Low Energy Aspects of Heavy Meson Decays.

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I discuss low energy aspects of heavy meson decays, where there is at least one heavy meson in the final state. Examples are $B - \bar{B}$ mixing, $B \rightarrow D\bar{D}$, $B \rightarrow D\eta'$, and $B \rightarrow D\gamma$. The analysis is performed in the heavy quark limit within heavy-light chiral perturbation theory. Coefficients of $1/N_c$ suppressed chiral Lagrangian terms (beyond factorization) have been estimated by means of a heavy-light chiral quark model.

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1. Introduction

In this paper we consider non-leptonic “heavy meson to heavy meson(s)” transitions, for instance $B - \bar{B}$-mixing [1], $B \rightarrow DD$ [2] and with only one $D$-meson in the final state, like $B \rightarrow D\eta'$ [3] and $B \rightarrow \gamma D^*$ [4, 5, 6].

The methods [2] used to describe heavy to light transitions like $B \rightarrow \pi\pi$ and $B \rightarrow K\pi$ are not suited for the decays we consider. We use heavy-light chiral perturbation theory (HL$\chi$PT). Lagrangian terms corresponding to factorization are then determined to zeroth order in $1/m_Q$, where $m_Q$ is the mass of the heavy quark ($b$ or $c$). For $B - \bar{B}$-mixing we have also calculated $1/m_b$ corrections [1].

Colour suppressed $1/N_c$ terms beyond factorization can be written down, but their coefficients are unknown. However, these coefficients can be calculated within a heavy-light chiral quark model (HL$\chi$QM) [8] based on the heavy quark effective theory (HQEFT) [9] and HL$\chi$PT [10]. The $1/N_c$ suppressed non-factorizable terms calculated in this way will typically be proportional to a model dependent gluon condensate [1, 2, 3, 6, 8, 11].

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(1)
2. Quark Lagrangians for non-leptonic decays

The effective non-leptonic Lagrangian at quark level has the form [12]:

\[ \mathcal{L}_W = \sum_i C_i(\mu) \hat{Q}_i(\mu) , \]  

where the Wilson coefficients \( C_i \) contain \( G_F \) and KM factors. Typically, the operators are four quark operators being the product of two currents:

\[ \hat{Q}_i = j_\mu^W(q_1 \rightarrow q_2) j_\mu^W(q_3 \rightarrow q_4) , \]  

where \( j_\mu^W(q_i \rightarrow q_j) = (q_j)_L \gamma^\mu (q_i)_L \), and some of the quarks \( q_{i,j} \) are heavy. To leading order in \( 1/N_c \), matrix elements of \( \hat{Q}_i \) factorize in products of matrix elements of currents. Non-factorizable \( 1/N_c \) suppressed terms are obtained from “coloured quark operators”. Using Fierz transformations and

\[ \delta_{ij} \delta_{in} = \frac{1}{N_c} \delta_{in} \delta_{ij} + 2 t^a_i t^a_j , \]  

where \( t^a_i \) are colour matrices, we may rewrite the operator \( \hat{Q}_i \) as

\[ \hat{Q}_i^F = \frac{1}{N_c} j_\mu^W(q_1 \rightarrow q_4) j_\mu^W(q_3 \rightarrow q_2) + 2 j_\mu^W(q_1 \rightarrow q_4)^a j_\mu^W(q_3 \rightarrow q_2)^a , \]  

where \( j_\mu^W(q_i \rightarrow q_j)^a = (q_j)_L \gamma^\mu t^a (q_i)_L \) is a left-handed coloured current. The quark operators in \( \hat{Q}_i^F \) give \( 1/N_c \) suppressed terms.

3. Heavy-light chiral perturbation theory

The QCD Lagrangian involving light and heavy quarks is:

\[ \mathcal{L}_{Quark} = \pm Q_v(\pm) i v \cdot DQ_v(\pm) + O(m_Q^{-1}) + \bar{q}i\gamma \cdot Dq + ... \]  

where \( Q_v(\pm) \) are the quark fields for a heavy quark and a heavy anti-quark with velocity \( v \), \( q \) is the light quark triplet, and \( iD_\mu = i\partial_\mu - q A_\mu - g_s t^a A^a_\mu \). The bosonized Lagrangian have the following form, consistent with the underlying symmetry [10]:

\[ \mathcal{L}_\chi(Bos) = \mp Tr \left[ H_{\mu}(\pm)(iv \cdot Df_a)H_f(\pm) \right] - g_A Tr \left[ H_{\mu}(\pm)H_f(\pm) \gamma_\mu \gamma_5 A^a_{fa} \right] + ... \]  

where the covariant derivative is \( iD^\mu_{fa} = \delta_{af}(i\partial^\mu - e_H A^\mu) - \gamma^\mu_{fa} \); \( a, f \) being SU(3) flavour indices. The axial coupling is \( g_A \simeq 0.6 \). Furthermore,

\[ \gamma_\mu(\text{or } A_\mu) = \pm \frac{i}{2}(\xi \partial_\mu \xi \pm \xi \partial_\mu \xi^\dagger) , \]
where \( \xi = \exp(i\Pi/f) \), and \( \Pi \) is a 3 by 3 matrix containing the light mesons \((\pi, K\eta)\), and the heavy \((1^-, 0^-)\) doublet field \((P_\mu, P_5)\) is
\[
H^{(\pm)} = P_\pm(P_\mu^{(\pm)}\gamma^\mu - iP_5^{(\pm)}\gamma_5)\, , \quad P_\pm = (1 \pm \gamma \cdot v)/2\, ,
\]
where superscripts \((\pm)\) means meson and anti-meson respectively. To bosonize the non-leptonic quark Lagrangian, we need to bosonize the currents. Then the \( b, c \), and \( \tau \) quarks are treated within HQEFT, which means the replacements \( b \to Q_b^{(+)}v_b \), \( c \to Q_c^{(+)}v_c \), and \( \tau \to Q_\tau^{(-)} \). Then the bosonization of currents within HQEFT for decay of a heavy \( B \)-meson will be:
\[
\bar{Q}_{vb} \gamma^\mu Q_v^{(+)} \longrightarrow \frac{\alpha_H}{2} Tr\left[\xi^\dagger \gamma^\mu L H_B^{(+)}\right] \equiv J_{\mu b} \, ,
\]
where \( L \) is the left-handed projector in Dirac space, and \( \alpha_H = f_H \sqrt{M_H} \) for \( H = B, D \) before pQCD and chiral corrections are added. Here, \( H_b^{(+)} \) represents the heavy meson (doublet) containing a \( b \)-quark. For creation of a heavy anti-meson \( \bar{B} \) or \( \bar{D} \), the corresponding currents \( J_{\mu b} \) and \( J_{\mu c} \) are given by (9) with \( H_b^{(+)} \) replaced by \( H_b^{(-)} \) and \( H_c^{(-)} \), respectively. For the \( B \to D \) transition we have
\[
\bar{Q}_{vb} \gamma^\mu LQ_v^{(+)} \longrightarrow -\zeta(\omega) Tr\left[H_c^{(+)}\gamma^\mu LH_b^{(+)}\right] \equiv J_{\mu b\to c} \, ,
\]
where \( \zeta(\omega) \) is the Isgur-Wise function, and \( \omega = v_b \cdot v_c \). For creation of \( D\bar{D} \) pair we have the same expression for the current \( J_{\mu c} \) with \( H_b^{(+)} \) replaced by \( H_c^{(-)} \), and \( \zeta(\omega) \) replaced by \( \zeta(-\lambda) \), where \( \lambda = \bar{v} \cdot v_c \). In addition there are \( 1/m_Q \) corrections for \( Q = b, c \). The low velocity limit is \( \omega \to 1 \). For \( B \to D\bar{D} \) and \( B \to D^*\gamma \) one has \( \omega \simeq 1.3 \), and \( \omega \simeq 1.6 \), respectively.

3.1. Factorized lagrangians for non-leptonic processes

For \( B - \bar{B} \) mixing, the factorized bosonized Lagrangian is
\[
\mathcal{L}_B = C_B J_{\mu b}^\mu (J_b)^{\mu} \, ,
\]
where \( C_B \) is a short distance Wilson coefficient (containing \((G_F)^2\)), which is taken at \( \mu = \Lambda_\chi \simeq 1 \text{ GeV} \), and the currents are given by (9).

For processes obtained from two different four quark operators for \( b \to \bar{c} \bar{c} q \) \((q = d, s)\), we find the factorized Lagrangian corresponding to Fig. 1:
\[
\mathcal{L}_{F \text{act}}^{\text{Spec}} = (C_2 + \frac{C_1}{N_c}) J_{\mu b\to c} (J_c)^{\mu} \, ,
\]

where \( \xi = \exp(i\Pi/f) \), and \( \Pi \) is a 3 by 3 matrix containing the light mesons \((\pi, K\eta)\), and the heavy \((1^-, 0^-)\) doublet field \((P_\mu, P_5)\) is
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\]
Fig. 1. Factorized contribution for $B^0_d \to D^+D^-$ through the spectator mechanism, which does not exist for decay mode $B^0_d \to D^+_sD^-_s$.

Fig. 2. Factorized contribution for $B^0_d \to D^+_sD^-_s$ through the annihilation mechanism, which give zero contributions if both $D^+_s$ and $D^-_s$ are pseudoscalars.

where $C_i = \frac{4}{\sqrt{2}} G_F V_{cb} V_{cq}^* a_i$, and $a_1 \simeq -0.35 - 0.07i$, $a_2 \simeq 1.29 + 0.08i$. We have considered the process $B^0_d \to D^+_sD^-_s$. Note that there is no factorized contribution to this process if both $D$-mesons in the final state are pseudoscalars! But the factorized contribution to $B^0_d \to D^+_sD^-_s$ will be the starting point for chiral loop contributions to the process $B^0_d \to D^+_sD^-_s$.

The factorizable term from annihilation is shown in Fig. 2 and is:

$$\mathcal{L}^{Ann}_{Fact} = (C_1 + \frac{C_2}{N_c}) J^\mu_{cc}(J_b)_{\mu}.$$ (13)

Because $(C_1 + C_2/N_c)$ is a non-favourable combination of the Wilson coefficients, this term will give a small non-zero contribution if at least one of the mesons in the final state is a vector.

3.2. Possible $1/N_c$ suppressed tree level terms

For $B - \bar{B}$ mixing, we have for instance the $1/N_c$ suppressed term

$$Tr \left[ \xi^\dagger \sigma^{\mu \alpha} L H_b^{(+)} \right] \cdot Tr \left[ \xi^\dagger \sigma_{\mu \alpha} RH_b^{(-)} \right].$$ (14)
3.3. Chiral loops for non-leptonic processes

Within HL$\chi$QM, the leading chiral corrections are proportional to

$$\chi(M) \equiv \left( \frac{g_A m_M}{4\pi f} \right)^2 \ln \left( \frac{\Lambda^2_\chi}{m^2_M} \right),$$

(17)

where $m_M$ is the appropriate light meson mass and $\Lambda_\chi$ is the chiral symmetry breaking scale, which is also the matching scale within our framework.

For $B - \bar{B}$ mixing there are chiral loops obtained from (6) and (11) shown in Fig. 3 These have to be added to the factorized contribution.
Fig. 5. The $HL\chi_{QM}$ ansatz: Vertex for quark meson interaction

For the process $\overline{B}_d^0 \to D_s^+ D_s^-$ we obtain a chiral loop amplitude corresponding to Fig. 4. This amplitude is complex and depend on $\omega$ and $\lambda$ defined previously. It has been recently shown [5] that $(0^+, 1^+)$ states in loops should also be added to the result.

4. The heavy-light chiral quark model

The Lagrangian for $HL\chi_{QM}$ [8] contains the Lagrangian (5):

$$L_{HL\chi_{QM}} = L_{HQET} + L_{\chi_{QM}} + L_{Int},$$

where $L_{HQET}$ is the heavy quark part of (5), and the light quark part is

$$L_{\chi_{QM}} = \overline{\chi} [\gamma^\mu(iD^\mu + V^\mu + \gamma_5 A^\mu) - m] \chi.$$  

Here $\chi_L = \xi^\dagger q_L$ and $\chi_R = \xi q_R$ are flavour rotated light quark fields, and $m$ is the light constituent mass. The bosonization of the (heavy-light) quark sector is performed via the ansatz:

$$L_{Int} = - G_H \left[ \overline{Q}_f H^f_v Q_v + \overline{Q}_v H^v_f \chi_f \right].$$

The coupling $G_H$ is determined by bosonization through the loop diagrams in Fig [6]. The bosonization lead to relations between the model dependent parameters $G_H$, $m$, and $\langle \overline{\chi} \chi \rangle$, and the quadratic-, linear, and logarithmic- divergent integrals $I_1, I_{3/2}, I_1$, and the physical quantities $f_\pi$, $\langle \overline{q} q \rangle$, $g_A$ and $f_H$ ($H = B, D$). For example, the relation obtained for identifying the kinetic term is:

$$- i G_H^2 N_c \left( I_{3/2} + 2m I_2 + \frac{i(8 - 3\pi)}{384 N_c m^2} \left( \frac{\alpha_s}{\pi} G^2 \right) \right) = 1,$$

where we have used the prescription:

$$g_s^2 C_{\mu\nu}^a C_{\alpha\beta}^a \to 4\pi^2 \left( \frac{\alpha_s}{\pi} G^2 \right) \frac{1}{12} (g_{\mu\alpha} g_{\nu\beta} - g_{\mu\beta} g_{\nu\alpha}).$$

The parameters are fitted in strong sector, with $\langle \overline{\chi} \chi \rangle = [(0.315 \pm 0.020) \text{ GeV}]^4$, and $G_H^2 = \frac{2m}{T^2 \rho}$, where $\rho \simeq 1$. For details, see [8].
Fig. 6. Diagrams generating the strong chiral lagrangian at mesonic level. The kinetic term and and the axial vector term $\sim g_A$.

Fig. 7. Non-factorizable contribution to $B - \bar{B}$ mixing; $\Gamma \equiv t^a \gamma^\mu L$

5. $1/N_c$ terms from HL\(\chi\)QM

To obtain the $1/N_c$ terms for $B - \bar{B}$ mixing in Fig. 7, we need the bosonization of colored current in the quark operators of eq. (4):

$$\left( \overline{q_L} t^a \gamma^\alpha Q_{Q_b}^{(+)} \right)_{1G} \rightarrow -\frac{G_H g_s}{64\pi} G_{\mu\nu}^a Tr \left[ \xi^{\dagger} \gamma^\alpha L H_b^{(+)} \Sigma_{\mu\nu} \right], \quad (23)$$

$$\Sigma_{\mu\nu} = \sigma^{\mu\nu} - \frac{2\pi f^2}{m^2 N_c} [\sigma^{\mu\nu}, \gamma \cdot v_b]_+. \quad (24)$$

This coloured current is also used for $B \rightarrow D\bar{D}$ in Fig. 8, for $B \rightarrow D \eta'$ in Fig. 8, and for $B \rightarrow \gamma D^*$ in Fig. 10. In addition there are more complicated bosonizations of coloured currents as indicated in Fig. 5.

For $B \rightarrow D \eta'$ and $B \rightarrow \gamma D^*$ decays there are two different four quark operators, both for $b \rightarrow c\bar{u}q$ and $b \rightarrow \bar{c}uq$, respectively. At $\mu = 1$ GeV they have Wilson coefficients $a_2 \simeq 1.17$, $a_1 \simeq -0.37$ (up to prefactors $G_F$ and...
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Fig. 8. Non-factorizable $1/N_c$ contribution for $B^0 \to D_s^+ D_s^-$ through the annihilation mechanism with additional soft gluon emission.

Fig. 9. Diagram for $B \to D \eta'$ within $H \chi Q M$. $\Gamma = \gamma^\mu (1 - \gamma_5)$

5.1. $1/m_c$ correction terms

For the $B \to D$ transition we have the $1/m_c$ suppressed terms:

$$\frac{1}{m_c} Tr \left[ \left( Z_0 H_c^{(+)} + Z_1 \gamma^\alpha H_c^{(+)} \gamma_\alpha + Z_2 H_c^{(+)} \gamma \cdot v_b \right) \gamma^\alpha L H_b^{(+)} \right], \quad (25)$$

where the $Z_i$’s are calculable within $H \chi Q M$. The relative size of $1/m_c$ corrections are typically of order $20 - 30\%$.

6. Results

6.1. $B - \bar{B}$ mixing

The result for the $B(a g)$ parameter in $B - \bar{B}$-mixing has the form [1]

$$\hat{B}_{B_q} = \frac{3}{4} \rho \left[ 1 + \frac{1}{N_c} (1 - \delta^B G) + \frac{\tau_b}{m_b} + \frac{\tau_\chi}{32 \pi^2 f^2} \right], \quad (26)$$
Fig. 10. Non-factorizable contributions to $B \to \gamma D^*$ from the coloured operators similar to the $K - \overline{K}$-mixing case [11]. From perturbative QCD we have $\bar{b} \simeq 1.56$ at $\mu = \Lambda_{\chi} = 1$ GeV. From calculations within the HL$\chi$QM we obtain, $\delta_{\bar{b}} = 0.5 \pm 0.1$ and $\tau_b = (0.26 \pm 0.04)$GeV, and from chiral corrections $\tau_{\chi,s} = (-0.10 \pm 0.04)$GeV$^2$, and $\tau_{\chi,d} = (-0.02 \pm 0.01)$GeV$^2$. We obtained

$$\hat{B}_{B_d} = 1.51 \pm 0.09 \quad \hat{B}_{B_s} = 1.40 \pm 0.16 ,$$

in agreement with lattice results.

6.2. $B \to D \overline{D}$ decays

Keeping the chiral logs and the $1/N_c$ terms from the gluon condensate, we find the branching ratios in the “leading approximation”. For decays of $\overline{B}_d^0 (\sim V_{cb}V_{cd}^*)$ and $\overline{B}_s^0 (\sim V_{cb}V_{cs}^*)$ we obtain branching ratios of order few $\times 10^{-4}$ and $\times 10^{-3}$, respectively. Then we have to add counterterms $\sim m_s$ for chiral loops. These may be estimated in HL$\chi$QM.

6.3. $B \to D \eta'$ and $B \to \gamma D^*$ decays

The result corresponding to Fig. 9 is:

$$Br(B \to D \eta') \simeq 2 \times 10^{-4} .$$

The partial branching ratios from the mechanism in Fig. 10 are [6]

$$Br(\overline{B}_d^0 \to \gamma D^{*0}) \simeq 1 \times 10^{-5} ; \quad Br(\overline{B}_s^0 \to \gamma D^{*0}) \simeq 6 \times 10^{-7} .$$

The corresponding factorizable contributions are roughly two orders of magnitude smaller. Note that the process $\overline{B}_d^0 \to \gamma D^{*0}$ has substantial meson exchanges (would be chiral loops for $\omega \to 1$), and is different.

7. Conclusions

Our low energy framework is well suited to $B - \overline{B}$ mixing, and to some extent to $B \to D \overline{D}$. Work continues to include $(0^+, 1^+)$, states, counterterms, and $1/m_c$ terms. Note that the amplitude for $\overline{B}_d^0 \to D^+_sD^-_s$ is zero
in the factorized limit. For processes like $B \rightarrow D\eta'$ and $B \rightarrow D\gamma$ we can give order of magnitude estimates when factorization gives zero or small amplitudes.

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