Study of Decay Properties of Heavy Flavor and Exotic Hadrons

One of the most challenging task in particle physics is to encompass the diversity and the complexity observed in the decay modes and the fractions of particles. For example, there are twenty-two quantitative modes and total forty-nine decays modes of $K^{\pm}$, and ratio of highest to lowest of these fractions amounts to 10^{11}. The spectroscopy and decay rates of various hadronic states are quite important to study due to huge amount of high precession data acquired using large number of experimental facilities viz. BESIII at the Beijing Electron Positron Collider (BEPC), E835 at Fermilab and CLEO at the Cornell Electron Storage Ring (CESR), the B-meson factories, BaBar at PEP-II, Belle at KEKB, the CDF and D0 experiments at Fermilab, the Selex experiment at Fermilab, ZEUS and H1 at DESY, PHENIX and STAR at RHIC, NA60 and LHCb at CERN and new future facility $\overline{\text{P}}$ANDA at FAIR, GSI. The plethora of observations from these facilities offer greater challenges and opportunities in theoretical high energy physics. The hadronic states are not only identified with their masses but also with their various decay rates. All the hadronic states along with experimentally identified decay channels are reported in Particle Data Group (PDG) [1]. Decay properties of these sates are of special interest because they provide the further insight into the dynamics of these states. For example, the semileptonic decays of D and B mesons give the accurate determination of Cabibbo-Kobayashi-Maskawa (CKM) matrix since they involve strong as well as weak interaction. Heavy quarkonium states have very rich spectroscopy with narrow experimentally characterized states and the interaction potential is of prime importance for analysis of underlying physics of strong interaction.

Also, a large number of exotic hadronic states have been observed in the heavy flavor sector that do not fit into the conventional mesonic or baryonic states. Quite a few of these newly observed states are above the $D\bar{D}$ and $B\bar{B}$ threshold. There are variety of theoretical models available in the literature to study the production and decays of these states. The most successful theories are based on the first principle such as lattice quantum chromodynamics (LQCD) [2, 3] and QCD sum rules (QCDSR) [4]. Other attempts are based are QCD, perturbative QCD [5], effective field theory [6], Bethe-Salpeter approach [7, 8], quark models [9, 10]. There are nonrelativistic models such as nonrelativistic QCD (NRQCD) [11, 12], perturbative nonrelativistic QCD (pNRQCD) [13] and models based on phenomenological potential such as relativistic potential model [14] and nonrelativistic potential models [15, 16, 17] to study these hadronic states. Many of these approaches sometimes precisely explain the masses of hadrons but not the decay properties and vice-versa. A comprehensive review of experimental and theoretical status and challenges in study of hadronic decays are found in the literature [18, 19, 20, 21, 22].

In 2003, the Belle Collaboration [23] discovered a new exotic particle named $X(3872)$ in the $B \to K(\pi^+\pi^- J/\psi)$ channel followed by its repeated observations in different channels at other experimental facilities [24]. Later, several other resonances were also discovered near and above the first open flavor threshold region of $c\bar{c}$ and $b\bar{b}$. Several theoretical attempts have been made to understand exotic hadrons and their decay properties. Since they are not the part of standard model and Quark Model also fails to explain these states, these states are claimed to be a cluster of four quarks or multi-quark states, hydrocharmonium states, composition of hadronic molecules such as di-mesonic molecule, diquark-diantiquark molecule or $q\bar{q}g$ hybrid states according to the Quantum Chromodynamics [25, 26, 27].

Organization of the thesis:

The thesis entitled "Study of Decay Properties of Heavy Flavor and Exotic Hadrons has been organized in total 6 chapters. A chapter-wise brief description of the work done is as follows.

Chapter 1: Theoretical Developments in Particle Physics

This chapter introduces the field of particle physics and its key aspects. Some major experiments in hadron physics and theoretical approaches are outlined. This chapter provides the motivation and objectives of the present work.

Chapter 2: Heavy Quarkonium Spectroscopy

This chapter comprises of calculations for the mass spectra of heavy quarkonia in nonrelativistic quark-antiquark Cornell potential model. We have employed the numerical solution of Schrödinger equation to obtain their mass spectra using least number of parameters. The spin hyperfine, spin-orbit and tensor components of the one gluon exchange interaction are computed perturbatively to determine the mass spectra of excited S, P, D and F states.

The mass spectra and numerical solution of wave-function are then used to compute various decay properties such as decay constants, digamma, digluon and dilepton annihilation rates. We also compute the electromagnetic dipole transition rates between the S and P waves. The mass spectra, decay modes and the life time of the B_c^+ meson are also computed without introducing any new parameter and the results are consistent with available experimental data and other theoretical studies. The outcome of this study has been published in [28, 29].

Chapter 3: Decay Properties of Heavy Baryons

We compute the masses of heavy flavour baryons using confinement scheme based on harmonic approximation with Lorentz scalar plus vector character. The residual two body coulomb interaction is included to compute the spin average masses. The spin hyperfine interaction of confined one gluon exchange potential is added to the confinement energy to get the masses of baryons. The mass spectra of baryons are computed using spin-flavour wave function for constituent quarks. The magnetic moments in all systems are then computed without additional parameters. We also compute the radiative transition ($3/2^+ \to 1/2^+$) widths of these states. The computed masses, magnetic moments and decay widths are compared with the experimental data other theoretical models.

Chapter 4: Study of Exotic States as a Dimesonic Molecules

This chapter dedicate to the study of newly observed state which was not explained by the Standard Model, the exotic states. The exotic states are multiquark or hybrid states other than familiar mesons and baryons. In PDG, there are more than 25 exotic states reported by the experimental facilities world wide. We study the tetra quark states (X, Y and Z) considering a them as dimesonic molecules employing modified Woods-Saxon plus Coulomb potential for interaction between the constituent mesons. We compute the bound state masses of the exotic states by solving the Schrödinger equation numerically. We also compute the hadronic two body decay width using the method of Phenomenological Lagrangian mechanism.

Chapter 5: Weak Decays of Open Flavor Mesons

In this chapter we present the leptonic and semileptonic decays of charmed meson ($D_{(s)} \to \ell^+\nu_\ell$ and $D_{(s)} \to (P,V)\ell^+\nu_\ell$) in the Covariant Quark Model (CQM) formalism with the built-in infrared confinement within the Standard Model framework.

Here P and V corresponds to pseudoscalar and vector mesons respectively. The CQM is an effective quantum field approach for the hadronic interaction based on effective Lagrangian of hadrons interacting with the constituent quarks. The required form factors are computed in the entire range of momentum transfer and used to determine semileptonic branching fractions. Our findings have been published in PRD [30] and they are presented here along with the experimental, LQCD and other theoretical data.

Chapter 6: Conclusion and Future Scopes

This chapter is an accomplishment of the work done in the thesis. Along with that, we also discuss the future prospects of research in the area of weak decays using the covariant quark model.

References

[1] M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018).

[2] J. J. Dudek, R. G. Edwards, N. Mathur, D. G. Richards, Phys. Rev.D **77**, 034501 (2008).

[3] Y. Burnier, O. Kaczmarek, A. Rothkopf, JHEP **12**, 101 (2015).

[4] S. Cho, K. Hattori, S. H. Lee, K. Morita, S. Ozaki, Phys. Rev. D **91**, 045025 (2015).

[5] Y. Kiyo, Y. Sumino, Phys. Lett. B **730**, 76 (2014).

[6] W. Y. Wang, Y. L. Wu, and M. Zhong, Phys. Rev. D **67**, 014024 (2003).

[7] V. Sauli, Phys. Rev. D **86**, 096004 (2012)

[8] C. S. Fischer, S. Kubrak, R. Williams, Eur. Phys. J. A **51**, 10 (2015).

[9] T. Palmer and J. O. Eeg, Phys. Rev. D **89**, 034013 (2014).

[10] S. Fajfer and J. F. Kamenik, Phys. Rev. D **71**, 014020 (2005), **72**, 034029 (2005).

[11] T. Liu, A. A. Penin, A. Rayyan, JHEP **02**, 084 (2017).

[12] R. J. Dowdall, C. T. H. Davies, T. Hammant, R. R. Horgan, Phys. Rev. D **89**, 031502 (2014).

[13] Y. Koma, M. Koma, Prog. Theor. Phys. Suppl. **186**, 205 (2010).

[14] S. F. Radford, W. W. Repko, Phys. Rev. D **75**, 074031 (2007), Nucl. Phys. A **865**, 69 (2011).

[15] P. C. Vinodkumar, J. N. Pandya, V. M. Bannur, S. B. Khadkikar, Eur. Phys. J. A **4**, 83 (1999).

[16] J. N. Pandya and P. C. Vinodkumar, Pramana **57**, 821 (2001).

[17] A. K. Rai, J. N. Pandya, P. C. Vinodkumar, Eur. Phys. J. A **38**, 77 (2008).

[18] E. Eichten, S. Godfrey, H. Mahlke, J. L. Rosner, Rev. Mod. Phys. **80**, 1161 (2008).

[19] S. Godfrey, S. L. Olsen, Ann. Rev. Nucl. Part. Sci. **58**, 51 (2008).

[20] T. Barnes, S. L. Olsen, Int. J. Mod. Phys. A **24S1**, 305 (2009).

[21] N. Brambilla *et al.*, Eur. Phys. J. C **74**, 2981 (2014).

[22] A. Ryd and A. A. Petrov, Rev. Mod. Phys. **84**, 65 (2012).

[23] S. K. Choi *et al.* (Belle Collaboration), Phys Rev Lett. **91**, 262001 (2003).

[24] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **110**, 222001 (2013).

[25] R. F. Lebed, R. E. Mitchell and E. S. Swanson, Prog. Part. Nucl. Phys. **93**, 143 (2017).

[26] M. Nielsen, F. S. Navarra and S. H. Lee, Phys. Rept. **497**, 41 (2010).

[27] E. Klempt and A. Zaitsev, Phys. Rept. **454**, 1 (2007).

[28] J. N. Pandya, N. R. Soni, N. Devlani, A. K. Rai, Chin. Phys. C **39**, 123101 (2015).

[29] N. R. Soni, B. R. Joshi, R. P. Shah, H. R. Chauhan, J. N. Pandya, Eur. Phys. J. C **78**, 592 (2018).

[30] N. R. Soni and J. N. Pandya, Phys. Rev. D **96**, 016017 (2017).

* * * * * * * * *

Synopsis submitted by

Mr. Soni Nakul Rajendrakumar

Endorsement of the Supervisor:

Synopsis is approved by me

Dr. Jignesh Narendrakumar Pandya

Head
Dr. B. S. Chakrabarty
Applied Physics Department,
Faculty of Technology and Engineering,
The M. S. University of Baroda, Vadodara.

Dean
Prof. Arun Pratap
Faculty of Technology and Engineering,
The M. S. University of Baroda, Vadodara.

List of Publications

Papers in peer reviewed Journals

1. J. N. Pandya, N. R. Soni, N. Devlani, A. K. Rai, "Decay rates and electromagnetic transitions of heavy quarkonia", Chin. Phys. C **39**, 123101 (2015).

2. N. R. Soni and J. N. Pandya, "Decay $D \to K^{(*)}\ell^+\nu_\ell$ in covariant quark model", Phys. Rev. D **96**, 016017 (2017).

3. N. R. Soni, B. R. Joshi, R. P. Shah, H. R. Chauhan, J. N. Pandya "$Q\bar{Q}(Q \in \{b,c\})$ spectroscopy using Cornell potential", Eur. Phys. J. C **78**, 592 (2018).

4. N. R. Soni, C. T. Tran, M. A. Ivanov, J. N. Pandya, "Semileptonic decays of D and D_s mesons in covariant quark model" (manuscript under preparation).

Papers in Conference Proceedings

1. N. R. Soni and J. N. Pandya, "Masses and radiative leptonic decay properties of B_c meson", DAE Symp. Nucl. Phys. **58**, 674 (2013).

2. N. R. Soni and J. N. Pandya, "Semileptonic and pionic decays of doubly heavy baryons", DAE Symp. Nucl. Phys. **60**, 694 (2015).

3. A. N. Gadaria, N. R. Soni, J. N. Pandya, "Masses and magnetic moment of doubly heavy baryons", DAE Symp. Nucl. Phys. **61**, 698 (2016).

4. N. R. Soni, J. N. Pandya, "Masses and radiative decay of ω_{cc}^+ baryon", DAE Symp. Nucl. Phys. **62**, 770 (2017).

5. N. R. Soni, R. R. Chaturvedi. A. K. Rai, J. N. Pandya, "Mass and Hadronic Decay Widths of Z States as Di-meson Molecule", Springer Proc. Phys. **203**, 729 (2018).