Vantage: Journal of Thematic Analysis **ISSN: 2582-7391**
A Multidisciplinary Publication of Centre for Research
Maitreyi College, University of Delhi
April 2024, Volume 5 Issue 1

Review Article

Recent Progress in Charm and Bottom Mesons

Ritu Garg[*], K.K. Vishwakarma, Preeti Bhall, and Alka Upadhyay
School of Physics and Materials Science, Thapar Institute of Engineering and Technology, Patiala-147004, INDIA
[*]Correspondence: ritugarg039@gmail.com
Received: 10th September, 2023; Accepted: 11th March, 2024; Published: 30th April, 2024

ABSTRACT

In this paper, we aim to discuss recently observed charm and bottom mesons, which has enriched spectrum. We have given a brief discussion of heavy quark effective theory and potential model, which are the most reliable approaches to studying heavy-light mesons. The outcomes from these approaches are helpful for future experiments.

1. INTRODUCTION

Different experimental facilities like LHCb, BABAR, Belle, BESII/III, CDF, CMS, COMPASS, *DØ*, etc., are making continuous efforts to produce large amounts of data on hadrons. The data provided by these experimental facilities are masses, decay widths, branching ratio, spin, parity, polarisation amplitude, etc., of hadrons. In a recent breakthrough, LHCb observed new excited charmed strange mesons $D_{s0}(2590)^+$ in decay $B^0 \rightarrow D^- D^+ K^+ \pi^-$ with large statistical error (Aaij et al., 2021). The measured mass and decay width are:

$$M(D_{s0}(2590)) = 2591 \pm 6(stat) \pm 7(syst)\ Mev$$

$$\Gamma(D_{s0}(2590)) = 89 \pm 16 \pm 12\ MeV/c^2$$

Also, LHCb identified this state as radial excitation of the ground state, i.e., n=2, L= 0. Numerous available theoretical models studied charmed strange mesons D_{s0} $(2590)^+$ to uncover its nature. The state $D_{s0}(2590)^+$ studied with the semi-relativistic potential model (Ni et al., 2022), PCAC low energy theory (Chen et al., 2022), coupled channel framework (Ortega et al., 2022) and all these models suggested that more observations are needed in future experiments for placing $D_{s0}(2590)^+$ in charm spectra. In the charm meson sector, observations of some more excited states like $D_0(2550)$, $D_1^*(2600)$, $D_2(2740)$, $D_3^*(2760)$, D_J $(3000)^0$, D_J^* (3000) and strange states $D_{s1}(2860)$, D_{sJ} (3040), $D_{s0}(2590)$ (Aubert et al., 2006; Brodzicka et al., 2008; del Amo Sanchez et al., 2010; Aaij et al., 2013; Aaij et al., 2015; Aaij et al., 2016). They have not only broadened the spectra but also helped us in exploring their properties through decay studies. Different theoretical models like $^3P_0$ model (Godfrey & Moats, 2016), HQET (Gupta & Upadhyay, 2018), QCD sum rule (Narison, 2005), and relativised quark model (Godfrey & Isgur, 1985; Di Pierro & Eichten, 2001) examined all above-mentioned states, computed their masses and suggested their J^P values. States $D_0^*(2300)$, $D_1(2420)$, $D_1(2430)$ and $D_2^*(2460)$ are reported in PDG (Particle Data Group et al., 2022) and their assigned J^P are 1^3P_0, 1^1P_1, 1^3P_1, 1^3P_2 respectively. Results of $D(2550)^0$ state observed by BABAR (del Amo Sanchez et al., 2010) are similar to those of the D_J $(2580)^0$ state reported by LHCb (Aaij et al., 2016) and considered as a candidate of 2^1S_0 state. Information provided by LHCb group for the states $D_1^*(2680)$ in 2016 (Aaij et al., 2016) and D_1^* (2650) in 2013 (Aaij et al., 2013) are similar to those of state $D^*(2600)$ as observed by BABAR collaboration (del Amo Sanchez et al., 2010). States $D_1^*(2680)$, $D^*(2600)$, $D_1^*(2650)$ are probably same particle and theoretical studies suggested as 2^3S_1 state (Colangelo et al., 2006; Wang, 2011; Badalian & Bakker, 2011; Colangelo et al., 2012; Lu¨ & Li, 2014; Song et al., 2015; Chen et al., 2015; Wang, 2013). The mass and decay width of state $D_3^*(2750)$ reported by LHCb group in 2015 (Aaij et al., 2015) and $D_J{}^*(2760)^0$ in 2013 (Aaij et al., 2013) are close with results of $D^*(2760)^0$ observed by BABAR collaboration (del Amo Sanchez et al., 2010). So all these states $D_3^*(2750)$, $D^*(2760)^0$, and $D_J^*(2760)^0$ may be similar state and theoretical studies suggested them to be the candidate of $1D3^-$ state (del Amo Sanchez et al., 2010; Wang, 2011; Colangelo et al., 2006; Colangelo et al., 2012; Badalian & Bakker, 2011; Lu¨ & Li, 2014; Song et al., 2015; Chen et al., 2015; Wang, 2013; Godfrey & Moats, 2016). Observations of the state D_J (3000) with unnatural parity and D_J^* (3000) with natural parity by LHCb (Aaij et al., 2013) suggested possible assignment for state $D_J^*(3000)$ as 3^3S_1, 2^3P_2, 1^3F_2 and 1^3F_4, and for state D_J (3000) as 3^3S_0, 2^3P_1 respectively. LHCb detector observed the state $D_2^*(3000)^0$ with $J^P = 2^+$ (Aaij et al., 2016) and suggested it to be a candidate of 3^3P_2, 1^3F_2 state. Theoretical approaches also examined $D_2^*(3000)^0$, D_J^* (3000), D_J (3000) states and tried to assign their proper J^P state. Yu et al., (2016) and Wang et al. (2018) analysed the state $D_2^*(3000)^0$ and assigned it $1F$ (2^+). They also examined state $D_2^*(3000)^0$ with QPC (quark pair creation) model by studying decays of 3^3P_2 and 2^3F_2 charmed mesons. They suggested it to be 3^3P_2 state, but possibility of 2^3F_2 state was also not excluded. The states $D_J^*(3000)$ and D_J (3000) were also studied by Godfrey and Moats (2016), who identified them as 3^3P_2, 1^3F_2 respectively. However, experimental growth toward establishing the bottom sector is still lacking. Only ground states $B^{0,\pm}(5279)$, $B^*(5324)$, $B_s(5366)$, $B_s^*(5415)$ and some low lying states $B_1(5721)$, $B_J^*(5732)$, $B_2^*(5747)$, $B_{s1}(5830)$, $B_{s2}^*(5840)$, $B_{sJ}^*(5840)$, B_J (5840), B_J (5970) are observed experimentally and listed in PDG (Particle Data Group et al., 2022). But apart from these states, the whole bottom meson spectra are unknown. To fill this gap, experimentalists and theoretical models are trying to predict new states that could fill this gap. In this process, recently, LHCb collaborations discovered two new states B_{sJ} (6063) and B_{sJ} (6114) in B^+K^- mass spectrum (LHCb Collaboration et al., 2021). The measured masses and decay widths are given below:

$M\,(B_{sJ}(6063)) = 6063.5 \pm 1.2(stat) \pm 0.8(syst)\ MeV$

$\Gamma\,(B_{sJ}(6063)) = 26 \pm 4 \pm 4\ MeV/c^2$

$M\,(B_{sJ}(6114)) = 6114 \pm 3(stat) \pm 5(syst)\ MeV$

$\Gamma\,(B_{sJ}(6114)) = 66 \pm 18 \pm 21\ MeV/c^2$

The successes of the observations of these radially excited states by LHCb have demonstrated that more excited bottom meson states will be discovered in future LHC experiments. In theory, various theoretical studies have performed different analyses for higher excited bottom non-strange and bottom strange meson states (Di Pierro & Eichten, 2001; Ferretti & Santopinto, 2018; Wang, 2014a; Xu et al., 2014; Wang, 2014b; Zhang & Wang, 2010; Luo et al., 2009; Gupta & Upadhyay, 2019; Zhu & Dai, 1999; Hiorth Örsland & Högaasen, 1999; Yu et al., 2019; Sun et al., 2014; Colangelo et al., 2012; Zhong & Zhao, 2008; Godfrey et al., 2016; Lü et al., 2016; Asghar et al., 2018; Godfrey & Moats, 2019; Wang et al., 2018; Yu & Wang, 2020; Alhendi et al., 2016). With the help of theoretical models, states $B^0(5279)$, $B^*(5324)$, $B_s(5366)$, $B_s^*(5415)$ are assigned as $1S$ state which very well matches with experimental data. Further the states $B_1(5721)$, $B_2^*(5747)$ are also well established experimentally and classified as $1P(1^+, 2^+)$ respectively. But theoretically, state $B1(5721)$ is still a disputed candidate because some of the theoretical work with heavy meson effective theory favors it as $1P(1^+)$ state (Wang, 2014b; Colangelo et al., 2012), while other work using relativistic quark model and non-relativistic quark model explained this state as a mixture of $3P1$ and $1P1$ states (Sun et al., 2014; Zhong & Zhao, 2008; Lü et al., 2016). The J^P of state B_J (5840) is still ambiguous as different models suggest different J^P's state for it. Lü et al. (2016) and Asghar et al. (2018) explained B_J (5840) with the quark model and suggested the assignment as 2^1S0 while Yu and Wang (2020) with $3P0$ decay model analysis favours the assignments of state B_J (5840) as 2^3S1. But Heavy quark effective theory explained resonances B_J (5840) as 1^3D1 state (Gupta & Upadhyay, 2019). The state B_J $(5960)^{0,+}$ is assigned as 2^3S_1 or 1^3D_3 state or D(+1) state with different theoretical models (Wang, 2014a; Xu et al., 2014; Sun et al., 2014; Godfrey et al., 2016; Lü et al., 2016; Ferretti & Santopinto, 2018; Gandhi & Rai, 2022). But its J^P value is still a question mark in PDG, which only mentions its mass and decay width. We have discussed here a brief literature on these non-strange bottom states. The assignments of these states (B_1(5721), B_2^*(5747), B_J (5970)) are also suggested in our previous work (Gupta & Upadhyay, 2019). In case of strange bottom sector, only a few states have been observed, out of which B_{s1}(5830) and B_{s2}(5840) states are well observed by CDF, *DØ*, and LHCb collaborations and are identified as $1P(1^+, 2^+)$ respectively (Particle Data Group et al., 2022), but there is ambiguity for recently observed strange bottom meson states B_{sJ} (6063) and B_{sJ} (6114). The states B_{sJ} (6063) and B_{sJ} (6114) in non-relativistic quark potential model are identified as 1^3D_1 and 1^3D_3 states respectively, while Gandhi and Rai (2022) assign these states as 1^3D_1 and 2^3S_1 states, respectively. Theoretical analysis for these newly observed states is thus limited in the literature, indicating it needs more attention. As mesons are bound state of quark and antiquark, the total parity P of meson is $(-1)^{L+1}$, where L is the total angular momentum of the meson. On the basis of J^P, where $J= L + S$, further classification of heavy-light mesons takes place. However, recent observations of these numerous states in the excited heavy-light sector have proliferated interest in the study of $Q\bar{q}$ meson spectroscopy. So, the discovery of these heavy hadrons motivates us to test the authenticity of available theoretical models and make predictions about their properties like J^P values with their decay modes, branching ratios, magnetic moments, form factor, polarisation amplitude, and couplings. Theoretical methods focus on explaining these data and providing predictions for investigation by the upcoming experimental facilities. The theoretical approaches may be divided into three categories: (i) theories based on first principles such as lattice QCD (LQCD), (ii) QCD sum rules, and (iii) theories based on effective field theories as well as phenomenological potential models. We are interested in exploring the study of heavy-light mesons by discussing heavy quark effective theory and potential model.

2. POTENTIAL MODEL

The crucial problem in theoretical approaches in particle physics is quark confinement, wherein isolated colour-charged quark is not freely available, and quarks and gluons are permanently con- fined within hadrons. The confinement of quarks within hadrons is assumed in phenomenological approaches. This phenomenological approach exploits both relativistic as well as non-relativistic treatment of quarks comprising hadrons. One of the important phenomenological approaches is the Potential Model. The most commonly used potentials are Cornell potential, Harmonic potential, Logarithmic potential, Martin potential, Richardson potential, Mixed power law potentials etc. With these potentials, we are interested in the study of heavy mesons like charmonium, bottomonium, D mesons, B mesons, etc. (Ablikim et al., 2022).

3. HEAVY QUARK EFFECTIVE THEORY

It is an effective QCD theory describing the dynamics of heavy-light hadron systems. The mass of heavy quark m_Q is defined as $m_Q > \Lambda_{QCD}$ where Λ_{QCD} is a non-perturbative scale of 0.2 GeV. This theory provides us a unique opportunity to explore the understanding of low energy QCD physics and the associated properties like colour confinement and chiral symmetry breaking. This theory is based upon approximate symmetry - heavy quark symmetry, where the mass of heavy quark $m_Q > \Lambda_{QCD}$, so by taking limit $m_Q \rightarrow \infty$, the dynamics of light quark remain invariant of spin and flavor of heavy quark (c or b). This is called heavy quark spin-flavor symmetry. This symmetry plays a vital role in the study of heavy hadrons. Now, QCD lagrangian can be modified for these approximations and symmetries. The QCD lagrangian for quark field is expanded in orders of ($1/m_Q$). The leading order is free of m_Q, which relates to $m_Q \rightarrow \infty$, but is not free of light degrees of freedom like the mass of light quark and spins, etc. Also, many of the parameters of the heavy quark are not included here, which makes the theory easy to handle. Resultant effective HQET lagrangian can be solved for these systems under consideration by defining the fields of particles and their interaction fields. Then the effective lagrangian of these systems is written and solved for masses and decay widths of particles (Garg & Upadhyay, 2022).

4. SUMMARY

Due to the advancement of high-energy accelerators and detectors, a large amount of data has been coming from various experimental groups like LHCb, BABAR, Belle, BESII/III, CDF, CMS, COMPASS, *DØ*, etc. In 2021, LHCb observed state D^0_{s0} (2590) with mass M = 2591 ± 13 MeV and decay width Γ = 89 ± 28 MeV respectively. Several new candidates like D_2^*(3000), D_J^* (3000), D_J (3000), D_3^*(2760), D_1^*(2680), D_2^*(2460), D_J^*(2760), $D_{s0}(2590)^+$ observed by experiment facilities like LHCb, BABAR, BESIII, etc., have flourished charm meson spectrum. In case of the bottom sector, many new states like B_J (5840), B_J (5960), B_{s1}(5830), B_{s2}^*(5840), B_{s0} (6064), B^0(6114), B^0(6158) have broadened the bottom spectrum (Aubert et al., 2006; Aaij et al., 2013; Aaij et al., 2015). There is also remarkable growth in the field of the baryon sector with the observations of five narrow Ω_c resonances and doubly charmed Ξ_{cc} resonances. Several theoretical investigations have been made on these states, but the academic community has not formed a common understanding. The study of these states is important for the understanding of non- perturbative QCD, which is asymptotically free and, at the same time, quark confining. So, we are motivated to understand recent data on heavy mesons in the framework of heavy quark effective theory and Potential Model. The present work will be significant for the High energy accelerators and detectors, which are in search of new information on the properties of hadrons that can give a new direction to our better understanding of the hadronic structure. We will be able to have a better understanding of the internal structure of the heavy mesons and can have motivations for the upcoming facilities like LHCb and Belle, PANDA, etc. The obtained couplings and splittings will allow us to compute the strong decay widths of the missing hadronic states. We will also be able to examine the recently observed heavy hadron states with their properties like resonance masses, spin-parity, decay channels, decay widths, and magnetic moments. Thus, these predictions have opened a window to investigate the higher excitations of mesonic states at the LHCb, *DØ*, CDF.

STATEMENTS AND DECLARATIONS

All authors of this article have made substantial contributions towards the conception and design of the work, acquisition, analysis, and interpretation of data; as well as for the preparation of draft and editing of the manuscript and approved the final version for submission.

FUNDING

This work received no specific funding to any of the Authors.

CONFLICT OF INTEREST

The authors further declare that there are no financial or non-financial interests that are directly or indirectly related to the work submitted for publication; the work was not supported by any governmental or non-governmental financial institutions; and the authors declare no conflicting interests.

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How to cite this article: Garg, R., Vishwakarma, K. K., Bhall, P., & Upadhyay, A. (2024). Recent Progress in Charm and Bottom Mesons. *Vantage: Journal of Thematic Analysis*, 5(1), 18-25

DOI: https://doi.org/10.52253/vjta.2024.v05i01.03