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Heavy flavor weak decays

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Abstract : Weak decays of heavy flavor hadrons play a special role in our understanding of physics of the Standard Model and beyond. The measured quantities, however, result from a complicated interplay of weak and strong interactions. Weak leptonic and semileptonic decays are reasonably well understood, whereas weak hadronic decays present challenges to theory. In this talk, we review the present status of exclusive weak decays of charm and bottom hadrons.

Keywords : Quark Model, Heavy flavor, weak decays.

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1. Introduction

Soon after the discovery of $J/\psi(\bar{c}c)$ meson in 1974, weakly decaying pseudoscalar charm mesons (D^0, D^+ and D_s^+) were produced. Data on these hadrons have been collected at e^+e^- colliders and at fixed target experiments [1]. Study of B-physics began in 1977 with the discovery of $\Upsilon(\bar{b}b)$ state. However, further progress in measurements in naked bottom sector could occur only in the last decade with the development of high resolution silicon vertex detector and high energy colliders [2,3]. Three bottom pseudoscalar mesons (B^+, B^0 and B_s^0) have been studied whereas the fourth meson B_c^+ is also expected to be produced. In the baryon sector, a few weakly decaying charm baryons $\left(\Lambda_c^+, \Xi_c^+, \Xi_c^0 \text{ and } \Omega_c^0\right)$ and one bottom baryon Λ_b have been observed experimentally [1]. A number of charm and bottom baryons are expected to be seen in future experiments.

The weak currents in the Standard Model generate leptonic, semileptonic and hadronic decays of the heavy flavor hadrons. An intense activity on theoretical [2–7] and experimental [8–11] studies of these hadrons has been going on in this area. Experimental studies have mainly focused on precision measurements of branching ratios for their weak decays. Regarding their lifetime patterns, inclusive decays, exclusive leptonic and

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semileptonic decays, a complete picture is beginning to emerge [4], though a few discrepancies yet remain to be explained. However, a theoretical description of exclusive hadronic decays based on the Standard Model is not yet fully possible [3,5] as these involve low energy strong interactions. Weak decays of heavy quark hadrons provide an ideal opportunity to probe strong interactions, to determine the Standard Model parameters and to search for physics lying beyond the Model.

In this review, present status of exclusive weak decays of heavy falvor hadrons is given. We first discuss their lifetime pattern, leptonic and semileptonic decays. Then weak hadronic decays of charm and bottom mesons are presented. Particularly, emphasis is given on the factorization hypothesis and relating the hadronic modes with the semileptonic decays. Finally, baryon decays are briefly introduced. In preparing this short talk, it has been difficult to make a complete presentation of all the aspects of weak decays. For further information, reference is made to some review articles [2–6].

2. Lifetime pattern of heavy flavor hadrons

At quark level various diagrams can contribute to the weak decays (Figure 1). These are generally classified as (a) Spectator quark, (b) W-exchange, (c) W-annihilation and

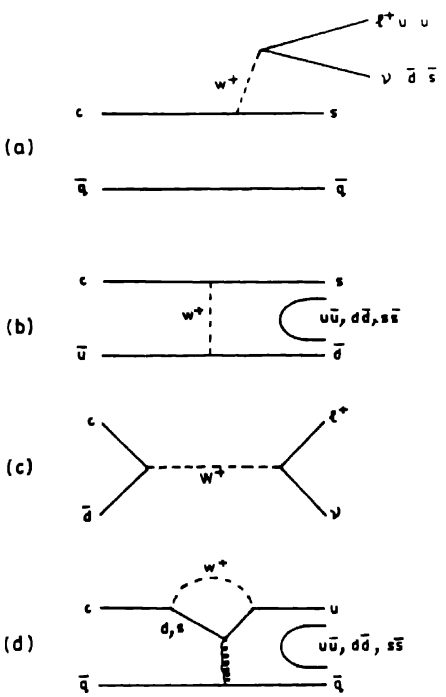

Figure 1. Various quark level weak processes : (a) Spectator quark diagram. (b) W-exchange diagram. (c) W-annihilation diagram. (d) Penguin diagram

(d) **Penguin diagrams.** W-exchange and W-annihilation diagrams are suppressed due to the helicity and color considerations. Penguin diagrams, contributing to Cabibbo suppressed modes, are also expected to be small in strength. Thus the dominant quark level processes seem to be those in which light quark/s behave like spectator. This simple picture then immediately yields decay width for a hadron containing a b quark,

$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3} \cdot |V_{bc}|^2 \times F_{ps}, \tag{1}$$

where F_{ps} is a phase-space factor. There is also a term with $|V_{bu}|^2$, which is very small and has been neglected [2]. Thus all the bottom hadrons are predicted to have equal lifetimes. For charm hadrons also, the spectator quark model leads to equal lifetimes. Though order of estimate of life-times is alright, the individual values [1] do show deviations from a common lifetime :

$$\tau(D^+) \approx 2.5\tau(D^0) \approx 2.5\tau(D_s^+) \approx 5.0\,\tau(\Lambda_c^+) \approx 3.0\,\tau(\Xi_c^+) \approx 10\,\tau(\Xi_c^0). \tag{2}$$

These differences seem to arise from many considerations [6], like

(a) interference among the spectator diagrams (color enhanced and color suppressed) which enhances D^+ life-time;

(b) nonspectator diagrams, life W-exchange diagram, which yield the following life-time pattern for the charm baryons :

$$\tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+). \tag{3}$$

Applying these considerations to the bottom hadrons, following observed pattern can be obtained [12] :

$$\tau(\Lambda_b) < \tau(B^0) \approx \tau(B_s^0) \approx \tau(B^+). \tag{4}$$

However, an exact agreement with experiment for B meson and Λ_b lifetime ratio is difficult to obtain. Recently, this ratio is described [13] by a simple ansatz that replaces the quark mass with the decaying hadron mass in the m_Q^5 factor in front of the hadronic width. However, there is yet no theoretical explanation for the ansatz.

3. Weak leptonic and semileptonic decays

In the Standard model, leptonic and semileptonic decays naturally involve factorizations of their amplitudes in terms of a well understood leptonic part and a more complicated hadronic current for the quark transition. Lorentz invariance is then used to express the matrix element in terms of a few formfactors which contain the nonperturbative strong interaction effects [4]. Explicit quark models [14–20] have been constructed to construct the hadron states which are then used to calculate the formfactors. In the last few years, a new theoretical approach known as the Heavy Quark Effective Theory (HQET) has emerged for analyzing heavy flavor hadrons. In the limit of heavy quarks, new symmetries [21] appear

which simplify the calculaions of the formfactors. Nonperturbative approaches like lattice simulations [22] and QCD sumrules [23] have also been used to calculate the formfactors.

Weak quark current generating the charm hadron decays is

$$J_\mu^{\Delta C=-1} = V_{cs}^*(\bar{s}c) + V_{cd}^*(\bar{d}c), \tag{5}$$

where $\bar{q}'q$ denotes the V-A current $\bar{q}'\gamma_\mu(1-\gamma_5)q$ and $V_{qq'}$ represents the corresponding Cabibbo-Kobayashi-Maskawa (CKM) matrix element. Selection rules for these decays are:

$\Delta Q = -1, \Delta C = -1, \Delta S = -1$ for Cabibbo enhanced $c \to s + l + \nu_l$ process,

$\Delta Q = -1, \Delta C = -1, \Delta S = 0$ for Cabibbo suppressed $c \to d + l + \nu_l$ process.

Similarly, the weak quark current

$$J_\mu^{\Delta b=1} = V_{cb}(\bar{c}b) + V_{ub}(\bar{u}b), \tag{6}$$

gives the following selection rules for bottom hadron decays :

$\Delta Q = 1, \Delta b = 1, \Delta C = 1$ for CKM enhanced $b \to c + l + \nu_l$ process,

$\Delta Q = 1, \Delta b = 1, \Delta C = 0$ for CKM suppressed $b \to u + l + \nu_l$ process.

3.1. Leptonic decays : $P(J^P = 0^-) \to l + \nu_l$:

These decays are the simplest to consider theoretically, and are usually helicity suppressed particularly when lighter leptons are emitted [24,25]. Decay amplitude for a typical decay $D \to l\nu_l$ involves the decay constant f_D defined as

$$< 0|A_\mu|D(p) > = if_D p_\mu \tag{7}$$

which measures the amplitude for the quarks to have zero separation. This leads to the following decay width formula :

$$\Gamma(D(\bar{q}c) \to l\nu_l) = \frac{G_F^2}{8\pi}|V_{qc}|^2 f_D^2 m_D m_l^2\left(1 - \frac{m_l^2}{m_D^2}\right. \tag{8}$$

For $D^+ \to l\nu_l$ decay, all the theoretical values [4] for f_D ranging from 170 MeV to 240 MeV, are well below the experimental limit [26] :

$$f_D < 310 \text{ MeV}. \tag{9}$$

For $D_s^+ \to l\nu_l$ decay, Particle Data Group [1,27] gives the following values :

$$f_{D_s} = 232 \pm 45 \pm 20 \pm 48 \text{ MeV}, 344 \pm 37 \pm 52 \pm 42 \text{ MeV},$$
$$430^{+150}_{-130} \pm 40 \text{ MeV}. \tag{10}$$

using the Mark and CLEO data. Potential models [4] give f_{D_s} between 190 MeV and 290 MeV. Lattice calculations [22,28] yield : $f_{D_s} = 220 \pm 35$ MeV, which matches with

QCD sumrules estimates [23]. More recently, E653 collaboration [29] has obtained $f_{D_s} = 194 \pm 35 \pm 20 \pm 14$ MeV and CLEO result has been updated to [30] : $f_{D_s} = 284 \pm 30 \pm 30 \pm 10$ MeV.

For B-mesons, leptonic decays are strongly suppressed by the small value of $|V_{ub}|^2$. Lattice simulations give $f_B = 180 \pm 40$ MeV whereas the scaling law derived in HQET [21],

$$f_P = \frac{A}{\sqrt{M_P}} \left[\alpha_s(M_P)^{-2/\beta_0} \times (1 + O(\alpha) + \cdots) \right] \tag{11}$$

predicts a rather lower estimate $f_B = 120$ MeV [28] which is expected to increase due to the radiative corrections. Potential model values [4] range from 125 MeV to 230 MeV. QCD sumrules estimate : $f_B = 180 \pm 50$ MeV is in good agreement with those from the lattice calculations. Thus, theory predicts [3]

$$B(B^+ \to \tau^+ \nu_\tau) \approx 4.0 \times 10^{-5},$$

for the most accessible of the leptonic B decays because the large τ mass reduces the helicity suppression. Experimentally, the following upper limit is available [1] :

$$B(B^+ \to \tau^+ \nu_\tau) < 1.8 \times 10^{-3}.$$

Measurement of f_B decay constant at future b-factories would have a significant impact on the phenomenology of heavy flavor decays. A precise knowledge of f_B would allow an accurate extraction of the CKM matrix element $|V_{ub}|$. Moreover, it enters into many other B-decay measurements, notably $B-\bar{B}$ mixing and CP violation in B-decays [3,31,32]. The standard model allows $B, B_s \to l^+l^-$ leptonic decays *via* box or loop diagrams. Theoretical values [3,33] for such modes, are well below the present experimental limits [1].

3.2. Semileptonic decays : $P \to M(J^P = 0^- \text{ or } 1^-) + l + \nu_l$:

With the enormous data samples now available for charm and bottom mesons, their semileptonic decays, particularly emitting a pseudoscalar meson or a vector meson, are well measured. These decays occur *via* spectator quark diagram and involve no final state interactions. So these decays are the primary source of the CKM elements and various formfactors. Decay amplitude for $P(\bar{q}'Q) \to M(\bar{q}'q) l \nu_l$ is given by

$$< M(\bar{q}'q) l \nu_l \left| H_W^{\text{semi-lep}} \right| P(\bar{q}'Q) > = \frac{G_F}{\sqrt{2}} V_{qQ}^*$$

$$< M \left| J_\mu(\bar{q}Q) \right| P > (\nu_e \gamma^\mu (1 - \gamma_5) l). \tag{12}$$

Using Lorentz invariance, the hadronic matrix elements are described by a few formfactors which are also needed in the analysis of the weak hadronic decays.

3.2.1. Semileptonic decays of charm mesons :

$D \to Pl\nu_l$ Decays :

When the final state meson is pseudoscalar, parity implies that only the vector component of the weak current contributes to the decay, whose matrix element is given by [6,14],

$$\langle P(\gamma')|V_\mu|D(p)\rangle = \left[(p+p')_\mu - \frac{m_D^2 - m_P^2}{q^2} q_\mu\right]$$

$$F_1(q^2) + \frac{m_D^2 - m_P^2}{q^2} q_\mu F_0(q^2), \tag{13}$$

where $F_1(0) = F_0(0)$ and $q_\mu = (p - p')_\mu$ The formfactors for Cabibbo enhanced transition represent the amplitude that the final state $(\bar{q}s)$ pair forms a K meson. Energy of K meson in the rest frame of D meson is linearly related to q^2,

$$E_K = \frac{m_D^2 + m_K^2 - q^2}{2m_D} \tag{14}$$

At $q^2 = q^2_{max} = (m_D - m_K)^2$, the K meson is at rest in the rest frame of D meson. Then the overlap of the initial and final state is maximum and so the formfactor is at its maximum value. At $q^2 = 0$, E_K is maximum and so the formfactor is at its minimum value. This q^2 dependence is usually expressed through the pole dominance formula [14],

$$F(q^2) = \frac{F(0)}{1 - q^2/m_*^2}, \tag{15}$$

which is studied by measuring the differential decay rate [4]. Present data [4,34] on differential decay rate for $D \to \bar{K}l\nu_l$ yields, for $|V_{cs}| = 0.974$ and the pole mass $m^* = 2.00 \pm 0.11 \pm 0.16$ GeV,

$$F_1^{DK}(0) = 0.75 \pm 0.03. \tag{16}$$

Quark model values lie between 0.7 to 0.8 [14–20], lattice calculations give 0.6 to 0.9 [22] and QCD sumrules approach gives 0.6 [23] for this formfactor.

Decay width ratio of Cabibbo suppressed decay $D \to \pi l\nu_l$ and the $D \to \bar{K}l\nu_l$ serves to deliver $F_1^{D\pi}/F_1^{D\bar{K}}$. Mark III and CLEO data [34] yield the following respective values :

$$F_1^{D\pi}/F_1^{D\bar{K}} = 1.0^{+0.6}_{-0.3} \pm 0.1, \quad 1.29 \pm 0.21 \pm 0.1. \tag{17}$$

These results are consistent with theoretical predictions which range from 0.7 to 1.4 [4].

$D \to V(J^P = 1^-) l \nu_l$ *decays*:

When the final state meson is a vector meson, there are four independent form factors [14] :

$$\langle V(p',\varepsilon)|J_\mu|D(p)\rangle = \frac{2}{m_D + m_V}\varepsilon_{\mu\nu\rho\sigma}\varepsilon^{*\nu}p^\rho p'^\sigma V(q^2)$$

$$+ i\Big[(m_D + m_V)\varepsilon^*_\mu A_1(q^2) - \frac{\varepsilon^*\cdot q}{m_D + m_V}(p+p')_\mu A_2(q^2)$$

$$- 2m_V\frac{\varepsilon^*\cdot q}{q^2}q_\mu\left(A_3(q^2) - A_0(q^2)\right)\Big], \qquad (18)$$

where ε_μ is the polarization vector of the vector meson, and $q_\mu = (p - p')_\mu$ is the momentum transfer. Total decay width $\Gamma(D \to \bar{K}^* l \nu_l)$ is dominated by A_1 formfactor. Ratios of other formfactors V and A_2 with A_1 are determined from the angular distribution [2-4]. Present data [34] yield: .

$$A_1^{D\bar{K}^*}(0) = 0.56 \pm 0.04, \quad A_2^{D\bar{K}^*}(0) = 0.40 \pm 0.08,$$
$$V^{D\bar{K}^*}(0) = 1.1 \pm 0.2. \qquad (19)$$

Theoretically quark models [14–20] give large values $A_1(0) = 0.80$ to 0.88 and $A_2(0) = 0.6$ to 1.2, whereas the predictions for $V(0)$ range from 0.8 to 1.3 in good agreement with experiment. Lattice calculations [22] and QCD sumrules estimates [23] are in better agreement with experiment [4].

For Cabibbo suppressed mode, experimental value [1]

$$B(D^+ \to \rho^0\mu^+\nu_\mu)/B(D^+ \to \bar{K}^{*0}\mu^+\nu_\mu) = 0.044^{+0.031}_{-0.025} \pm 0.014, \qquad (20)$$

is consistent with theoretical expectations [4,18] within the errors.

Semileptonic decays of strange-charm meson $(D_s \to \phi/\eta/\eta' + l + \nu_l)$ have also been measured [1]. These decays appear to follow the pattern of D decays in terms of the formfactor ratios [4].

3.2.2. Semileptonic decays of B mesons :

For B-decays, following data is available for CKM enhanced mode [1] :

$$B(B^0 \to D^- l^+ \nu) = 1.9 \pm 0.5\%,$$

$$B(B^0 \to D^{*-} l^+ \nu) = 4.56 \pm 0.27\%,$$

$$B(B^+ \to \bar{D}^0 l^+ \nu) = 1.6 \pm 0.7\%,$$

$$B(B^+ \to \bar{D}^{*0} l^+ \nu) = 5.3 \pm 0.8\%.$$

Using $|V_{cb}| = 0.038 \pm 0.004$, present data yield [34,35]

$$A_1(0) = 0.65 \pm 0.09,\ V(0)/A_1(0) = 1.30 \pm 0.36 \pm 0.14,$$

$$A_2(0)/A_1(0) = 0.64 \pm 0.26 \pm 0.12, \tag{21}$$

which are consistent with quark models estimates [4].

In nonperturbative problems, exploitation of all the available symmetries is very important. For the heavy flavor physics, the use of spin-flavor symmetries, that are present when masses of the heavy quarks are $>> \Lambda_Q$, leads to considerable simplifications [21] In going to the limit $m_c,\ m_b \to \infty$, all the formfactors are expressed in terms of one universal function called Isgur-Wise function $\zeta(\omega)$,

$$F_1(q^2) = V(q^2) = A_0(q^2) = A_2(q^2)$$

$$= \left[1 - \frac{q^2}{(M_B + M_D)^2}\right]^{-1} A_1(q^2) = \frac{M_B + M_D}{2\sqrt{M_B M_D}}\,\zeta(\omega), \tag{22}$$

where $\omega = v_B \cdot v_D$ These relations are valid up to perturbative and power corrections [4,28]. Theoretical difficulty in making predictions for the form factors lies in calculating these corrections with sufficient precision. At present, in the presence of these corrections, 1.30 and 0.79 are obtained [4,35] for the ratios V/A_1 and A_2/A_1 respectively.

Charmless semileptonic branching fraction is expected to be around 1% of that of the semileptonic decays emitting charm meson based on the present estimate $\left|V_{ub}/V_{cb}\right| = 0.08 \pm 0.02$ [1]. Heavy quark symmetry is less predictive for heavy $\to$ light decays than it is for heavy $\to$ heavy ones. Experimentally two branching ratios have been measured recently by CLEO collaboration [36] :

$$B(B^0 \to \pi^- l^+ \nu) = (1.8 \pm 0.4 \pm 0.3 \pm 0.2) \times 10^{-4},$$

$$B(B^0 \to \rho^- l^+ \nu) = (2.5 \pm 0.4^{+0.5}_{-0.7} \pm 0.5) \times 10^{-4},$$

which are consistent with theoretical expectations.

In addition to single meson emission in the final state, semileptonic decays also permit the production of two or more mesons. Quite often these mesons are produced through decay of a meson resonance produced in the weak decays [1]. For D-mesons, known resonant exclusive modes come close to saturating the inclusive semileptonic rates. In B decays, there is some room for nonresonant multi-hadron final state. Semileptonic decays of charm and bottom baryons have also been observed However, experimental results currently have limited statistical significance. Much larger data on these decays are expected in the future, allowing tests of various theoretical models [37].

4. Weak hadronic decays

Weak hadronic decays of heavy flavor hadrons are considerably complicated to treat theoretically. At current level of understanding these require model assumptions. Even if the short distance effects due to hard gluon exchange can be resummed and the effective Hamiltonian has been constructed at next to leading order, evaluation of its matrix elements is not straightforward. Various theoretical and phenomenological approaches have been employed to study weak hadronic decays. Broadly, these are :

(i) Flavor symmetry frameworks :

In the flavor symmetry frameworks, initial and final state mesons and weak Hamiltonian belong to their irreducible representations. Using Wigner-Eckart theorem, decay amplitudes are expressed in terms of few reduced amplitudes. Thus useful sumrules among different decay amplitudes are obtained [38] using isospin and SU(3) flavor symmetries. However, SU(3) violation has been shown by the charm meson decay data [39].

(ii) Quark line diagram approach :

Quark diagrams appearing in the weak decays are classified according to the topology of weak interaction with all the strong interaction effects included. With each quark line diagram, a corresponding parameter is attached and appropriate C.G. coefficients are introduced depending upon the initial and final state particles [40]. Using experimental values, relative strengths of various quark diagrams are then obtained.

(iii) Relativistic and nonrelativistic quark models :

Explicit quark model calculations have been done to determine the strength of various quark level processes. These models usually employ factorization [41] which can be used to relate hadronic decays to the semileptonic decays [42].

(iv) Nonperturbative methods :

QCD sumrules [23] approach has provided the general trends but agreement with present data is poor at a quantitative level. Lattice QCD calculations [22], though promising, are still in progress. Further these methods have their own uncertainties.

At present extensive data [1,43] exist for weak hadronic decays of charm and bottom mesons; though in the baryon sector, only a few decay modes of Λ_c^+, Ξ_c^+ and Λ_b have been studied experimentally [1,44]. The heavy flavor hadrons have many channels available for their decay involving two or more hadrons in their final states. However, for charm hadron decays, two-body decays dominate the data as multibody decays show resonant structure. Due to the considerably larger phase space that is available in bottom hadron decays and to the much higher number of open channels such a feature cannot extend to the bottom hadrons. Nevertheless these are expected to make up significant fraction of their hadronic decays.

Most of the observed two-body decays of heavy flavor mesons involve pseudoscalar (P) and vector (V) mesons (s-wave mesons) in their final state : $P \rightarrow PP/PV/VV$. In addition, some of the decays of charm mesons emitting axial (A), Scalar (S) and tensor (T) mesons (p-wave mesons), like $P \rightarrow P + A/S/T$ have also been measured [1]. Bottom mesons, being massive, can also decay to vector meson and another p-wave meson, or two p-wave mesons. In addition to these modes, weak decays accompanying photon (like $B \rightarrow K^* + \gamma$) are also observed.

4.1. Weak hadronic decays of charm mesons :

The general weak ⊗ current weak Hamiltonian for hadronic weak decays in terms of the quark fields is given by

$$H_W^{\Delta C = \Delta S = -1} = \frac{G_F}{\sqrt{2}} V_{ud} V_{cs}^* (\bar{u}d)(\bar{s}c), \tag{23a}$$

for Cabibbo enhanced mode,

$$H_W^{\Delta C=-1, \Delta S=0} = \frac{G_F}{\sqrt{2}} \left[V_{us} V_{cs}^* (\bar{u}s)(\bar{s}c) + V_{ud} V_{cd}^* (\bar{u}d)(\bar{d}c) \right], \tag{23b}$$

for Cabibbo suppressed mode, and

$$H_W^{\Delta C=-\Delta S=-1} = \frac{G_F}{\sqrt{2}} V_{us} V_{cd}^* (\bar{u}s)(\bar{d}c), \tag{23c}$$

for doubly Cabibbo suppressed mode. Since only quark fields appear in the weak Hamiltonian, the weak hadronic decays are seriously affected by the strong interactions One usually identifies the two scales [6] in these decays : short distance scale at which W-exchange takes place and long distance scale where final state hadrons are formed As the hard gluon effects at short distances are calculable using the perturbative QCD, long distance effects, being nonperturbative, are the source of major problems in understanding the weak hadronic decays. The hard gluon exchanges renormalize the weak vertex and introduce new color structure [6]. Effective weak Hamiltonian thus acquires effective neutral current term. For instance, weak Hamiltonian for Cabibbo enhanced mode becomes

$$H_W^{\Delta C=\Delta S=-1} = \frac{G_F}{\sqrt{2}} V_{ud} V_{cs}^* \left[c_1 (\bar{u}d)(\bar{s}c) + c_2 (\bar{s}d)(\bar{u}c) \right], \tag{24}$$

where the QCD coefficients $c_1 = \frac{1}{2}(c_+ + c_-)$, $c_2 = \frac{1}{2}(c_+ - c_-)$ and $c_\pm(\mu) = \frac{\alpha_s(\mu^2)}{\alpha_s(m_W^2)}^{d_\pm/2b}$ with $d_- = -2d_+ = 8$ and $b = 11 - \frac{2}{3} N_f$, N_f being the number of effective flavors, μ the mass scale [6].

4.1.1. $D \to PP/PV/VV$ decays :

Decay width for a two-body decay of D meson is given by

$$\Gamma(D \to M_1 + M_2) = G_F^2 (\text{CKM factors})^2 k^{2l+1} \times \sum (\text{mass factors}) \left| \langle (M_1 M_2) | O_i | D \rangle \right|^2 \tag{25}$$

where l denotes the angular momentum between the final state mesons M_1, M_2, and i denotes the helicity of these mesons. The operators O_i correspond to the quark processes responsible for the decays. In the evaluation of matrix element of the weak Hamiltonian, one usually applies the factorization hypothesis [6,14] which expresses hadronic decay amplitude as the product of matrix elements of weak currents between meson states,

$$\langle P_1 P_2 | H_\omega | D \rangle \propto \langle P_1 | J_\mu | 0 \rangle \langle P_2 | J^{\dagger\mu} | D \rangle, \tag{26a}$$

$$\langle PV | H_\omega | D \rangle \propto \left[\langle P | J_\mu | 0 \rangle \langle V | J^{\dagger\mu} | D \rangle + \langle V | J_\mu | 0 \rangle \langle P | J^{\dagger\mu} | D \rangle \right], \tag{26b}$$

$$\langle V_1 V_2 | H_\omega | D \rangle \propto \langle V_1 | J_\mu | 0 \rangle \langle V_2 | J^{\dagger\mu} | D \rangle. \tag{26c}$$

Matrix elements of weak current between meson and vacuum state are given by eq. (7) and

$$\langle V(p, \varepsilon) | J_\mu | 0 \rangle = \varepsilon_\mu^* m_V f_V. \tag{27}$$

Meson to meson matrix elements appearing here have already been given in eqs. (13) and (18). Thus factorization scheme allows us to predict decay amplitudes of hadronic modes in terms of the semileptonic formfactors and meson decay constants.

For the sake of illustration, we consider Cabibbo enhanced decays $D \to PP$. Separating the factorizable and nonfactorizable parts, the matrix element of the weak Hamiltonian, given in eq. (24), between initial and final states can be written [6,45] as

$$\begin{aligned} \langle P_1 P_2 | H_\omega | D \rangle = \frac{G_F}{\sqrt{2}} V_{ud} V_{cs}^* \big[& a_1 \langle P_1 | (\bar{u} d) | 0 \rangle \langle P_2 | (\bar{s} c) | D \rangle \\ & + a_2 \langle P_2 | (\bar{s} d) | 0 \rangle \langle P_1 | (\bar{u} c) | D \rangle \\ & + \left(c_2 \langle P_1 P_2 | H_\omega^8 | D \rangle + c_1 \langle P_1 P_2 | \tilde{H}_\omega^8 | D \rangle \right)_{\text{non fac}} \end{aligned} \tag{28}$$

where $a_{1,2} = c_{1,2} + \dfrac{c_{2,1}}{N_c}$,

$$H_\omega^8 = \frac{1}{2} \sum (\bar{u} \lambda^a d)(\bar{s} \lambda^a c), \quad \tilde{H}_\omega^8 = \frac{1}{2} \sum_{a=1}^{8} (\bar{s} \lambda^a d)(\bar{u} \lambda^a c).$$

In addition, nonfactorizable effects may also arise through the color singlet currents [46]. Matrix elements of the first and the second terms in eq. (28) can be calculated using the factorization scheme. So long as one restricts to the color singlet intermediate states,

remaining terms are usually ignored and one treats a_1 and a_2 as input parameters in place of using $N_c = 3$ in reality. The charm hadron decays are classified in three classes, namely

(i) Class I transitions that depend on a_1 (color favored),

(ii) Class II transitions that depend solely on a_2 (color suppressed),

(iii) Class III transitions that involve interference between terms with a_1 and a_2.

It has been believed [6,14] that the charm meson decays favor $N_c \to \infty$ limit, *i.e.*, $a_1 \approx 1.26, a_2 \approx -0.51$, indicating destructive interference in D^+ decays.

4.1.2. Long distance strong interaction effects :

The simple picture of spectator quark model works well in giving reasonable estimates for the exclusive semileptonic decays. However, success in predicting individual hadronic decays is rather limited. For example, spectator quark model yields the following ratios :

$$\frac{\Gamma(D^0 \to \bar{K}^0 \pi^0)}{\Gamma(D^0 \to K^- \pi^+)} = 0.1\,(0.5 \pm 0.1\ \text{Expt.}) \tag{29a}$$

for Cabibbo enhanced mode and

$$\frac{\Gamma(D^0 \to K^+ K^-)}{\Gamma(D^0 \to \pi^+ \pi^-)} = 0.9\,(2.5 \pm 0.4\ \text{Expt.}) \tag{29b}$$

for Cabibbo suppressed mode.

Similar problems exist for $D \to \bar{K}^* \pi / \bar{K}^* \rho$ decay widths. Besides these, other measured decays, involving single isospin final state, also show discrepancy with theory. For instance, the observed $D^0 \to \bar{K}^0 \eta$ and $D^0 \to \bar{K}^0 \eta'$ decay widths are considerably larger than those predicted in the spectator quark model. Also measured branching ratios for $D^0 \to \bar{K}^{*0} \eta, D_s^+ \to \eta / \eta' + \rho^+$, are found to be higher than those predicted by the spectator quark diagrams. For $D_s^+ \to \eta / \eta' + \pi^+$, though factorization can account for substantial part of the measured branching ratios, it fails to relate them to corresponding semileptonic decays $D_s^+ \to \eta / \eta' + e^+ \nu$ consistently [47].

In addition to the spectator quark diagram, factorizable *W*-exchange or W-annihilation diagrams may contribute to the weak nonleptonic decays of D mesons. However, for $D \to PP$ decays, such contributions are helicity suppressed. For D meson decays, these are further color-suppressed as these involve QCD coefficient c_2, whereas for $D_s^+ \to PP$ decays these vanish due to the conserved vector (CVC) nature of the isovector current ($\bar{u}d$) [47].

It is now established that the factorization scheme does not work well for the charm meson decays. The discrepancies between theory and experiment are attributed to various long distance effects which are briefly discussed in the following.

(i) Final state interaction effects :

Elastic final state interactions (FSI) introduce phase shifts in the decay amplitudes [48], which can be analyzed in the isospin framework. For instance, the isospin amplitudes 1/2 and 3/2 appearing in $D \to \bar{K}\pi$ decays may develop different phases leading to

$$A(D^0 \to K^- \pi^+) = \frac{1}{\sqrt{3}}\left[A_{3/2} e^{i\delta_{3/2}} + \sqrt{2} A_{1/2} e^{i\delta_{1/2}}\right], \tag{30a}$$

$$A(D^0 \to \bar{K}^0 \pi^+) = \frac{1}{\sqrt{3}}\left[\sqrt{2} A_{3/2} e^{i\delta_{3/2}} - A_{1/2} e^{i\delta_{1/2}}\right], \tag{30b}$$

$$A(D^+ \to \bar{K}^0 \pi^+) = \sqrt{3} A_{3/2} e^{i\delta_{3/2}} . \tag{30c}$$

Similar treatment can be performed for $D \to \bar{K}^* \pi$, $\bar{K}\rho$, $\bar{K}^* \rho$ modes. These decays are seriously affected as their final states lie close to meson resonances. Experimental data on these modes yield [48,49] :

$$|A_{1/2}|/|A_{3/2}| = 3.99 \pm 0.25 \text{ and } \delta_{3/2} - \delta_{1/2} = 86 \pm 8^\circ \text{ for } \bar{K}\pi \text{ mode},$$

$$|A_{1/2}|/|A_{3/2}| = 5.14 \pm 0.54 \text{ and } \delta_{3/2} - \delta_{1/2} = 101 \pm 14^\circ \text{ for } \bar{K}^* \pi \text{ mode},$$

$$|A_{1/2}|/|A_{3/2}| = 3.51 \pm 0.75 \text{ and } \delta_{3/2} - \delta_{1/2} = 0 \pm 40^\circ \text{ for } \bar{K}\rho \text{ mode},$$

$$|A_{1/2}|/|A_{3/2}| = 5.13 \pm 1.97 \text{ and } \delta_{3/2} - \delta_{1/2} = 42 \pm 48^\circ \text{ for } \bar{K}^* \rho \text{ mode},$$

for Cabibbo enhanced mode, and

$$|A_0|/|A_2| = 3.51 \pm 0.75 \text{ and } \delta_0 - \delta_2 = 0 \pm 40^\circ \text{ for } \pi\pi \text{ mode},$$

$$|A_0|/|A_1| = 3.51 \pm 0.75 \text{ and } \delta_0 - \delta_1 = 0 \pm 40^\circ \text{ for } \bar{K}K \text{ mode},$$

for Cabibbo suppressed mode.

In addition to the elastic scattering, inelastic FSI can couple different decay channels. For example, $D \to \bar{K}^* \pi$ and $D \to \bar{K}\rho$ decays are found to be affected by such inelastic FSI [48].

(ii) Smearing effects :

Further, in certain decays a wide resonance is emitted, like $D \to \bar{K}\rho$. The large width of the meson modifies the kinematical phase space available to the decay. These effects can be studied using a running mass (m) of the resonance, and then averaging is done by introducing an appropriate measure $r(m^2)$ like Breit-Wigner formula. For instance, $D \to P\rho$ decay width is calculated as [50] :

$$\bar{\Gamma}(D \to P\rho) = \int_{2m_\pi}^{m_D - m_P} r(m^2)\, \Gamma(D \to P\rho(m^2))\, dm^2 . \tag{31}$$

Such effects can be as large as 25%. For example,

$$\bar{\Gamma}(D^0 \to K^- \rho^+)/\Gamma(D^0 \to K^- \rho^+) = 0.77. \tag{32}$$

Smearing effects have been studied [51] for $D \to VV$ also.

(iii) Nonfactorizable contributions :

Indeed factorization, combined with the assumption that FSI are dominated by nearby resonances, has been in use for the description of charm meson decays. Recently, this issue has been reopened. In the factorization scheme, one works in the large N_c limit, and ignores the nonfactorizable terms, which behave like $1/N_c$. However, this approach has failed when extended to B meson decays [52]. So D-meson decays are being reanalyzed keeping the 'canonical' value $N_c = 3$, real number of colors. Efforts have been made to investigate the nonfactorizable contributions. It is well known that nonfactorizable terms cannot be determined unambiguously without making some assumptions [45] as these involve nonperturbative effects arising due to the soft-gluon exchange. QCD sumrules approach has been used to estimate them [53], but so far these have not given reliable results. In the absence of exact dynamical calculations, search for a systematics in the required nonfactorizable contributions has been made using isospin [54] and SU(3)-flavor-symmetries [46].

4.1.3. $D \to P(0^-) + p$ – wave meson $(0^+, 1^+, 2^+)$ decays

Weak hadronic decays involving mesons of intrinsic orbital momentum $l > 0$ in final state are expected to be kinematically suppressed. Some measurements are available on these decays. Contrary to the naive expectations, their branching are found to be rather large [1]. Estimate for formfactors appearing in the matrix elements $< p$ – wave meson $| J | D >$ are available only in the nonrelativistic ISGW quark model [17,18]. In general, theoretical values are lower than the experimental ones [55].

4.2. Weak hadronic decays of B-mesons :

Weak Hamiltonian involving the dominant $b \to c$ transition [2,3] is given by

$$H_W^{\Delta b=1} = \frac{G_F}{\sqrt{2}} \left[V_{cb} V_{ud}^* (\bar{c}b)(\bar{d}u) + V_{cb} V_{us}^* (\bar{c}b)(\bar{s}u) + V_{cb} V_{cd}^* (\bar{c}b)(\bar{d}c) + V_{cb} V_{cs}^* (\bar{c}b)(\bar{s}c) \right]. \tag{33}$$

A similar expression can be obtained for decays involving $b \to u$ transition by replacing $\bar{c}b$ with $\bar{u}b$. Following $\Delta b = 1$ decays modes are allowed :

(i) CKM enhanced modes :

$$\Delta C = 1, \Delta S = 0, \text{ and } \Delta C = 0, \Delta S = -1; \tag{34a}$$

(ii) CKM suppressed modes :

$$\Delta C = 1, \Delta S = -1, \text{ and } \Delta C = 0, \Delta S = 0; \tag{34b}$$

(iii) CKM doubly suppressed modes :

$$\Delta C = -1, \Delta S = -1, \text{ and } \Delta C = -1, \Delta S = 0. \tag{34c}$$

These provide a large number of decay products to B-hadrons. Including hard gluon exchanges, the effective Hamiltonian can be written as

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb} V_{ud}^* \left\{ a_1 \left[(\bar{d}u)(\bar{c}b) + (\bar{s}c)(\bar{c}b) \right] + a_2 \left[(\bar{c}u)(\bar{d}b) + (\bar{c}c)(\bar{s}b) \right] \right\}. \tag{35}$$

In the large N_c limit, one would expect :

$$a_1 \approx c_1 = 1.1, \quad a_2 \approx c_2 = -0.24.$$

4.2.1. Determination of a_1 and a_2 :

Like charm meson decays, depending upon the quark content of mesons involved, B-meson decays can also be classified in the three categories. Several groups have developed models of hadronic B-decays based on the factorization hypothesis [2,3]. Recently, it has also been argued that the factorization hypothesis is expected to hold better in the heavy quark limit [56], for some decay channels, as the ultrarelativistic final state mesons don't have time to exchange gluons. Present data seem to go well with theoretical expectations for most of the B-meson decays [3]. For instance,

$$\frac{B(\bar{B}^0 \to D^{*+}\rho^-)}{B(\bar{B}^0 \to D^{*+}\pi^-)} = 2.8 \; (2.59 \pm 0.67 \text{ Expt.}), \tag{36a}$$

$$\frac{B(\bar{B}^0 \to D^{*+}a_1^-)}{B(\bar{B}^0 \to D^{*+}\pi^-)} = 3.4 \; (4.5 \pm 1.2 \text{ Expt.}). \tag{36b}$$

By comparing B^- and $\bar{B}^0$ decays, $|a_1|$, $|a_2|$ and the relative sign of a_2/a_1 can be determined. Thus $\bar{B}^0 \to D^+\pi^- / D^+\rho^- / D^{*+}\pi^- / D^{*+}\rho^-$ yield :

$$|a_1| = 1.03 \pm 0.04 \pm 0.16, \tag{37a}$$

$\bar{B}^0 \to \psi X$ decays yield :

$$|a_2| = 0.23 \pm 0.01 \pm 0.01, \tag{37b}$$

and data on $B^- \to D^0\pi^-/D^0\rho^-/D^{*0}\pi^-/D^{*0}\rho^-$ clearly yield [3,52] :

$$a_2/a_1 = 0.26 \pm 0.05 \pm 0.09. \tag{37c}$$

Note that though magnitude of the ratio is in agreement with theoretical expectation, its sign is opposite indicating constructive interference in B^- decays. Other uncertainties of decay constants, FSI and formfactors may change its value but not its sign [3]. This situation is in contrast to that in the charm meson decays, where the ratio $a_2/a_1 = -0.40$ implies destructive interference in D^+ decays. Interestingly, the constructive interference enhances the hadronic decay width of B_u meson and reduce its semileptonic branching ratio [57] bringing it closer to the experimental value.

4.2.2. Final state interaction :

Factorization breaks down in the charm sector due to the presence of final state interactions. The strength of such long distance effects in B-decays can also be determined by performing the isospin analysis of related channels, such as $B \to D\pi$ decays. At present level of experimental precision, there is no evidence for nonzero isospin phase shifts in B-decays, as the data gives [3] $\cos(\delta_{1/2} - \delta_{3/2}) > 0.82$ for $B \to D\pi$.

4.2.3. Tests of factorization :

Since a common matrix element $\langle M/J/B \rangle$ appears in both semileptonic and factorized hadronic decays, the factorization hypothesis can be tested by comparing these two processes. Eliminating the common matrix terms in these decays, the following relation can be derived [2,3,57] :

$$\frac{\Gamma(\bar{B}^0 \to D^{*+}\pi^-)}{\dfrac{d\Gamma}{dq^2}(\bar{B}^0 \to D^{*+}l^-\bar{\nu}_l)_{q^2=m_\pi^2}} = 6\pi^2 c_1^2 f_\pi^2 |V_{ud}|^2$$

$$= 1.22 \pm 0.15 \text{ (theory)}, \; 1.14 \pm 0.21 \text{ (Expt.)}. \tag{38a}$$

Here, we require that the lepton-neutrino system has the same kinematic properties as does the pion in hadronic decay. Similar relations can be obtained for $\bar{B}^0 \to D^*\rho$ and $\bar{B}^0 \to D^* a_1$ decays.

$$\frac{\Gamma(\bar{B}^0 \to D^{*+}\rho^-)}{\dfrac{d\Gamma}{dq}(\bar{B}^0 \to D^{*+}l^-\bar{\nu}_l)_{q^2=m_\rho^2}} = 6\pi^2 c_1^2 f_\rho^2 |V_{ud}|^2$$

$$= 3.26 \pm 0.42 \text{ (theory)}, \; 2.80 \pm 0.69 \text{ (Expt.)}, \tag{38b}$$

$$\frac{\Gamma(\bar{B}^0 \to D^{*+}a_1^-)}{\dfrac{d\Gamma}{dq^2}(\bar{B}^0 \quad D^{*+}l^-\bar{\nu}_l)\Big|_{q^2=m_{a_1}^2}} = 6\pi^2 c_1^2 f_{a_1}^2 |V_{ud}|$$

$$= 3.0 \pm 0.5 \text{ (theory)}, \; 3.6 \pm 0.9 \text{ (Expt.)}. \tag{38c}$$

Theory agrees well with experiment within errors.

4.2.4. Application of factorization :

Having factorization tested, one may exploit this to extract information about poorly measured semileptonic decays. For example, integrating over q^2-dependence and using experimental value $B(B^- \to D^{**0}\pi^-) = 0.15 \pm 0.05$, one obtains [3] :

$$B(B \to D^{**}l\nu) = 0.48 \pm 0.16\% \;\; (1.00 \pm 0.30 \pm 0.07 \text{ Expt.}). \tag{39}$$

Another application of relating hadronic mode with semileptonic decay is to determine f_{D_s}. For instance, $B(B^0 \to D^{*+}D_s^-) = 0.93 \pm 0.25\%$ gives [3]

$$f_{D_s} = 271 \pm 77 \text{ MeV}. \tag{40}$$

using $B(D_s \to \phi\pi^+) = 3.7\%$. Similarly, one can obtain

$$f_{D^*_s} = 248 \pm 69 \text{ MeV}. \tag{41}$$

4.2.5. Results from heavy quark effective theory :

Spin symmetry, appearing in the limit of heavy quark mass, combined with factorization relates different decays [3]. For instance,

$$\frac{B(\bar{B}^0 \to D^+\pi^-)}{B(\bar{B}^0 \to D^{*+}\pi^-)} = 1.03\ (1.11 \pm 0.22 \pm 0.08 \text{ Expt.}), \tag{42}$$

$$\frac{B(\bar{B}^0 \to D^+\rho^-)}{B(\bar{B}^0 \to D^{*+}\rho^-)} = 0.89\ (1.06 \pm 0.27 \pm 0.08 \text{ Expt.}). \tag{43}$$

Using a combinations of HQET, factorization and data on semileptonic decay $B \to D^* l\nu_l$, Mannel *et al* [58] have obtained the following predictions for

$$\frac{B(\bar{B}^0 \to D^+\rho^-)}{B(\bar{B}^0 \to D^+\pi^-)} = 3.05,\ 2.52,\ 2.61 \tag{44}$$

for three different parameterizations of the Isgur-Wise function. Experimental value for this ratio is

$$\frac{B(\bar{B}^0 \to D^+\rho^-)}{B(\bar{B}^0 \to D^+\pi^-)} = 2.7 \pm 0.6. \text{ (Expt.)}$$

Similarly predictions have also been made for $B \to DD_s$ / D^*D_s / $D^*D_s^*$ decays [3].

4.2.6. Rare B-decays :

Charmless decays involving $b \to u$ transition, like $B \to \pi\pi/\pi\rho/K\pi$, are important to find V_{ub}, to probe penguin contributions and to study CP-violation [3,59]. Weak radiative B-meson decays present a very sensitive probe of new physics, like Supersymmetry particle contributions. Precise measurements of exclusive radiative decays, like $B \to K^*\gamma$ would throw light on V_{tq} elements [2,3]. B-mesons have enough energy to create p-wave mesons also. Branching ratios of such decays have been estimated using the ISGW model [60]. B mesons provide an unique opportunity to study baryon-antibaryon decays of a meson. However, only a few upper limits are available experimentally [1,61]. There is now a considerable experimental evidence for $B - \bar{B}$ oscillations, which can be used to determine V_{td} and V_{ts} elements [2,3].

4.3. Weak hadronic decays of baryons :

For heavy flavor baryon decays, data has only recently started coming in. Two-body decays of the baryons are of the following types :

$$B(1/2^+) \to B(1/2^+)/D(3/2^+) + P(0^-)/V(1^-).$$

Experimentally, branching ratios of almost all the Cabibbo enhanced $\Lambda_c^+ \to B(\frac{1}{2}^+) + P(0^-)$ decays have now been measured [1,44]. A recent CLEO measurement [62] of decay asymmetries of $\Lambda_c^+ \to \Lambda\pi^+ / \Sigma^+\pi^0$, give the following sets of PV and PC amplitudes (in units of $G_F V_{ud} V_{cs} \times 10^{-2}\,\mathrm{GeV}^2$) :

$$A(\Lambda_c^+ \to \Lambda\pi^+) = -3.0^{+0.8}_{-1.2} \quad \text{or} \quad -4.3^{+0.8}_{-0.9},$$

$$B(\Lambda_c^+ \to \Lambda\pi^+) = +12.7^{+2.7}_{-2.5} \quad \text{or} \quad +8.9^{+3.4}_{-2.4};$$

$$A(\Lambda_c^+ \to \Sigma^+\pi^0) = +1.3^{+0.9}_{-1.1} \quad \text{or} \quad +5.4^{+0.9}_{-0.7},$$

$$B(\Lambda_c^+ \to \Sigma^+\pi^0) = -17.3^{+2.3}_{-2.9} \quad \text{or} \quad -4.1^{+3.4}_{-3.0}.$$

Recently, CLEO-II experiment [63] has measured $B(\Xi_c^+ \to \Xi^0\pi^+) = 1.2 \pm 0.5 \pm 0.3\%$. This small data has already shown discrepancies with conventional expectations. In the beginning, it was thought that like charm meson decays, charm baryon decays may be dominated by the spectator quark process. This scheme allows only the emission of π^+/ρ^+ and $\bar{K}^0/\bar{K}^{*0}$ mesons. However, observation of certain decays like $\Lambda_c^+ \to \Xi^0 K^+ / \Sigma\pi, \Sigma\eta$ gives clear indication of the nonspectator contributions. In fact, W-exchange quark diagram, suppressed in the meson decays due to the helicity arguments, can play a significant role due to the appearance of spin 0 two-quark configuration in the baryon structure. Due to the lack of a straightforward method to evaluate these terms, flavor symmetry [64] and model calculations [65] have been performed. So far no theoretical model could explain the experimental values.

Study of bottom baryon decays is just beginning to start its gear. So far, only exclusive weak hadronic decay $\Lambda_b \to J/\psi + \Lambda$ has been measured. Recent CDF Collaboration experiment [66] gives $B(\Lambda_b \to J/\psi + \Lambda) = (3.7 \pm 1.7 \pm 0.4) \times 10^{-4}$ which is consistent with theoretical expectation [67].

5. Conclusions

In the last several years, tremendous progress has been achieved in understanding the heavy flavor weak decays. We make the following observations :

(1) Leptonic decays are the simplest to be treated theoretically, but have very small branching ratios. Since a direct determination of meson decay constants is highly desirable, particularly for $B-\bar{B}$ mixing, it is important to improve their measurements as larger data samples are accumulated.

(2) Semileptonic decays are next in order of simplicity from theory side. Here all the strong interaction effects are expressed in terms of a few formfactors, which are reasonably obtained in theoretical calculations, based on quark models, HQET, lattice simulation and QCD sum-rule approaches. However, higher precision measurements are needed to find V_{ub}.

(3) Weak hadronic decays experience large interference due to the strong interactions and pose serious problems for theory, particularly for the charm hadrons. Though qualitative explanation can be obtained for these decays, discrepancies between theory and experiment indicate the need of additional physics. For instance, final state interaction effects play significant role at least in the charm meson decays. Smearing effects due to the large width help to improve the agreement when a wide resonance, like ρ, is emitted in a decay.

(4) Results from CLEO II have significantly modified our understanding of weak hadronic B-decays. Data on their branching are now of sufficient quality to perform nontrivial tests of factorization hypothesis. It seems to be consistent at the present level of experiment. Large sample of B-decay data will be obtained in next few years which will present more accurate tests for the factorization scheme.

(5) The ratio a_2/a_1 is demanded to be positive for bottom meson decays in contrast to what is found in the charm meson decays. This has opened the issue of nonfactorizable terms for the weak hadronic decays. It is now clear that significant nonfactorizable contributions are there in the weak hadronic decays of charm mesons. For bottom sector, a quantitative estimate of their size require precise measurements of their decays. Study of rare decays, like radiative decays and charmless B-decays, has a good potential to throw new lights on our understanding of the penguin terms and CP violation.

(6) Weak hadronic decays of charm baryon have recently come under active experimental investigation, though search for bottom baryon decays is merely begun. These decays are difficult to treat theoretically. Observed data for Λ_c decays clearly demand significant W-exchange contributions. More data on baryon decays, which will be accumulated in the near future, is expected to confront theory with new challenges.

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