CHAPTER 1

INTRODUCTION AND MOTIVATION

In the early sixties, Gell-Mann and Zweig independently put forth the idea of quark structure of the hadrons. They suggested that mesons and baryons are composites of three flavors of the quarks called up, down and strange (u, d, s) and their antipartners called antiquarks [1]. On the leptonic side, at that time four leptons, electron (e), muon (µ) and their respective neutrino partners (eν, µν), had been observed. Inspired by the quark-lepton analogy, Bjorken and Glashow proposed the existence of the fourth flavor of quark named charm (c) in 1964. Later, in 1970, mass of the charm quark was estimated through Glashow, Illiopoulos and Maiani (GIM) mechanism, which explained the observed suppression of certain processes, like \( K^0 \rightarrow \mu^+ \mu^- \). Discovery of the \( J/\psi \) (cc) having mass 3.1 GeV in 1974, at SLAC and Brookhaven laboratory finally confirmed the existence of the charm quark [2], i.e. the first heavy flavor quark. Subsequently, evidence for even heavier quark called bottom quark (b) was obtained in 1977 with the discovery of another narrow resonance \( \Upsilon \) (bb) meson carrying mass 9.5 GeV. Around the same time, a heavy lepton namely tau (τ) was added to the list of the leptons. Again quark-lepton analogy suggested existence of the sixth quark called top quark (t) which eluded its discovery for

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1 In 1965, Greenberg introduced the new property of the quark that is color charge and suggested that the hadrons are color neutral.
some time. Finally in 1994, existence of the top quark with mass around 175 GeV has been established at Fermilab Tevatron collider [2, 3].

At the present energy scale, the fundamental constituents of the matter are pointlike quarks and leptons carrying spin half. The six quarks are grouped in three generations as \((u, d), (c, s), (t, b)\) similar to the six leptons \((e, \nu_e), (\mu, \nu_\mu), (\tau, \nu_\tau)\). On the basis of mass pattern, quarks are classified as the light \((u, d, s)\) and heavy \((c, b, t)\) flavors [4]. The heavy flavor hadrons contain at least one heavy flavor quark. It may be remarked here that quarks are not observed as free particles, experimentally baryons and mesons, the bound states of these quarks\(^2\), are produced.

Study of the heavy flavor hadrons is a very rich source of information for the fundamental interactions. There are four types of the fundamental interactions; strong, electromagnetic, weak and gravitational, in terms of which we can understand, in principle, all the processes occurring in nature from the elementary particles to the extra-galactic level. At the present energy scale of high-energy accelerators, the gravitational interactions are not relevant in the study of hadrons. The electromagnetic interactions are mediated by photon \((\gamma)\), the weak interactions are carried out by exchange of three intermediate bosons \((W^\pm, Z^0)\), and the strong interactions among the quarks are mediated by eight gluons \((g)\).

After the development of the well-tested quantum electrodynamics (QED), through the independent works of Feynman, Schwinger and Tomonaga by 1950, a major step in this direction was taken by Weinberg and Salam in 1967, who independently developed the unified electroweak quantum gauge field theory based on the \(SU(2)_L \times U(1)\) symmetry originally suggested by Glashow in 1964. This theory predicted the existence of the three bosons mediating the weak interactions\(^3\). In 1973, \(SU(3)\) based quantum field theory of the

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\(^2\) The top quark cannot form bound states because of its short life time.

\(^3\) They also predicted an additional scalar boson called the Higgs Boson that has not yet been observed.
strong interactions at the quark level was formulated by Politzer, Gross and Wilczek, which is similar in structure to the quantum QED. Since the strong interaction deals with color-charge, it is called quantum chromodynamics (QCD) [5], in which gluons act as massless quanta of the strong-interactions. In QCD, diminution of the strong interaction charge occur at the short distances. So a perturbative theory could be successfully employed in the high energy domain, but at large distances ($\approx 1\text{ fm}$) quarks are subjected to the confining forces, which have not yet been derived from the first principles. Finally, all these theoretical efforts culminated in the development of the ‘Standard Model’ (SM) of the strong and electroweak interactions among the quarks and leptons, which is based on the $SU(3)_c \times SU(2)_L \times U(1)_Y$ relativistic quantum gauge field theory [6].

Though the Standard Model [7] has achieved a remarkable success in understanding various phenomena involving the elementary particles, it does not yield the final picture. For instance, the model has many free parameters, like Cabibbo-Kobayashi-Maskawa (CKM) weak mixing angles, which are empirically determined from the weak hadronic decays. Study of properties and decays of the heavy flavor hadrons can provide useful information on these parameters and to investigate the strong interaction effects at low energies. An intense activity on theoretical and experimental studies of the decays of the heavy flavor hadrons have been going on for the last few decades. Soon after the discovery of $J/\psi(c\bar{c})$ meson, weakly decaying pseudoscalar charm mesons ($D^0, D^+ \text{ and } D_s^+$) and their excited states were produced [4]. Data on their masses and decays have been collected at electron-positron collider and fixed target experiments. After the discovery of $\Upsilon(b\bar{b})$ state, naked bottom states ($B^0, B^+ \text{ and } B_s^+$) came into observation, and their masses were observed in such experiments [4]. However, major progress for measurements of their decays could occur only in the last few decades. At present, there exist rich amount of
experimental data for the weak decays of heavy flavor mesons particularly for low lying spin zero particles [4].

Weak quark and lepton currents in the Standard Model generate leptonic, semileptonic and hadronic weak decays. The lifetime of the hadrons, their exclusive leptonic and semileptonic decays are reasonably well understood in this model [8, 9]. However, theoretical description of the exclusive weak hadronic decays confronts serious problems as these decays experience strong interaction interference due to the gluons exchange among the quarks involved. Fortunately, the short time-scale of weak decays allows one to separate the possible corrections from the strong interactions into short and long distance parts [8]. The asymptotic freedom property of the QCD allows a perturbative calculation of the effects of hard-gluon exchange on the weak Hamiltonian. The short distance effects can be resummed in the QCD coefficients, and the effective weak Hamiltonian has been constructed [8]. However, evaluation of matrix elements of the weak Hamiltonian between initial and final hadron states is not straightforward, due to the nonperturbative nature of the confinement mechanism responsible for forming the hadrons out of the interacting quarks. [8, 9]. Due to the lack of exact dynamics of the long distance strong interactions, hadronization of the quarks is generally studied through phenomenological approaches [8-19] like quark models, QCD sum rules, heavy quark effective theory (HQET) and lattice QCD.

Experimental data for the weak hadronic decays of the charm and bottom mesons, show the dominance of two-body decay modes. Initially, one expected their weak decays to have less interference due to the strong interactions, their measurements have revealed the contrary. The present data on these decays have posed serious problems for theory, which have led to several theoretical efforts [8-19] incorporating new ideas. At present, all over the world, several groups [20-22] at Fermilab, Cornell, CERN, DESY, KEK and
Beijing Electron Collider etc. are working to ensure wide knowledge of the heavy flavor physics. Thus, in the near future a large quantity of new and more accurate data on decays of the heavy flavor hadrons, including $B_c$, $J/\psi$ and $\Upsilon$, can be expected which calls for their comprehensive theoretical analysis. One of the goals of heavy flavor hadron physics is to elucidate the relationship among the particles of different generations. The $b$ quark is specially interesting in this respect as it has $W$-mediated transitions to both first generation ($u$) and second generation ($c$) quarks. Therefore, in this thesis, we have investigated the two-body weak hadronic decays of heavy flavor mesons in the framework of standard model.

In chapter 2, we lay down the physical and mathematical preliminaries which have been applied for the study of weak decays of mesons emitting the $s$-wave mesons, pseudoscalar ($P$) and vector ($V$) mesons. To start with, we present the hadron spectroscopy upto the bottom level and classification of the weak decays into leptonic, semileptonic and nonleptonic decays. In general, these weak decays proceed through exchange of virtual $W$-boson between the charged weak ($V$-$A$) currents. Since leptons do not participate in the strong interactions, leptonic decays remain unaffected by the strong interaction effects and thus are well understood in the standard model [23]. We discuss the semileptonic decays of the bottom ($B$) mesons as they provide information about binding of the quarks. Since these decays proceed via spectator quark diagrams, their decay amplitudes can easily expressed in terms of the matrix elements of the hadronic weak currents between the parent and daughter meson states, which are usually calculated from the phenomenological models [8, 10, 11]. This forms the basis of the ‘factorization approach’, later applied to the weak nonleptonic decays. Theoretically, the two-body nonleptonic decays occur through several quark level processes, like $W$-emission (spectator diagram), $W$-exchange, $W$-annihilation and penguin diagrams. Out of these, $W$-emission diagrams are found to be dominant, as the
$W$-exchange and $W$-annihilation processes are helicity and color suppressed at the tree level. Weak decay amplitudes arising through the spectator diagrams can be expressed in terms of products of appropriate meson decay constants and the same form factors that are required for the semileptonic decays. We use the $B \rightarrow P$ form factors obtained in the Bauer, Stech and Wirbel (BSW) quark model framework [8]. Majority of these decay modes are seen to result in a large variety of $s$-wave mesons [18, 19, 24]. However, $B$ mesons being heavy can also emit $p$-wave mesons like axial-vector ($A$), tensor ($T$) and scalar mesons ($S$) along with a pseudoscalar meson [25-27] which have attracted the attention of the experimentalist in the last few decades and the branching ratios of some of such decays have been measured. Therefore, we investigate $p$-wave meson emitting decays of heavy flavor hadrons in the following chapters.

In chapter 3, we extend factorization approach to study two-body hadronic weak decays of bottom emitting pseudoscalar and axial-vector mesons, i.e. $B / \bar{B}^0 / B_s \rightarrow PA / PA^\prime$. After describing the spectroscopy of the two kinds of axial-vector mesons, i.e. $A(1^{++})$ and $A'(1^{+-})$, we proceed to obtain the weak decay amplitudes in the Standard Model framework. Similar to the $s$-wave mesons emitting decays, here also two kinds of the spectator diagrams, color-favored and color-suppressed diagrams, can contribute to $B \rightarrow PA / PA^\prime$ decays. Using the factorization scheme, decay amplitudes are expressed in terms of the meson to meson form factors and meson decay constants. Though the meson decay constants are now reasonably known, the form factors are not properly understood. Isgur, Scora, Grinstein and Wise (ISGW I) model has been the first to calculate the form factors for $s$-wave meson to $p$-wave meson transitions [10] needed for $B \rightarrow PA / PA^\prime$ decays [25]. However, the form factors evaluated in this model are reliable only at the maximum momentum transfer, whereas the weak hadronic decays require them at relatively lower momentum transfer. This model has now been improved,
called as ISGW II model [10], in which the form factors provide a more realistic behavior. Therefore, we adopt this model for our purpose and calculate the $B \to A / A'$ transition form factors in the ISGW II model [10]. Consequently, we predict branching ratios of $B \to PA$ decays involving $b \to c$ and $b \to u$ transitions in the CKM-favored and CKM-suppressed modes. Experimentally [4], at present, branching ratios of eleven decays have been measured and upper limits are also available for five other decays. We compare our theoretical predictions with the available experimental measurements and also with other theoretical works.

In chapter 4, we have studied hadronic weak decays of bottom mesons emitting pseudoscalar and tensor mesons [26]. We first calculate the decay amplitudes in terms of the form factors and appropriate meson decay constants. Decay constants of tensor mesons vanish due to the tracelessness of the polarization tensor of spin 2 meson and its auxiliary condition. Therefore, either color-favored diagram or color-suppressed diagram can contribute to these decays and thus analysis of these decays becomes free of the interference between these diagrams. Here also, we employ ISGW II model [10] to determine the $B \to T$ transition form factors appearing in the decay matrix elements of weak currents involving $b \to c$ and $b \to u$ transitions. Consequently, we predict the branching ratios of $B \to PT$ decays in the CKM-favored and CKM-suppressed modes. Experimentally [4], branching ratios of only six decay modes have been measured and upper limits are available for five other decays. We compare the predicted branching ratios with the experimental results and with other theoretical values.

In chapter 5, we have studied hadronic weak decays of bottom mesons emitting pseudoscalar and scalar involving $b \to c$ and $b \to u$ transitions. We extend our model by employing the ISGW II model to determine the form factors appearing in the decay matrix element of weak currents for $B \to S$ transition. Consequently, we calculate the decay
amplitude and predict branching ratios in the CKM-favored and CKM-suppressed modes. Though, for these decays both kinds of the spectator diagrams, color-favored and color-suppressed diagrams, can contribute, usually one of these gets suppressed due to the small values of the scalar meson decay constants. Experimentally not much data exist for $B \rightarrow PS$ decays, only three measured branching ratios decays are available [4]. We compare our results with other theoretical calculations.

In chapter 6, we study hadronic weak decays of uniquely observed bottom-charm ($B_c$) meson. In 1998, $B_c$ meson, a unique state, composed of the two heavy quarks, bottom and charm, has been observed by the CDF collaboration [28]. Later, it announced an accurate determination of the $B_c$ meson mass, $m_{B_c} = (6.2857 \pm 0.0053 \pm 0.0012) \text{ GeV}$ and its life time $\tau_{B_c} = 0.45^{+0.12}_{-0.10} \pm 0.12 \text{ ps}$ [29] in conformity with theoretical predictions. A peculiarity of the $B_c$ decays, with respect to the decays of $B$ and $B_s$ mesons, is that both the quarks ($b$ and $\bar{c}$) may decay weakly, thereby generating bottom changing and bottom conserving decay modes, respectively. The investigation of the $B_c$ meson is of special interest as unlike its diagonal heavy quarkonium ($\bar{b}b, \bar{c}c$) partners it decays only through weak interactions. Study of $B_c^+$ meson is becoming one of the most interesting topics of research in high-energy physics (HEP) both on experimental and theoretical side. Already there exists an extensive literature for the semileptonic and nonleptonic decays of $B_c$ emitting $s$-wave mesons, pseudoscalar and vector mesons. However, relatively less work has been done on the $p$-wave meson emitting weak decays of $B_c$ meson. Therefore, we extend our analysis to $B_c$ meson decays emitting a pseudoscalar meson and a $p$-wave meson ($B_c \rightarrow PA/PT/PS$) [30]. In case of $B_c$ meson decays, one naively expects the bottom conserving (and charm changing) decay modes to be kinematically suppressed in comparison to the bottom changing mode [30]. On the contrary, we find that the bottom
conserving decays have branching ratios larger than that of the bottom changing modes due to the significant difference in the corresponding CKM factors.

Summary and conclusions of the work done are given in the last chapter.
REFERENCES


