Non-Leptonic two body decays of Charmed and $Λ_b$

Baryons

Alakabha Datta

Physics Department, University of Hawaii at Manoa, 2505 Correa Road, Honolulu, HI 96822, USA.

Abstract

We calculate the two body Cabibbo allowed non-leptonic decays of charmed baryons $Λ_c$ and $Ξ_c$ which involve transitions of a heavy quark to a light quark. We use data on the Cabbibo favoured non-leptonic decays $Λ_c → Λπ^+$ and $Λ_c → Σ^+π^0$ to obtain information on the form factors in the $c → s$ transition. We also calculate the decay $Λ_c → pϕ$. Using HQET the information on form factors from the $c → s$ transition is used to model the form factors in $b → s$ transition which are then used in the study of $Λ_b → J/ψΛ$ decay.

1 Introduction

There is now a fair amount of experimental data available on charmed baryon decays while more data on bottom baryon decays will be available in the future and there are already several calculations of these decays in the literature. A crucial input in the calculation of the semi-leptonic as well as the non-leptonic decays of charmed and bottom baryons are the hadronic form factors. These form factors can be calculated in specific models like the quark model or the MIT bag model \cite{1, 2}. Another approach is to use HQET to find relations
among form factors for baryons containing a heavy quark. For instance in the heavy-to-heavy transition of the type \( \Lambda_b \to \Lambda_c \) all form factors are expressible in terms of one Isgur-Wise function and a HQET mass parameter \( \bar{\Lambda} \) up to order \( 1/m_Q \) where \( m_Q \) is the c or b quark mass. For a heavy to light transition of the type \( \Lambda_c \to \Lambda \), the use of HQET in the limit \( m_Q \to \infty \) allows one to express all the form factors in terms of only two form factors \(^3\). Semileptonic decay of \( \Lambda_c \) has been studied in this limit \(^3\) where Ref.\(^5\) in addition also assumes \( 1/m_s \) expansion for the semi-leptonic decay of \( \Lambda_c \to \Lambda \).

In heavy to light transitions \( 1/m_Q \) corrections can be important, especially for the charm sector. Pure HQET analysis of these \( 1/m_Q \) corrections in the heavy to light transitions does not lead to interesting phenomenology as there are too many form factors and there is hardly any predictive power left \(^3\). However in Ref.\(^6\) it is shown that using a combination of HQET and some reasonable assumptions, all the form factors up to \( 1/m_Q \) corrections can be expressed in terms of only two form factors evaluated at maximum momentum transfer. A specific choice for the \( q^2 \) dependence of the form factors(e.g, a monopole,dipole etc) can be used for the form factors to extrapolate to arbitrary values of the four momentum transfer \( q^2 \). In this model therefore there are two inputs, the zeroth order form factors \( F_1^0 \) and \( F_2^0 \) at maximum \( q^2 \) or \( \omega = v.v' = 1 \), where \( v \) and \( v' \) are the initial and final baryon velocities. In this work we use a slightly modified version of the model for the form factors developed in Ref.\(^7\) to study the non-leptonic decays of charmed and bottom baryons. To proceed with our calculations we need the zeroth order form factors \( F_1^0 \) and \( F_2^0 \) at maximum \( q^2 \) or alternatively \( F_1^0 \) and \( r = F_2^0/F_1^0 \) at maximum \( q^2 \). The best place to fix these inputs would be from measurements of semi-leptonic decays. For instance the asymmetry measurement in \( \Lambda_c \to \Lambda l \nu_l \) could be used to fix \( r \). There are measurements of \( \Lambda_c \to \Lambda l^+ \nu_l \) form factors by the CLEO collaboration \(^8\) but the fit to data in these studies assumes the KK model \(^5\) for the form factors and hence is not general enough for our use.

We next look into the data on non-leptonic decays of charmed baryons. The theoretical description of these processes is model dependent and to that extent an extraction of \( F_1^0(\omega = 1) \) and \( r = F_2^0(\omega = 1)/F_1^0(\omega = 1) \) using non-leptonic data would also be model dependent. Using the current algebra model we can use the value of the decay rate of \( \Lambda_c \to \Sigma \pi^0 \) to fix the non-factorizable contribution to the Cabibbo favoured charmed baryon decays. Next, we can use the values of the decay rate and asymmetry of \( \Lambda_c \to \Lambda \pi^+ \) to fix \( F_1^0 \) and \( r = F_2^0/F_1^0 \) at \( \omega = 1 \). We calculate the decay rates and asymmetries of the \( \Lambda_c \) and the \( \Xi_c \) charmed baryons decaying into an uncharmed baryon and a pseudoscalar or a vector meson. In our calculations we use SU(3) symmetry to relate the form factors in the \( c \to s \) transition to
\(c \rightarrow u\) transitions. Using the flavour symmetry of HQET one can use the same inputs \(F_1^0(\omega = 1)\) and \(r\), extracted from the charm sector, in the bottom sector to study the decays of the bottom baryon. Below we describe the basic features of the current algebra model that we employ in the calculation of the non-leptonic decays of the charmed and bottom baryons.

The starting point of non-leptonic decay calculations is the QCD corrected weak Hamiltonian. This effective current×current Hamiltonian gives rise to the following quark diagrams [9]: the internal and external W-emission diagrams, which result in the factorizable contribution, and the W-exchange diagrams which gives rise to the non-factorizable contribution. The W-annihilation diagram is absent in baryon decay and the W-loop diagram does not contribute to Cabibbo allowed decays. In the large \(N_c\) limit the non-factorizable contribution is no longer color suppressed because of \(N_c\) W-exchange diagrams. This combinatorial factor \(N_c\) cancels a similar factor in the denominator.

The factorizable part of the decay amplitude is expressed in terms of six form factors. For the decay of the charmed baryon into an uncharmed baryon and the light pseudoscalar, to a very good approximation, only two form factors contribute for a pion in the final state. When the pseudoscalar is replaced by a vector meson four of these form factors contribute. We use the pole model to calculate the non-factorizable part. This model assumes that the non-factorizable decay amplitude receives contributions primarily from one particle intermediate states and these contributions then show up as simple poles in the decay amplitude. The various intermediate single particle states are the ground state positive parity baryons which contribute only to the parity conserving amplitude, the parity violating amplitude being small [10]. The parity violating amplitude may receive contribution from excited negative parity baryons. In the limit that the momentum of the pseudoscalar \(q \rightarrow 0\), the parity violating piece of the amplitude reduces to the usual current commutator term of current algebra. Even though in charmed baryon decay the final state pseudoscalar meson is not soft, we will still work in the soft-meson limit and represent the parity violating piece of the amplitude by the current commutator term. It is important to note that using SU(3) symmetry all the weak matrix element between the positive parity baryon states can be expressed in terms of only one matrix element and therefore in this model the non-factorizable contribution is completely determined by one weak matrix element between positive parity ground state baryons. Hence the prediction for the asymmetry parameter for decays, which have no factorizable contribution (eg, \(\Lambda_c \rightarrow \Sigma^+\pi^0\)), is independent of the baryon-baryon weak matrix element and depends only on the baryon masses.
It is relevant to compare our model with some of the recent models employed in the calculation of Cabibbo favoured charmed baryon decays. In our model we use a completely different model for the form factors than has been used in other models to calculate the factorizable piece of the decay amplitude. Regarding the non-factorizable contributions, we have assumed that the current commutator term represents the parity violating non-factorizable amplitude even in the case of charmed baryon decays where the pseudoscalar momentum $q$ is far from zero. Large corrections to this current algebra results have been calculated in Ref. [11] and Ref. [12]. However these corrections depend on the model used to estimate the baryon to baryon weak matrix element and the corrections calculated in Ref. [11] and Ref. [12] are quite different. Phenomenologically both these calculations fail in their prediction of the asymmetry measured in the decay $\Lambda_c \to \Sigma^0 \pi^+$. This is also true for another recent calculation on non-leptonic charmed baryon decays using a spectator quark model by Körner and Kramer [13]. However the central value of the measured asymmetry for the decay $\Lambda_c \to \Sigma^0 \pi^+$ compares very well with the current algebra prediction. This seems to indicate that, at least for the decay, $\Lambda_c \to \Sigma^0 \pi^+$, the correction to the current algebra result is small. In the light of the experimental results we have therefore adopted the position that the major contribution to the non-factorizable parity violating part of the amplitude comes from the current algebra commutator term. The advantage of such a scenario is that the only parameter needed to specify the non-factorizable contribution is a single baryon-baryon matrix element which can be fixed from the decay rate of a process like $\Lambda_c \to \Sigma^+ \pi^0$ (which has no factorizable contribution) and we do not have to rely on model dependent calculation of the weak matrix element.

The decay $\Lambda_c \to p\phi$ is Cabibbo suppressed and has only factorizable contribution. The same form factors that characterize the $c \to u$ transition in Cabibbo favoured decays can also be used for this decay.

For the $\Lambda_b$ decay we ignore the non-factorizable contribution. For the form factors in this decay we have used the same value of $F^0_1(\omega = 1)$ and $F^0_2(\omega = 1)$ used in charmed baryon decays as $F^0_1(\omega = 1)$ and $F^0_2(\omega = 1)$ are the form factors for $m_Q \to \infty$ at $\omega = 1$ and so by heavy flavour symmetry they are the same for the charm and bottom sector.

The paper is organized in the following way. In the next section we outline our model for the calculation of the various charmed and bottom baryon decays while in the third section we present our results.
2 Model

Non-Leptonic Decays: Here we develop the formalism for the Cabibbo favoured decay of a charmed baryon into an uncharmed baryon and either a pseudoscalar or a vector meson. This formalism will also be used in the decay \( \Lambda_b \rightarrow J/\psi \Lambda \). We start with the decay of a charmed baryon into a baryon and a pseudoscalar. The amplitude for such a decay can be written as

\[
M(B_i \rightarrow B_f P) = i u_{B_f} (A + B \gamma_5) u_{B_i}
\]

(1)

In the rest frame of the parent baryon the decay amplitude reduces to

\[
M(B_i \rightarrow B_f P) = i \chi_{B_f} (S + P \sigma, q) \chi_{B_i}
\]

(2)

where \( q \) is the unit vector along the direction of the daughter baryon momentum and \( S = \sqrt{2m_c (E_f + m_f)} A \) and \( P = \sqrt{2m_c (E_f - m_f)} B \) with \( E_f \) and \( m_f \) referring to the final baryon energy and mass. The decay rates and various asymmetries are given by

\[
\Gamma = \frac{Q}{8\pi m_c^2} (|S|^2 + |P|^2); \quad \alpha = \frac{2Re(S^*P)}{|S|^2 + |P|^2}; \quad \beta = \frac{2Im(S^*P)}{|S|^2 + |P|^2} \quad \text{and} \quad \gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}
\]

(3)

where \( Q \) is the magnitude of the three momentum of the decay products. The starting point of our dynamical analysis is the QCD corrected effective weak Hamiltonian for Cabibbo favoured decays

\[
H_W = \frac{G_F}{2\sqrt{2}} V_{cs} V_{ud} (c_+ O_+ + c_- O_-)
\]

(4)

with \( O_\pm = (\bar{s}c)(\bar{u}d) \pm (\bar{s}d)(\bar{u}c) \) where we have omitted the Dirac structure \( \gamma_\mu (1 - \gamma_5) \) between the quark fields inside each parentheses. \( V_{cs} \) and \( V_{ud} \) are the usual CKM matrix elements while \( c_\pm \) are the Wilson’s coefficients evaluated at the charm quark mass scale. In our model we write the decay amplitude as

\[
M(B_i \rightarrow B_f P) = M(B_i \rightarrow B_f P)_{fac} + M(B_i \rightarrow B_f P)_{non\_fac}
\]

(5)

From the structure of the Hamiltonian factorization occurs with a \( \pi^+ \) and \( \bar{K}^0 \) in the final state. The factorizable contribution is given by

\[
M(B_i \rightarrow B_f \pi^+) = \frac{G_F}{2\sqrt{2}} V_{cs} V_{ud}[c_1 + \frac{c_2}{N_c}] < \pi^+ | \bar{u}d | 0 \rangle \langle B_f | \bar{s}c | B_i >
\]

(6)

\[
M(B_i \rightarrow B_f \bar{K}^0) = \frac{G_F}{2\sqrt{2}} V_{cs} V_{ud}[c_2 + \frac{c_1}{N_c}] < \bar{K}^0 | \bar{s}d | 0 \rangle \langle B_f | \bar{u}c | B_i >
\]

(7)

where \( c_1 = \frac{1}{2}(c_+ + c_-) \); \( c_2 = \frac{1}{2}(c_+ - c_-) \) with \( N_c \) being the number of colors. The \( N_c \) suppressed terms come from the Fierz reordering of the operators \( O_\pm \). For a satisfactory
description of non-leptonic decays of mesons it was found that the Fierz ordered contribution
should be omitted \cite{14}. This can be justified in the $1/N_c$ expansion method with $N_c \to \infty$
\cite{15}. We shall therefore also work in the large $N_c$ limit. The matrix elements of the current
between baryonic states that appear in the equation above is parametrized in terms of form
factors. We define the six vector and axial vector form factors through the following equations

$$
\langle B'(p', s') | \bar{q} \gamma^\mu Q | B_Q(p, s) \rangle = \bar{u}_{B'}(p', s') \left[ f_1 \gamma^\mu - i \frac{f_2}{m_{B_c}} \sigma^{\mu\nu} q_\nu + \frac{f_3}{m_{B_c}} q^\mu \right] u_{BQ}(p, s)
$$

$$
\langle B'(p', s') | \bar{q} \gamma^\mu \gamma^5 Q | B_Q(p, s) \rangle = \bar{u}_{B'}(p', s') \left[ g_1 \gamma^\mu - i \frac{g_2}{m_{B_c}} \sigma^{\mu\nu} q_\nu + \frac{g_3}{m_{B_c}} q^\mu \right] \gamma^5 u_{BQ}(p, s) \quad (8)
$$

where $q^\mu = p^\mu - p'^\mu$ is the four momentum transfer, $B_Q$ is the baryon with a heavy quark
and $B'$ is the light baryon. In Ref. \cite{7} we studied the form factors for heavy to light
transitions involving baryons in HQET including corrections up to $1/m_Q$ (Even though we
studied charmed baryons in Ref. \cite{7} the results are applicable to the heavy to light transition
of any Λ type baryon containing a heavy quark). We found that at $\omega = 1$, in addition to
the two zeroth order form factors form factors $F_1^0$ and $F_2^0$, there were five other unknown
matrix elements, four of which represent corrections from the chromomagnetic operator. In
Ref. \cite{7} we made some assumptions about these unknown matrix elements and we were able
to express all the form factors in terms of two form factors $F_1^0$ and $F_2^0$. Without making
any assumptions about the corrections coming from the chromomagnetic operator we write the
form factors as

$$
\frac{f_1}{F_1^0} = 1 + a + (m_{B_Q} + m_{B'}) \left[ \frac{r + b/3}{2m_{B_Q}} - \frac{a' + b/3}{2m_{B'}} \right]
$$

$$
\frac{f_2}{F_1^0 m_{B_Q}} = -\frac{r + b/3}{2m_{B_Q}} + \frac{a'' + b/3}{2m_{B'}}
$$

$$
\frac{f_3}{F_1^0 m_{B_Q}} = \frac{r + b/3}{2m_{B_Q}} + \frac{a'' + b/3}{2m_{B'}}
$$

$$
\frac{g_1}{F_1^0} = 1 + r + \frac{2b}{3} - (m_{B_Q} - m_{B'}) \left[ \frac{r - a - \rho b/3}{2m_{B_Q}} + \frac{\rho b'/3}{2m_{B'}} \right]
$$

$$
\frac{g_2}{F_1^0 m_{B_Q}} = -\frac{r - a - \rho b/3}{2m_{B_Q}} - \frac{\rho b''/3}{2m_{B'}}
$$

$$
\frac{g_3}{F_1^0 m_{B_Q}} = \frac{r - a - \rho b/3}{2m_{B_Q}} - \frac{\rho b''/3}{2m_{B'}} \quad (9)
$$

where

$$
\bar{\Lambda} = m_{B_Q} - m_Q
$$
\[\hat{m}_{B^{'}} = m_{B^{'}} - m_q\]
\[z_1 = \left(\bar{\Lambda} + \hat{m}_{B^{'}}\right)\]
\[z_2 = \left(\bar{\Lambda} - \hat{m}_{B^{'}}\right)\]
\[r = \frac{F_2^0}{F_1^0}\]
\[a = \frac{(z_1 + \frac{4}{3} z_2) + r(z_1 + \frac{1}{3} z_2)}{2m_Q}\]
\[\rho = -\frac{6r \hat{m}_{B^{'}}}{1 + r} z_2\]
\[b = -\frac{(1 + r)}{2m_Q} z_2\]

and \(m_{B_Q}\) and \(m_{B^{'}}\) are the heavy and the light baryon masses while \(m_Q\) and \(m_q\) are the masses of the heavy and the light quark respectively. The model used in this paper corresponds to \(a' = a'' = 0\), \(\rho b' = \rho b\) \((1 + 2m_{B^{'}}/m_{B_Q})\) and \(\rho b'' = \rho b\). The quantities \(a'''\) and \(\rho b'''\) are now calculable since the four matrix element that represent the chromomagnetic corrections are determined by our choice of \(a', a'', \rho b'\) and \(\rho b''\). The expressions for \(a'''\) and \(\rho b'''\) are

\[
a''' = a + a\left[1 - \frac{2m_{B_Q}}{m_{B_Q} - m_{B^{'}}} + \frac{\rho b}{a} \frac{m_{B^{'}}}{m_{B_Q}}\right]
\]
\[
\frac{\rho b'''}{3} = \frac{\rho b}{3} + \left[\frac{2m_{B^{'}}}{3m_{B_Q}} + \frac{4m_{B^{'}}^2}{(m_{B_Q} - m_{B^{'}})m_{B_Q}}\right] \rho b - \frac{4m_{B^{'}}m_{B_Q}}{(m_{B_Q} - m_{B^{'}})^2} a\]

The choice of the model described above is dictated by the fact that it works well phenomenologically and the fact that an expansion in \(1/m_Q\) is valid. The condition for the validity of the \(1/m_Q\) expansion is defined through the constraint \(|r| \leq 1\). To connect these assumptions with the ones made in Ref. [7], we review the assumptions made about the corrections coming from the chromomagnetic operator in Ref. [7]. We consider \(m_{B^{'}}/m_{B_Q}\) to be small and we relax some of the assumptions about the chromomagnetic corrections in Ref. [4]. While we retain \(\delta F_1 + \delta F_2 + \delta F_3 = 0\) (eqn.33 of Ref. [7]) we only assume (at \(\omega = 1\)) \(\chi_{11} \sim \chi_{12} \sim \chi_1\) but do not constrain \(\chi_{21}\) and \(\chi_{22}\). The above assumptions lead to \(\chi_1(\omega = 1) = x(\omega = 1)/m_c\) [7]. The model for the form factors used in this work corresponds to \(\chi_{21} = \chi_{22} = \chi_2 = -a\) in the limit \(m_{B^{'}}/m_{B_Q}\) is small. So we see that the model employed here is almost identical to the model in Ref. [7] (except for \(\chi_1\) not equal to \(\chi_2\)) in the limit \(m_{B^{'}}/m_{B_Q}\) is small. For the decays of charmed baryons considered in this paper the difference between the two models can be significant given the fact that \(m_{B^{'}}/m_{B_Q}\) is no longer small. For bottom baryon decays we expect the two models to yield essentially identical results.
Imposing the constraint on $r$ we find that we can fix $f$ and $g$ from the measured asymmetry and decay rate of $\Lambda_c \to \Lambda \pi^+$. Taking into account the experimental errors, the form factors $f$ and $g$ are such that $(g - f)/g \leq 0.35$ if $f < g$ and $(f - g)/f \leq 0.35$ if $g < f$. Note that in the $m_c \to \infty$ limit the form factors $f$ and $g$ are equal. The inclusion of $1/m_c$ corrections destroys this equality, and so the inequalities above represent the size of the $1/m_c$ corrections. We also assume $F_1(\omega = 1)^0 > 0$ in our analysis. The factorizable contributions to the decay amplitude can now be written as

$$A_{fac} = \frac{G_F}{\sqrt{2}} V_{cs} V_{ud} f P c_k \left[ (m_f - m_i) f_1 (m_P^2) + f_3(m_P^2) \frac{m_P^2}{m_i} \right]$$

$$B_{fac} = \frac{G_F}{\sqrt{2}} V_{cs} V_{ud} f P c_k \left[ (m_f + m_i) g_1 (m_P^2) + g_3(m_P^2) \frac{m_P^2}{m_i} \right]$$

where $c_1(c_2)$ refer to $\pi^+$ or $\bar{K}^0$ emission, $f_P$ is the pseudoscalar decay constant and $f_1$ and $g_1$ are the form factors defined in eqn.(8). In our analysis we shall use the SU(3) results

$$f_{1,\Lambda^0} = \sqrt{\frac{2}{3}} f \bar{\Xi}^{0,\Lambda} \Xi = -\sqrt{\frac{2}{3}} f \bar{e}^{0,\Lambda} \Xi = -\sqrt{\frac{2}{3}} f_{1,\Lambda e^p}$$

$$= -\sqrt{\frac{2}{3}} f \bar{\Xi}^{0,\Sigma^+} = \sqrt{\frac{4}{3}} f_1 \bar{\Xi}^{0,\Sigma^0} = 2 f_1 \bar{\Xi}^{0,\Lambda}$$

It is important to note that strictly we should use the SU(3) relations for the zeroth order form factors since the $1/m_Q$ corrections involve the baryon masses and hence break SU(3), but this effect is small and is therefore neglected in our analysis.

For the non-factorizable term we will use the pole model and current algebra as outlined in the introduction. Following Ref. [16] we write the non-factorizable amplitude $R(k)$ as

$$R(q) = R_{Born}(q) + \bar{R}(k)$$

The usual approximation is to assume

$$R(q, q^2 = m_P^2) \simeq R_{Born}(q, q^2 = m_P^2) + \bar{R}(0)$$

Finally using reduction techniques for the amplitude one obtains

$$R(q, q^2 = m_P^2) \simeq -\frac{\sqrt{2}}{f_P} < B||Q_5, H^{PV}||B_c > + R_{Born}(q, q^2 = m_P^2) - \bar{R}(0)$$

where $Q_5$ is the axial charge and $f_P$ is the pseudoscalar decay constant.

Clearly the first term in the amplitude above contributes to the parity violating amplitude while the remaining terms contribute to the parity conserving amplitude as the parity violating amplitude is small [10]. (In the case of non-leptonic hyperon decays $< B_f|H^{PV}|B_i >= 0$.
in the SU(3) limit [16]). Note in the case of charmed baryon decays, as opposed to the hyperon decay case, \( \bar{R}(0) \) is no longer small compared to \( R_{\text{Born}}(q, q^2 = m_P^2) \). Hence in our model we have

\[
A = \frac{-\sqrt{2}}{f_P} < B|[Q_5, H^{PV}]|B_c >
\]

\[
B = -[g_{B''B'}F^{B''} < B''|H^{PC}|B > m_B + m_{B'} + g_{BB''} F^{B''} < B'|H^{PC}|B'' > m_B + m_{B''}]
\]

The first term in the expression for \( B \) is the s-channel pole contribution while the next term is the u-channel pole contribution. The strong pseudoscalar meson-baryon coupling \( g_{B_iB_jP} \) can be related via the Goldberger-Treiman relation to the axial vector form factors \( g^{A}_{B_iB_j} \) as

\[
g_{B_iB_jP} = \frac{1}{f_P}(m_{B_i} + m_{B_j})g^{A}_{B_iB_j}
\]

The axial form factors \( g^{A}_{B_iB_j} \) are of two types, those between non-charmed baryons and those between charmed baryons. For the first type we use SU(3) parametrization with

\[
D + F = 1.25 ; \quad D/F \approx 1.8
\]

where the D/F ratio is taken from a fit to hyperon semileptonic decay [17]. The second type of form factors are between charmed baryons and it is reasonable to use SU(4) symmetry and use the same D and F is this case also. The justification for this lies in the fact the the transitions are \( \Delta C = 0 \) and so the baryon wavefunction mismatch in the overlap integral is small [12]. For the weak matrix element between the positive parity baryons we will use the following SU(3) relation

\[
a_{\Sigma^+\Sigma^0} = a_{\Xi^-\Xi^0} = a_{\Xi^+\Xi^-} = \sqrt{\frac{1}{3}}a_{\Xi^+\Xi^-} = \sqrt{\frac{1}{3}}a_{\Xi^+\Xi^-} = -\sqrt{\frac{1}{3}}a_{\Xi^-\Xi^0}
\]

where \( a_{B_iB_j} = < B_f|H^{PC}|B_i > \). Using the above SU(3) relations the non-factorizable term is completely specified in terms of one weak matrix element which we choose to be \( a_{\Xi^0\Xi^0} \), and which we fix from the measured decay rate of \( \Lambda_c \rightarrow \Sigma^+\pi^0 \).

For the decay where the meson in the final state is a vector meson we can write the decay amplitude as

\[
M(B_c \rightarrow B_fV) = iu_{B_f} \epsilon^{\mu}[\gamma_\mu(a + b\gamma_5) + 2(x + y\gamma_5)P_\mu]u_{B_c}
\]
where $P_{1\mu}$ is the four-momentum of the parent baryon and $\epsilon^{*\mu}$ is the polarization of the vector meson. The kinematics for this decay has been worked out in details in Ref. [18]. We can write down the factorizable contribution as

$$a_{fac} = \frac{G_F}{\sqrt{2}} V_{cs} V_{u d} f_V m_{V} c_k \left[ f_1 (m_{V}^2) + \frac{m_f + m_i}{m_i} f_2 (m_{V}^2) \right]$$

$$b_{fac} = \frac{G_F}{\sqrt{2}} V_{cs} V_{u d} f_V m_{V} c_k \left[ g_1 (m_{V}^2) + \frac{m_f - m_i}{m_i} g_2 (m_{V}^2) \right]$$

$$x_{fac} = \frac{G_F}{\sqrt{2}} V_{cs} V_{u d} f_V m_{V} c_k \left[ f_2 (m_{V}^2) \right]$$

$$y_{fac} = \frac{G_F}{\sqrt{2}} V_{cs} V_{u d} f_V m_{V} c_k \left[ g_2 (m_{V}^2) \right]$$

(22)

where $c_1(c_2)$ refer to $\rho^+$ or $\bar{K}^{*0}$ emission, $f_V$ is the vector meson decay constant, $m_{V}$ is the vector meson mass and $f_1, f_2$ and $g_1, g_2$ are the form factors. For the pole term we will work in the approximation that $\rho$ generates isospin and so the couplings $g_{BBV}$ are pure F-type. Similar results apply to the decays $\Lambda_c \to p \phi$ and $\Lambda_b \to J/\psi \Lambda$ with the appropriate changes in the QCD correction factor and the CKM matrix elements.

Before we present our results in the next section we list the various inputs used in the calculations. We begin with the calculations on the non-leptonic decays of the charmed baryons. As outlined in the introduction a fit to the decay rate and the asymmetry for the decay $\Lambda_c \to \Lambda \pi^+$ used to extract $F_1^0(\omega = 1)$ and $r$. The extracted values are $F_1^0(\omega = 1) = 0.46$ and $r = -0.47$. The values for the Wilson’s coefficients $c_1$ and $c_2$ were taken $\approx 1.32$ and -0.59 respectively and we have used $m_c = 1.4$ GeV and $m_s = 0.2$ GeV [19]. We found that the non-factorizable contribution could be expressed in terms of the single matrix element $a_{\Xi^0 A \Xi^0}$. The measured decay rate of $\Lambda_c \to \Sigma^+ \pi^0$ is used to extract $a_{\Xi^0 A \Xi^0} = -5.48 \times 10^{-8}$ GeV. For the vector meson decays we use, following Ref. [11], $f_\rho = f_K = 0.221$ GeV. For the mode $\Lambda_c \to p \phi$ we have used $f_\phi = 0.23$ GeV for the $\phi$ decay constant. For the $\Lambda_b$ decay we have used $|V_{cb}| = 0.040$ [22], $c_2 \approx 0.23$, $f_{J/\psi} = 395$ MeV, and pole masses $m_V \approx 5.42$ GeV, $m_A \approx 5.86$ GeV [2]. The quark masses were taken as $m_b = 4.74$ GeV and $m_s = 0.20$ GeV [19].

3 Results

Starting with the results on the non-leptonic decays of the charmed baryons, in table 1 and 2 we give the predictions for the decay rates and asymmetry for the non-leptonic decays
Table 1: Decay rates ($\times 10^{11} \text{s}^{-1}$), branching ratios ($\times 10^{-3}$) and asymmetry predictions for Cabibbo favoured $B_i \to B_f P$ decays. The asterisks indicate the input values.

| Process           | $\Gamma_{Th}$ | $BR_{Th}$  | $\Gamma_{Expt}$ | $BR_{Expt}$ | $\alpha_{Th}$ | $\alpha_{Expt}$ |
|-------------------|---------------|------------|-----------------|-------------|---------------|----------------|
| $\Lambda_c \to \Lambda \pi^+$ | 0.40          | 7.9*       | 0.40 ± 0.11     | 7.9 ± 0.18 [20] | -0.94*        | -0.94 ± 0.06 [20] |
| $\Lambda_c \to \Sigma^0 \pi^+$ | 0.44          | 8.7*       | 0.44 ± 0.10     | 8.7 ± 0.20 [21] | -0.47         | --             |
| $\Lambda_c \to \Sigma^+ \pi^0$ | 0.44          | 8.7        | 0.44 ± 0.12 [20] | 8.7 ± 0.22 [21] | -0.47         | -0.45 ± 0.31 ± 0.06 [20] |
| $\Lambda_c \to p \bar{K}^0$ | 0.68          | 13.4       | 1.05 ± 0.20     | 21 ± 0.4 [21]  | -0.91         | --             |
| $\Lambda_c \to \Xi^0 K^+$ | 0.25          | 4.9        | 0.17 ± 0.05     | 3.4 ± 0.9 [21] | 0             | --             |
| $\Xi^+_c \to \Xi^- \pi^+$ | 0.17          | 1.6        | --              | --           | 0.06          | --             |
| $\Xi^{0A}_c \to \Xi^0 \pi^+$ | 0.88          | 31         | --              | --           | 0.03          | --             |
| $\Xi^{0A}_c \to \Xi^0 K^0$ | 0.62          | 6.1        | --              | --           | -0.89         | --             |
| $\Xi^{+A}_c \to \Sigma^+ \bar{K}^0$ | 0.31         | 3.1        | --              | --           | -0.005        | --             |
| $\Xi^{0A}_c \to \Lambda \bar{K}^0$ | 0.42          | 4.1        | --              | --           | -0.76         | --             |
| $\Xi^{0A}_c \to \Sigma^0 \bar{K}^0$ | 0.23          | 2.2        | --              | --           | 0.006         | --             |
| $\Xi^{0A}_c \to \Sigma^+ K^-$ | 0.24          | 2.3        | --              | --           | 0             | --             |

$B_i \to B_f P$ and $B_i \to B_f V$. In table. 3 we show the predictions for the mode $\Lambda_c \to p \phi$ and in table. 4 we show the predictions for $\Lambda_b \to J/\psi \Lambda$. In table. 5 and table. 6 we show the form factors for the $\Lambda_c \to \Lambda$ transition while in table. 7 and table. 8 we show the form factors for the $\Lambda_b \to \Lambda$ transition.
Table 2: Decay rates ($\times 10^{11}s^{-1}$), branching ratios ($\times 10^{-3}$) and asymmetry predictions for Cabbibo favoured $B_i \to B_f V$ decays

| Process         | $\Gamma_{Th}$ | $BR_{Th}$ | $\Gamma_{Expt}$ | $BR_{Expt}$ | $\alpha_{Th}$ | $\alpha_{Expt}$ |
|-----------------|---------------|-----------|-----------------|-------------|---------------|-----------------|
| $\Lambda_c \to \Lambda\rho^+$ | 0.55          | 11        | $< 2.1$         | $< 42^{[23]}$ | 0.46          | ---             |
| $\Lambda_c \to \Sigma^0\rho^+$ | 0.15          | 3         | ---             | ---          | 0.0           | ---             |
| $\Lambda_c \to \Sigma^+\rho^0$ | 0.15          | 3         | $< 0.6$         | $< 12^{[21]}$ | 0             | ---             |
| $\Lambda_c \to pK^*$ | 0.57          | 11.3      | ---             | ---          | 0.45          | ---             |
| $\Lambda_c \to \Xi^0K^{*+}$ | 0.002         | 0.8       | ---             | ---          | 0             | ---             |
| $\Xi^0_c \to \Xi^-\rho^+$ | 1.3           | 12.8      | ---             | ---          | 0.54          | ---             |
| $\Xi^+_c \to \Xi^0\rho^+$ | 0.88          | 31        | ---             | ---          | 0.46          | ---             |
| $\Xi^0_{cA} \to \Xi^0\rho^0$ | 0.11          | 1.1       | ---             | ---          | 0             | ---             |
| $\Xi^{+}_{cA} \to \Sigma^+K^{*0}$ | 0.36          | 12.8      | ---             | ---          | 0.47          | ---             |
| $\Xi^0_{cA} \to \Lambda K^{*0}$ | 0.10          | 1         | ---             | ---          | -0.56         | ---             |
| $\Xi^0_{cA} \to \Sigma^0K^{*0}$ | 0.17          | 1.7       | ---             | ---          | 0.37          | ---             |
| $\Xi^0_{cA} \to \Sigma^+K^{*-}$ | 0.016         | 0.15      | ---             | ---          | 0             | ---             |

Table 3: Decay rate ($\times 10^{11}s^{-1}$), branching ratio relative to $pK^-\pi^+$ mode and asymmetry predictions for $\Lambda_c \to p\phi$

| Process        | $\Gamma_{Th}$ | $BR_{Th}$ | $\Gamma_{Expt}$ | $\alpha_{Th}$ | $\alpha_{Expt}$ |
|----------------|---------------|-----------|-----------------|---------------|-----------------|
| $\Lambda_c \to p\phi$ | 0.02, $BR \approx 0.01$ | --- | 0.31 | --- |

Table 4: Decay rate ($\times 10^{11}s^{-1}$), branching ratio relative to the total decay width and asymmetry predictions for $\Lambda_b \to J/\psi\Lambda$ decays

| Process        | $\Gamma_{Th}$ | $\Gamma_{Expt}$ | $\alpha_{Th}$ | $\alpha_{Expt}$ |
|----------------|---------------|-----------------|---------------|-----------------|
| $\Lambda_b \to J/\psi\Lambda$ | $0.4 \times 10^{-3}$, $BR \approx 0.4 \times 10^{-4}$ | --- | 0.25 | --- |
Table 5: Form factors at the point $q_{\text{max}}^2$ for $\Lambda_c \to \Lambda$

| $f_1(q_{\text{max}}^2)$ | $f_2(q_{\text{max}}^2)$ | $f_3(q_{\text{max}}^2)$ | $g_1(q_{\text{max}}^2)$ | $g_2(q_{\text{max}}^2)$ | $g_3(q_{\text{max}}^2)$ |
|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| 0.46                    | 0.11                    | -0.84                   | 0.46                    | 0.26                    | -1.88                   |

Table 6: Form factors at the point $q^2 = 0$ for $\Lambda_c \to \Lambda$

| $f_1(q^2 = 0)$ | $f_2(q^2 = 0)$ | $f_3(q^2 = 0)$ | $g_1(q^2 = 0)$ | $g_2(q^2 = 0)$ | $g_3(q^2 = 0)$ |
|----------------|----------------|----------------|----------------|----------------|----------------|
| 0.22           | 0.05           | -0.40          | 0.28           | 0.16           | -1.15          |

Table 7: Form factors at the point $q_{\text{max}}^2$ for $\Lambda_b \to \Lambda$

| $f_1(q_{\text{max}}^2)$ | $f_2(q_{\text{max}}^2)$ | $f_3(q_{\text{max}}^2)$ | $g_1(q_{\text{max}}^2)$ | $g_2(q_{\text{max}}^2)$ | $g_3(q_{\text{max}}^2)$ |
|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| 0.38                    | 0.11                    | -0.29                   | 0.46                    | 0.22                    | -0.0175                 |

Table 8: Form factors at the point $q^2 = 0$ for $\Lambda_b \to \Lambda$

| $f_1(q^2 = 0)$ | $f_2(q^2 = 0)$ | $f_3(q^2 = 0)$ | $g_1(q^2 = 0)$ | $g_2(q^2 = 0)$ | $g_3(q^2 = 0)$ |
|----------------|----------------|----------------|----------------|----------------|----------------|
| 0.040          | 0.012          | -0.03          | 0.08           | 0.04           | -0.003         |
In conclusion we have studied the non-leptonic two body decays of charmed and bottom baryons involving transition of a heavy to light quark based on a model for form factors that includes $1/m_Q$ corrections.

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**References**

[1] H.Y. Cheng and B. Tseng, IP-ASTP-03-95, [hep-ph/9502391](http://arxiv.org/abs/hep-ph/9502391).

[2] R. Pérez-Marcial, R. Huerta, A. García and M. Avila-Aoki, Phys. Rev. D 40, 2955 (1990); D 44, 2203(E) (1991); H.Y. Cheng and B. Tseng, Phys. Rev. D 48, 4188 (1993).

[3] T. Mannel, W. Roberts and Z. Ryzak, Nucl. Phys. B 355, 38 (1991); F. Hussain, J.G. Körner, M. Kramer and G. Thompson, Z. Phys. C 51, 321 (1991).

[4] T. Mannel, W. Roberts and Z. Ryzak, Phys. Lett. B 255, 593 (1991).

[5] J.G. Körner and M. Kramer, Phys. Lett. B 275, 495 (1992).

[6] Guey-Lin Lin, T. Mannel, Phys. Lett. B 321, 417 (1994).

[7] Alakabha Datta, UH-511-809-94, hep/ph 9411432 (To appear in Phys. Lett. B).

[8] G. Crawford et al., CLNS 94/1306, CLEO 94-34.

[9] L.L. Chau, Phys. Rep. 95, 1 (1983); L.L. Chau, H.Y. Cheng, Phys. Rev. Lett 56, 1655 (1996); Phys. Rev. D 36, 137 (1987);

[10] D. Ebert and W. Kallies, Yad. Fiz. 40, 1250 (1984); H.Y. Cheng, Z. Phys C 29, 453 (1985).

[11] H.Y. Cheng and B. Tseng, Phys. Rev. D 46, 1042 (1992); H.Y. Cheng and B. Tseng, Phys. Rev. D 48, 4188 (1993).

[12] Q.P. Xu and A.N. Kamal, Phys. Rev. D 46, 270 (1992).

[13] J.G. Körner, M. Kramer, Z. Phys. C 55, 659 (1992).
[14] M. Bauer, B. Stech, M. Wirbel, Z. Phys. C 34, 103 (1987).

[15] A.J. Buras, J.M. Gérard, R. Rückl, Nucl. Phys. B 293, 787 (1987); B.Y. Blok and M.A. Shifman, Yad. Fiz. 45, 221, 478, 841 (1987); M.A. Shifman, Nucl. Phys. B(Proc.Suppl.) 3, 289 (1988).

[16] R.E. Marshak, Riazudddin, C.P. Ryan, Theory of Weak Interactions in Particle Physics (Wiley Interscience, New York, 1969).

[17] D.F. Donoghue, B.R. Holstein, S.W. Klimt, Phys. Rev. D 35, 2903 (1987).

[18] S. Pakvasa, S. F. Tuan, S.P. Rosen, Phys. Rev. D 42, 3746 (1990).

[19] Particle Data Group, Phys. Rev. D 50, 1435 (1994).

[20] M. Bishai et al., CLNS 95/1319, CLEO 95-1.

[21] Particle Data Group, Phys. Rev. D 50, 1225 and 1783-1786 (1994).

[22] M. Neubert, Phys. Lett. B 338, 84 (1994).

[23] P. Avery et al., Phys. Lett. B 325, 257 (1994).