Chapter 7

SUMMARY AND OUTLOOK

Weak decays have always been a rich source of information about the nature of elementary particle interactions. Many years ago, $\beta$ and $\mu$ decay experiments revealed the form of the effective weak interaction at low momentum transfer. The selection rules and other consequences of the weak interactions were instrumental in exploring the properties of nuclei. Data on semileptonic and nonleptonic decays of hyperons gave the selection rules which guided the formation of weak interaction theory of strange particles.

Today we are in a similar situation: weak decays of heavy quarks are employed for tests of the standard model and measurements of its parameters. Quite obviously, they offer the most direct way to determine the weak mixing angles and to test the unitarity of the Kobayashi-Maskawa matrix. On the other hand, weak transitions are also of great help in studying that part of strong interaction physics which is least understood, the nonperturbative confinement forces. Both tasks complement each other: an understanding of long-range QCD - of the connection between quark and hadron properties - is a necessary prerequisite for a precise determination of the weak mixing angles and the CP-violating phase.

The simplest processes are those involving a minimum number of hadrons, i.e., a
single hadron (or hadron resonance) in the final state of a semileptonic decay, or two hadrons in a nonleptonic decay. In recent years, much progress has been achieved towards an understanding of these transitions. Simple bound-state models are able to describe, in a semi-quantitative way, the current matrix elements occurring in semileptonic decay amplitudes [7,159,160].

A factorization prescription for reducing the hadronic matrix elements of four-quark operators to a product of current matrix elements shed light onto the dynamics of nonleptonic processes [8,161], where even drastic effects had been lacking an explanation before. More recently, the extensive study of symmetries of QCD arising in the limit of infinite quark mass [98,155,162] constituted a further step forward. Starting from this limit and working out the corrections to it in a systematic way, one obtains normalization and consistency conditions for hadronic matrix elements and can minimize the model-dependence for the quantities of interest [97,101,105,163].

In the present work, we have mainly restricted ourselves to the treatment of exclusive weak decays of heavy hadrons and to the study of their masses. The work in this thesis is based on the spectator quark model, where one assumes the $W$-emission or the spectator diagram to be the dominant decay mechanism as the $W$-loop is suppressed due to GIM cancellations, and the $W$-exchange and $W$-annihilation processes seem to be helicity and color suppressed at tree level. The spectator process involves the expansion of the transition amplitude in terms of a few invariant form factors which contain information on the structure of the hadrons involved. To evaluate the hadronic matrix elements, we have employed the factorization approach throughout this work. Factorization is an interesting phenomenological idea which allows us to predict the nonleptonic amplitudes in terms of semileptonic form factors and pseudoscalar/vector decay constants. This hypothesis has been able to explain...
most of the data on heavy meson decays, but enough data are not present in the case of heavy baryon decays to test its validity.

**Masses of Heavy Hadrons**

An estimate has been made of the masses of heavy hadrons in nonrelativistic quark model, which includes spin and flavor-dependent hyperfine splitting for two quarks. The wavefunction value at origin i.e. $|\psi(0)|^2$ and the strong coupling constant $\alpha_s$, being flavor dependent, their variation with quark flavor have been included in calculating the mass values. By doing so, we are able to bring a lot of masses of both the baryons and the mesons closer to the observed values [9]. We have also tried to predict the wave function values at origin, respectively, for $c$ and $b$ sectors, in terms of the ratios $|\psi_{cu}|^2/|\psi_{su}|^2$ and $|\psi_{bu}|^2/|\psi_{sb}|^2$.

**Weak Decays of $B$ and $B_s$ Mesons**

It need not be emphasized time and again that the bottom-quark behaviour holds most of the hope of measuring and understanding some of the fundamental and delicate parameters of the SM, in particular, the elements of the CKM mixing matrix. Also interwoven into this is the subject of CP violation, and its proposed interpretation in terms of electroweak mixing. The findings in this arena can be summarized as follows:

1. BSW model, based on the factorization assumption, has been quite successful in the heavy meson sector. This simple and economical model along with final state interactions, has been able to explain most of the experimental data in D-sector. We have evaluated [12] the decay rates for some exclusive nonleptonic decay modes of $B$ and $B_s$ mesons in BSW model improved to $1/m_Q$ corrections. These decays involve mainly the heavy to heavy transitions. The branching ratios thus obtained match well with the experimental values wher-
ever available, in the case of $B$-meson. In the case of $B_s$ meson, one will have to wait for the experimental data yet to come to verify the results. It is interesting to note that the decay modes which involve vector particle(s) in the final state generally have higher values than determined experimentally. Smearing effects may help us to account for this discrepancy.

2. In the second part, a special class of decays has been discussed. The dominant decay modes in the case of heavy mesons are the ones which involve a change of heavy flavor, either from heavy to heavy or from heavy to light. Against this usual possibility, there is also a chance that when the heavy flavor remains as such i.e. behaves as a spectator and the accompanying light quark(antiquark) may undergo a transition. These decays are of special interest in the case of $B$-mesons, since the CKM matrix element governing such decays i.e. $V_{us}$, is much larger than the CKM elements $V_{cb}$ or $V_{ub}$, governing $b$-changing decay modes. On the other hand, in $c$-sector, such decays are Cabibbo suppressed as the CKM element $V_{cs}$ involved in charm changing decays is much larger than the element $V_{us}$ which governs the charm conserving and strangeness decay modes. However, the phase space available in these decay modes is very small. We have evaluated [13] the decay rates of two such decay modes of $B_s$ meson. The branching ratios although very small (of the order of $10^{-8}$ or $10^{-9}$), can be measured in the future experiments at $B$-LHC and at Fermilab Tevatron. Such type of decay modes are important as they can give information on hadron structure and hyperon decays. Since $q^2$ is nearly zero in these decays, one need not extrapolate the form factors for their $q^2$ dependence and can just use the form factor value at zero. As no parameter is involved, by matching the predictions with experimental values, we may be able to get the values of the
form factors at small $q^2$ and thus may be able to distinguish between various models which predict form factor values at $q^2 = 0$.

**Weak Decays of Heavy Baryons**

Up to now, most of the the theoretical and experimental efforts have gone into studying $B$-meson decays. Nonetheless, it is hoped that in the future, the branching ratios for many exclusive bottom-baryon decays will also be measured. With this prospect in mind we have explored the study of weak decays of heavy baryons and the contents can be summarized as follows:

1. Two body nonleptonic weak decays of heavy baryon are studied [22] in a BSW-type model proposed by B. König et al. The model based on the factorization assumption, includes the $1/mQ$ corrections and satisfies the constraints imposed by HQET. The decay rates thus obtained are also compared with those evaluated by other workers.

2. Next the two body nonleptonic and an exclusive semileptonic decay modes of $A_b$ baryon into proton have been studied. These decays clearly involve the heavy to light transitions and will thus be described by two form factors in HQET. So the latter is inadequate for the decays involving heavy to light transitions and one will have to stick to phenomenological models to evaluate the form factors associated with such decay modes. We have employed the nonrelativistic quark model (NRQM) improved to $1/mQ$ corrections and proposed by Cheng and Tseng. The branching ratios evaluated [23] in this model satisfy the upper limits defined by experimental data wherever available. In the second part of this section, an exclusive semileptonic decay, $A_b \rightarrow p e\nu$, has been studied [24] by splitting the whole $q^2$ range into low and high $q^2$ regimes.
Form factors for low $q^2$ region, are evaluated by employing NRQM proposed by Cheng and Tseng, whereas for high $q^2$ range, a perturbative QCD (PQCD) technique developed by Brodsky et al. has been used. The decay rate depends on the boundary value at which we choose to use PQCD. The results thus obtained are compared with those of other workers and has been found that the NRQM alone predicts the decay rate to be very large as compared to other models. The importance of studying such decays lies in the fact that these decays can give us information on the least accurately known CKM matrix element $V_{ub}$, which is required to constrain the allowed range of CP asymmetries in the B sector.

3. Beauty conserving strangeness changing rare semileptonic decays of heavy baryons constitute the third part of this study. In the case of heavy mesons, some such decay modes have significant branching ratios, as mentioned above and could be measured in the coming future. The situation is not so in the case of heavy baryons. Here the branching ratios [25] come out to be very very small and it seems hard to be able to measure these numbers.

**Smearing Effects**
In the case of decay modes which involve vector particle(s) in their final state, experimental data on heavy mesons is found to show discrepancies with theoretically obtained values. The latter values are found to be higher than the former ones. One can notice that the major discrepancy lies in the branching ratios of $M \rightarrow PV$ and $M \rightarrow VV$ modes involving $\rho$ or $a_1$ mesons, where $M$ is a heavy meson. Kamal, Verma and Uppal [108,109] have assigned the cause of the discrepancy, to the large width of the $\rho$ and $a_1$ resonances and employed smearing technique to study these
decays and in particular, the D-meson decays. In this technique, one considers a weighted average of the resonance mass over the entire width rather than taking the fixed mass at its peak. This is done by integrating over a running mass, using an appropriate measure to account for the increased effective phase space. We have extended this technique to the case of B and $B_s$ meson decays. The results are in nice agreement with the experimental data, wherever available. Although a very little data are available in heavy baryon sector, following the success of smearing technique in heavy meson decays, the same has also been applied to the two body decays of heavy baryons. The smearing effects are found to lower the branching ratios of both the B-meson decays and heavy baryon decays involving a $\rho$ or $a_1$ meson by about 15-40\% [26]. Here we would like to mention that we have ignored QCD effects while evaluating the decay rates of $\Lambda_b$ baryon decays with $\rho$ or $a_1$ in the final state. Although at present, it is very crucial to include the QCD coefficients in the matrix element calculations, we just wanted to check what will happen to the branchings of heavy baryons with the inclusion of smearing effects. One can always use the QCD corrected Hamiltonian to obtain the branching ratios and then apply the technique. The overall effect of the smearing technique is to lower the branching ratios in the desired direction and is to bridge the gap between theory and experiment.

**Conclusions**

To conclude, we have concentrated in this thesis work, on the mass values and decay properties of heavy hadrons. The exclusive weak decays in both the sectors, heavy mesons and heavy baryons, have been studied following the factorization approach. One can expect a wealth of data on heavy hadron physics in the future to be confronted with the predictions made.
At present there are strong experimental programmes on heavy hadron physics at high energy laboratories all over the world. SLAC is tooling up with its approved $B$ factory project which is expected to start its bottom physics program very shortly. The HERA-$B$ project at DESY, $B$ factory project at KEK, CERN LHC-$B$, and Fermilab Tevatron are on their way to deliver data in a short time to come.

All in all, we can expect an abundance of interesting new data on charm and bottom baryons in the next few years. The field is very much alive and one can be sure that there will be plenty of experimental and theoretical activity in heavy baryon physics in the future. As experience has shown, real progress is achieved when theoretical and experimental advances go hand in hand. In this sense the theoretical heavy quark physics community is looking forward to a lot of new experimental results on heavy quark physics in general and on heavy baryon physics in particular.