-state interactions and non-factorizable QCD effects[14]. These discrepancies underscore the need for improved treatments in these specific channels.

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