Chapter 1

INTRODUCTION AND MOTIVATION

"Now the smallest Particles of matter may cohere by the strongest attractions, and compose bigger particles of weaker virtue.... There are therefore agents in nature able make the particles of Bodies stick together by very strong attractions and it is the Business of experimental Philosophy to find them out."

Newton, ‘Optics’, 1680.

The quest for the fundamental constituents of matter around us and the forces that operate among them, has been on in the history of mankind, from the time of Greeks or even before. It has been a long, tortuous but often exciting route from that stage to our present knowledge of ‘elementary’ particles and the interactions among them. In the beginning of the century, it was believed that the basic building blocks of all matter are atoms. However, the atom was soon found to be divisible into electrons and a nucleus, made of protons and neutrons. Later, a host of new experimental results made possible by a new generation of particle accelerators and detectors, and the convergence of theoretical ideas, brought to the subject a new coherence. They revealed that the nucleons (proton+neutron) and a large number of other hadrons are further made up of smallest particles called ‘quarks’. Our current
outlook has thus been shaped by the identification of quarks and leptons as the fundamental constituents of matter, which are supposedly point-like and spin-1/2 particles. In all, there are six quarks, grouped in three generations as \((u,d), (s,c), (b,t)\), similar to six leptons \((e,\nu_e), (\mu,\nu_\mu), (\tau,\nu_\tau)\). However, on the basis of mass pattern, quarks can be classified as (i) Light quarks \((u,d,s)\) and (ii) Heavy quarks \((c,b,t)\). It may be remarked here that these quarks are not observed as free particles. Experimentally baryons and mesons, together known as hadrons, the bound states of quarks, are produced in high energy accelerators which reveal their interesting decay patterns. It is worthwhile to note that the study of heavy flavor hadrons is a very rich source of information about the fundamental interactions.

There are four types of fundamental interactions observed in nature: (i) Gravitational, (ii) Electromagnetic, (iii) Weak, and (iv) Strong. In terms of these interactions, we can understand, in principle, all the processes occurring in nature from the elementary particles to the extra-galactic level. The gravitational force can act over large distances among the bodies of universe and is always attractive. At the present energy scale, the gravity is not relevant in the study of hadrons. The electromagnetic interactions are mediated by photons \((\gamma)\) and affect the electrically charged particles like electrons and quarks. The strong interactions are limited to a range of \(10^{-15}\ m\) and the mediating particles are 8 gluons. These are responsible for binding of the quarks to form hadrons. The weak interactions with an even shorter range of \(\approx 10^{-18}\ m\), are so weak that they do not bind anything but play an important role in the instability of matter. They are carried out by the intermediate vector bosons \((W^\pm, Z^0)\). Except for the gravitational force, the remaining three interactions are well understood in terms of quantum gauge field theory. After the development of the well-tested quantum electrodynamics (QED), a major step in this direction
was made by Weinberg and Salam who developed [1] the SU(2)$_L \times$ U(1)$_Y$ gauge field theory for electroweak unification. The gauge symmetry further motivated the development of SU(3) color gauge field theory known as the Quantum Chromodynamics (QCD) for the strong interactions [2], which are responsible for confining the quarks inside the hadrons. In QCD, interactions among the gluons result in the diminution of the effective strong interaction charge at short distances. So a perturbative theory could be successfully employed in the high energy domain, but at large distances ($\approx$1 fm), quarks are subjected to the confining forces, which have not been derived from the first principles. This aspect may be studied in a phenomenological manner for which the hadrons provide a good laboratory.

Finally, the theoretical efforts culminated in the development of the 'Standard Model' (SM) of strong and electroweak interactions based on the gauge group SU(3)$_c \times$SU(2)$_L \times$U(1)$_Y$ [3]. Though it has achieved a remarkable success in understanding various phenomena involving elementary particles, it does not yield the final picture [4]. For instance, the model has many free parameters, like weak mixing angles, fermion masses etc. Study of weak hadronic decays, particularly in the heavy flavor sector, can provide a 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 weak decays have been going on for the last two decades. Soon after the discovery, in 1974, of the so-called hidden charm state $J/\psi$, the open charm hadrons composed of a charm quark and light (u:up, d:down, s:Strange) quarks/antiquarks were found.

The discovery, in 1977, of the $\Upsilon$ family of mesons was the first indication of the existence of a fifth quark, the bottom quark $b$, with mass $m_b \approx$ 5 GeV and a charge $\frac{-1}{3}$. Again, open bottom meson states composed of a heavy bottom quark
and a light antiquark were identified at a somewhat later stage. Concerning bottom baryons the experimental situation is not yet quite conclusive. Unlike charm sector, where a lot of charm unity ($C = 1$) baryons ($\Lambda_c$, $\Sigma_c$, $\Xi_c$ and $\Omega_c$) have been observed experimentally, the presence of only one bottom baryon $\Lambda_b$ has been confirmed and the other $B = 1$ and higher baryons are still in the hidden state.

The existence of sixth quark i.e. top quark ($t$) with mass around 175 GeV has also been established by CDF and D0 groups at Fermilab Tevatron collider [5]. The study of these heavy flavor hadrons began a new era in the development of theoretical particle physics. Experimental studies [6] have mainly been focussed on the precision measurement of their weak decays.

Weak currents in the SM generate leptonic, semileptonic and hadronic decays of the heavy flavor hadrons. Regarding their lifetime patterns, inclusive weak decays, exclusive leptonic and semileptonic decays, a detailed picture is beginning to emerge, though a few discrepancies yet remain to be explained. However, a theoretical description of the exclusive weak hadronic decays based on the SM is not yet obtained as these experience strong interaction interference. The short time-scale of weak decays allows one to separate the possible corrections from strong interactions into short and long-distance parts. The asymptotic freedom property of the QCD allows a perturbative calculation of the effects of hard-gluon exchange on the weak Hamiltonian. Due to the lack of exact dynamics of long-distance strong interactions, the study of weak decays of heavy flavor hadrons is rather done phenomenologically. Even if the short distance effects can be re-summed in the QCD coefficients $c_1$ and $c_2$, and the effective weak Hamiltonian has been constructed at the next to leading order, evaluation of its matrix elements between initial and final hadron states is not straightforward. Since the quarks are confined inside the colorless hadrons,
matching between theory and experiment requires an exact knowledge of the low energy strong interactions. Thus the weak decays of heavy quark hadrons provide a unique opportunity to learn more about QCD particularly on the interface between the perturbative and non-perturbative regimes, to determine SM parameters and finally to search for the physics lying beyond the model.

Various theoretical and phenomenological approaches have been employed to study weak hadronic decays of charm and bottom hadrons. Broadly, these include, flavor symmetry, factorization, current algebra, quark line diagram approaches, relativistic and nonrelativistic quark models, QCD sum rules, recently developed heavy quark effective theory (HQET) and Lattice QCD frameworks. For exclusive weak decays of heavy hadrons, usually factorization hypothesis is applied to obtain the transition matrix elements. In these matrix elements, the strong interactions are expressed through the form factors which may be determined from the semileptonic decays or can be estimated various phenomenological models. The factorization approach [7,8] has been quite successful in describing the heavy meson decays. However, the situation is not very satisfactory for the baryon decays, while the hyperon decays can be tackled with the help of current algebra, a reliable approach suited for investigating the weak decays of heavy baryons does not exist yet. This is due to the fact that neither of current algebra, factorization or pole terms etc. seem to be the ultimate tool to analyze the heavy baryon decays.

Experimentally, an extensive information is available [6] on the weak decays of charm and bottom mesons, showing the dominance of two-body decay modes. The observed three or multi-body decays usually have resonance structure, though there exists a small non-resonant contribution. Recent measurements and theoretical calculations have substantially enhanced our understanding of charm mesonic states,
their spectroscopy and decays. Experimental results on charm baryons (with $C = 1$) and their decays are beginning to be good enough to apply and test what has been learned in the charm baryon sector. Furthermore, there is a very active ongoing experimental program at various laboratories like Fermilab Tevatron, LHC-B etc., to study the beauty hadrons, their masses, lifetimes and weak decays. The building of new B-factories have also now brought the doubly heavy hadrons under active investigation. In the near future, a large quantity of new and more accurate data on the exclusive weak decays of the heavy flavor hadrons can be expected, which call for their comprehensive analysis.

In this thesis, we study mainly the two-body weak nonleptonic decays alongwith the study of masses and the weak semileptonic decays of the heavy flavor hadrons in the framework of SM. Initially, one expected charm and bottom hadron decays to have less interference due to the strong interactions, their decays patterns have revealed the contrary. The present data on these decays have posed serious problems for theory. In our work, we search for the missing physics which may bridge the gap between theory and experiment.

Usually, heavy quark transitions can take place via two possible ways: (i) heavy to heavy, which is the dominant decay mode of $b$ quark, (ii) heavy to light, e.g. $b \rightarrow u$ which can throw light on the CKM matrix element $V_{ub}$. Apart from this usual behaviour, there is a possibility that the heavy quark remains unaffected i.e. it behaves as a spectator and it is the light quark in the hadron that undergoes weak transition. In the charm sector, charm-conserving strangeness changing ($\Delta c = 0, \Delta s \neq 0$) decays will be Cabibbo suppressed and are governed by the CKM element $V_{us}$ which is much smaller than the CKM diagonal element $V_{cs}$, so may be of little interest. On the other hand, in the b-sector, beauty-conserving strangeness changing
(\Delta b = 0, \Delta s \neq 0) decays will be CKM allowed as the CKM matrix element \( V_{us} \) governing such decays is much larger than \( V_{bc} \) or \( V_{bu} \) which govern respectively the \( b \rightarrow c \) or \( b \rightarrow u \) transitions. The phase space available, however, will be too small. In some such decay modes, however, the rate for such decays may have a significant fraction. Since in the decays under consideration, only the light quark participates in weak interactions, it is possible that the information we obtain about the decay of light quark(s) may help us in the understanding of K-meson decays, hyperon decays and hadron structure. So, in our work, we will also be studying the heavy flavor conserving strangeness changing rare decay modes of heavy hadrons.

Chapter 2 starts with the basic review of the SM and its ingredients. Then, the weak decays are discussed in detail and the weak transition Hamiltonian for \( B \) decays has been constructed within the framework of SM. The strong interaction effects that can modify our naive expectations have been included. A brief review of the form factors, the factorization hypothesis and the Heavy Quark Symmetry has also been given. In short, the chapter talks about the mathematical and the physical preliminaries required for our work.

The masses and spectroscopy of heavy hadrons have been studied intensively in recent years. The study of hadronic physics forms the basis of our research work and is described briefly in terms of its spectroscopy in Chapter 3. We also calculate [9] the masses of heavy hadrons in the framework of nonrelativistic quark model which includes spin and flavor-dependent hyperfine splitting for two quarks. The effect of variation of the wavefunction value at origin i.e. \( |\psi(0)|^2 \) and the strong coupling constant \( \alpha_s \), with flavor, has also been included in calculating the mass values. The predictions made by us are in nice agreement with the experimental values wherever available.
In Chapter 4, we study the weak nonleptonic and semileptonic decays of $B$ and $B_s$ mesons. Since the top quark mass is large, $B$ mesons are the only mesons containing quarks of the third generation and thus their decays provide a unique opportunity to measure the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $V_{cb}$ and $V_{ub}$ which describe the couplings of the third generation quarks to the lighter quarks. The weak transitions $b \to c$, $b \to s$, $b \to u$, $b \to d$ are expected to be observable for $B$-meson decays [10]. Out of these $b \to c$, and $b \to u$ transitions arise from the $W$-emission diagrams. The $b \to s/d$ transition arises from the penguin diagrams which are always CKM-suppressed [11]. Thus, the spectator quark diagram involving $b \to c$ transition is the dominant process, where the virtual $W^-$ materialize into either a lepton and anti-neutrino or $\bar{u}d$ or $\bar{c}s$ quark pair in the dominant mode. In the hadronic decays, the quark pair becomes one of the final state hadrons while the produced $c$ quark pairs with the spectator anti-quark to form the other hadron, while in semileptonic decays, the $c$-quark and spectator anti-quark hadronizes independently of the leptonic current. The model has worked well in explaining the semileptonic decays [10,11]. In the hadronic decays, the factorization hypothesis has worked well for the $B$-meson decays. For the $B$-meson decays the FSIs are expected to be suppressed due to the fact that momentum available for the final state is quite large [11]. The chapter is divided in two sections. In the first section, we analyze the two body nonleptonic weak decays of $B$ and $B_s$ mesons [12]. Using the factorization hypothesis, we employ BSW model improved to $1/m_Q$ corrections to determine the form factors. Results obtained are compared with the available data. The second part of the chapter deals with beauty conserving strangeness changing semileptonic decays of $B_s$ meson [13]. The branching ratios come out to be very small but can be comparable to those in heavy flavor changing rare decay modes.
Chapter 5 deals with the weak decays of heavy flavor baryons. In contrast to the heavy flavor meson decays, the study on heavy flavor baryon decays belong to a less explored territory both theoretically and experimentally. In the past few years, charm baryon decays have come under active experimental investigations, whereas data on bottom baryon $\Lambda_b$ has merely begun. Various techniques have been developed employing the flavor symmetries [14], quark models [15], factorization [16], pole model [17,18], current algebra [19], and HQET [20,21] frameworks, to study the weak decays of heavy baryons. So far none of these attempts has been able to explain the available meager data on these decays.

In this chapter we first consider the two-body nonleptonic weak decays of $b$-baryons [22], involving heavy to heavy i.e. $b \rightarrow c$ transition, in BSW type model improved to $1/m_Q$ corrections and the results thus obtained are compared with those of other workers. The second part of this chapter is divided into two categories: two body nonleptonic decay modes of $\Lambda_b$ baryon involving heavy to light i.e. $b \rightarrow u$ transition, have been studied using the nonrelativistic quark model approach in the first part [23]. The decay rates thus obtained satisfy the upper limits set by experimental data wherever available. And, the second one includes the evaluation of exclusive semileptonic decay rate of $\Lambda_b$-baryon into proton [24]. The importance of studying such decays lies in the fact that these can give us information on the CKM matrix element $V_{ub}$. In the third section, we explore the possibility of heavy flavor conserving strangeness changing semileptonic rare decay modes of heavy baryons [25]. The decay rates in such cases come out to be too small to be measured experimentally.

Chapter 6 deals with weak decays of beauty hadrons involving $\rho$ or $a_1$ mesons in the final state. The exclusive two body weak decays of $D$ and $B$ mesons have been explained reasonably well in a relativistic quark model approach proposed
by BSW. However, the decays which involve vector particle(s) in the final state are still at variance with experimental predictions, even in the presence of final state interactions. A major discrepancy lies in the decays involving a large width resonance like $\rho$ or $a_1$, where all these channels are predicted larger than their experimental measurements. We have studied [26] such decays with the appropriate consideration of the effective phase space [27] by applying smearing effect technique, which involves averaging a running mass over the entire width of the resonance rather than considering a peak value of the mass. Using the Breit-Wigner measure to account for the broad resonance width, we calculate the branchings for the B-meson decays and obtain a better agreement with experiments. Following the success of the same in meson sector, this technique has also been applied to heavy baryons, where the experimental data is eagerly awaited by the theoretical community.

The last Chapter 7 contains our theoretical summary, and the conclusions drawn from the work done. It also gives an outlook on the heavy hadron (in particular heavy baryon) physics that lies ahead of us.