SU(3)$_{\text{FLAVOR}}$-ANALYSIS OF NONFACTORIZABLE CONTRIBUTIONS TO $D \to PP$ DECAYS

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ABSTRACT

We study charm D - meson decays to two pseudoscalar mesons in Cabibbo favored mode employing SU(3)-flavor for the nonfactorizable matrix elements. Using $D \to \bar{K}\pi$ and $D_s \to \bar{K}K$ to fix the reduced matrix elements, we obtain a consistent fit for $\eta$ and $\eta'$ emitting decays of $D$ and $D_s$ mesons.
It is now fairly established that the naive factorization model does not explain the data on weak hadronic decays of charm mesons. On one hand large $N_c \to \infty$ limit, which apparently was thought to be supported by D-meson phenomenology [1,2], has failed to explain B-meson decays, as B-meson data clearly demands [3] a positive value of the $a_2$-parameter. On the other hand even in D-meson decays, the two body Cabibbo favored decays of $D^0$ and $D_s^+$ involving $\eta$ and $\eta'$ in their final state have proven to be problematic for a universal choice of $a_1$ and $a_2$ [4]. Annihilation terms, if used to bridge the discrepancy between theory and experiment, require large form factors, particularly for $D \to \bar{K}^0 + \eta/\eta'$ and $D^0 \to \bar{K}^{*0} + \eta$ decays [4]. Further, factorization also fails to relate $D_s^+ \to \eta/\eta' + \pi^+ / \rho^+$ decays with semileptonic decays $D_s^+ \to \eta/\eta' + e^+ \nu$ [4,5] consistently.

Recently, there has been a growing interest in studying nonfactorizable terms for weak hadronic decays of charm and bottom mesons [6]. In an earlier work [7], we have searched for a systematics in the nonfactorizable contributions for various decays of $D^0$ and $D^+$ mesons involving isospin 1/2 and 3/2 final states. We observe that the nonfactorizable isospin 1/2 and 3/2 amplitudes have nearly the same ratio for $D \to \bar{K} \pi / \bar{K} \rho / \bar{K}^* \pi / \bar{K} a_1 / \bar{K}^* \rho$ decay modes. In order to realize the full impact of isospin symmetry, and to relate $D_s^+$-decays with those of the nonstrange charm mesons, we generalize it to the SU(3)-flavor symmetry.

We analyze Cabibbo favored decays of $D^0, D^+$ and $D_s^+$ mesons to two pseudoscalar mesons. Determining the SU(3) reduced matrix elements from $D^+ \to \bar{K}^0 \pi^+$ and $D_s^+ \to \bar{K}^0 K^+$, we obtain a consistent fit for $D^0 \to \bar{K} + \pi / \eta / \eta'$ and $D_s^+ \to \pi + \eta / \eta'$ decays.
We start with the effective weak Hamiltonian

\[ H_w = \tilde{G}_F [c_1 (\bar{u}d)(\bar{s}c) + c_2 (\bar{s}d)(\bar{u}c)], \tag{1} \]

where \( \tilde{G}_F = \frac{g_F}{\sqrt{2}} V_{ud} V_{cs}^* \) and \( \bar{q}_1 q_2 \equiv \bar{q}_1 \gamma_\mu (1 - \gamma_5) q_2 \) represents color singlet \( V - A \) current and the QCD coefficients at the charm mass scale are

\[ c_1 = 1.26 \pm 0.04, \quad c_2 = -0.51 \pm 0.05. \tag{2} \]

Separating the factorizable and nonfactorizable parts, the matrix element of the operator \((\bar{u}d)(\bar{s}c)\) in eq. (1) between initial and final states can be written as

\[ <P_1 P_2 | (\bar{u}d)(\bar{s}c)|D> = <P_1 |(\bar{u}d)|0> <P_2 |(\bar{s}c)|D> + <P_1 P_2 |(\bar{u}d)(\bar{s}c)|D>_{nonfac}. \tag{3} \]

Using the Fierz identity

\[ (\bar{u}d)(\bar{s}c) = \frac{1}{N_c} (\bar{s}d)(\bar{u}c) + \frac{1}{2} \sum_{a=1}^{8} (\bar{s}\lambda^a d)(\bar{u}\lambda^a c), \tag{4} \]

where \( \bar{q}_1 \lambda^a q_2 \equiv \bar{q}_1 \gamma_\mu (1 - \gamma_5) \lambda^a q_2 \) represents color octet current, the nonfactorizable part of the matrix element in eq.(3) can be expanded as

\[ <P_1 P_2 |(\bar{u}d)(\bar{s}c)|D>_{nonfac} = \frac{1}{N_c} <P_2 |(\bar{s}d)|0> <P_1 |(\bar{u}c)|D> + \frac{1}{2} <P_1 P_2 |\sum_{a=1}^{8} (\bar{s}\lambda^a d)(\bar{u}\lambda^a c)|D>_{nonfac} + \frac{1}{N_c} <P_1 P_2 |(\bar{s}d)(\bar{u}c)|D>_{nonfac}. \tag{5} \]

Performing a similar treatment to the other operator \((\bar{s}d)(\bar{u}c)\) in eq.(1), the decay amplitude becomes

\[ <P_1 P_2 |H_w|D> = \tilde{G}_F [a_1 <P_1 |(\bar{u}d)|0> <P_2 |(\bar{s}c)|D> + a_2 <P_2 |(\bar{s}d)|0> <P_1 |(\bar{u}c)|D> + c_2 ( <P_1 P_2 |H^8_w|D> + <P_1 P_2 |H^1_w|D>)_{nonfac} \]
\[ + c_1 (\langle P_1 P_2 | \tilde{H}_w^8 | D \rangle + \langle P_1 P_2 | \tilde{H}_w^1 | D \rangle_{\text{nonfac}}), \]  

where

\[ a_{1,2} = c_{1,2} + \frac{c_{2,1}}{N_c}, \]

\[ H^8_w = \frac{1}{2} \sum_{a=1}^{8} (\bar{s} \lambda^a d)(\bar{u} \lambda^a c), \quad \tilde{H}^8_w = \frac{1}{2} \sum_{a=1}^{8} (\bar{u} \lambda^a d)(\bar{s} \lambda^a c); \]

\[ H^1_w = \frac{1}{N_c}(\bar{s} d)(\bar{u} c), \quad \tilde{H}^1_w = \frac{1}{N_c}(\bar{u} d)(\bar{s} c). \]

Thus nonfactorizable effects arise through the Hamiltonian made up of color-octet currents \( H^8_w \) and \( \tilde{H}^8_w \) and also of color singlet currents \( H^1_w \) and \( \tilde{H}^1_w \).

Matrix elements of the first and the second terms in eq. (6) can be calculated using the factorization scheme [1]. These are given in Table I. So long as one restricts to the color singlet intermediate states, remaining terms in eq.(6) are ignored and one usually treats \( a_1 \) and \( a_2 \) as input parameters in place of using \( N_c = 3 \) in reality. It is generally believed [1, 8] that the \( D \to \bar{K}\pi \) decays favour \( N_c \to \infty \) limit, i.e.,

\[ a_1 \approx 1.26, \quad a_2 \approx -0.51. \]

However, it has been shown that this does not explain all the decay modes of charm mesons [4,5]. 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 in \( D \to PV \) mode, measured branching ratios for \( D^0 \to \bar{K}^*\eta \), \( D_s^+ \to \eta/\eta' + \rho^+ \), are 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 [4,5]. 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 [1]. 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 [4] due to the conserved vector (CVC) nature of isovector current ($\bar{u}d$). Therefore, it is desirable to investigate nonfactorizable contributions more seriously.

It is well known that nonfactorizable terms cannot be determined unambiguously without making some assumptions [6] as these involve nonperturbative effects arising due to soft-gluon exchange. We thus employ SU(3)-flavor-symmetry [9] to handle these matrix elements. In the SU(3) framework, the weak Hamiltonians $H^8_w, \tilde{H}^8_w, H^1_w$ and $\tilde{H}^1_w$ for Cabibbo-enhanced mode behave like $H^2_{13}$ component of 6* and 15 representations of the SU(3). Since $H^8_w$ and $\tilde{H}^8_w$ transform into each other under interchange of $u$ and $s$ quarks, which forms V-spin subgroup of the SU(3), we assume the reduced amplitudes to follow

\[ < P_1 P_2 || H^8_w || D > = < P_1 P_2 || \tilde{H}^8_w || D >. \]  

(10)

Then, the matrix elements $< P_1 P_2 | H^8_w | D >$ can be considered as weak spurion $D \to P + P$ scattering process, whose general structure can be written as

\[ < P_1 P_2 | H^8_w | D > = b_1 (P^m_a P^c_m P^b_h) H^a_{[b,c]} + d_1 (P^m_a P^c_m P^b_h) H^a_{(b,c)} \]

\[ + e_1 (P^b_m P^c_a P^m_h) H^a_{(b,c)} + f_1 (P^m_a P^b_m P^c_h) H^a_{(b,c)} \]  

(11)

where $P^a$ denotes triplet of D-mesons $P^a \equiv (D^0, D^+, D^+_s)$ and $P^a_b$ denotes 3 $\otimes$ 3 matrix of uncharmed pseudoscalar mesons,

\[ P^a_b = \begin{pmatrix} P^1_1 & \pi^+ & K^+ \\ \pi^- & P^2_2 & K^0 \\ K^- & \bar{K}^0 & P^3_3 \end{pmatrix} \]

(12)

with

\[ P^1_1 = \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_0}{\sqrt{3}}, \]

\[ P^2_2 = \frac{\pi^+}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_0}{\sqrt{3}}, \]

\[ P^3_3 = \frac{K^+}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_0}{\sqrt{3}}. \]
\[ P_2^2 = -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_0}{\sqrt{3}}, \]
\[ P_3^3 = -\frac{2\eta_8}{\sqrt{6}} + \frac{\eta_0}{\sqrt{3}}. \]

Particle data group [10] defines the physical \( \eta - \eta' \) mixing as

\[ \eta = \eta_8 \cos \phi - \eta_0 \sin \phi, \]
\[ \eta' = \eta_8 \sin \phi + \eta_0 \cos \phi, \]

where \( \phi = -10^0 \) and \( \phi = -19^0 \) follow from the quadratic mass formula and the two photon decays widths respectively [10]. We employ the following basis [4]

\[ \eta = \frac{1}{\sqrt{2}} (u\bar{u} + d\bar{d}) \sin \theta - (s\bar{s}) \cos \theta, \]
\[ \eta' = \frac{1}{\sqrt{2}} (u\bar{u} + d\bar{d}) \cos \theta + (s\bar{s}) \sin \theta, \]

where \( \theta \) is given by

\[ \theta = \theta_{\text{ideal}} - \phi. \]

Performing a similar treatment for \( H_w^1 \) and \( \tilde{H}_w^1 \), i.e.

\[ <P_1P_2|\tilde{H}_w^1|D> = <P_1P_2|H_w^1|D>, \]

the matrix elements \( <P_1P_2|H_w^1|D> \) are obtained from

\[ <P_1P_2|H_w^1|D> = b_2(P_a^m P_c^m P_b^b)H_{[b,c]}^a + d_2(P_a^m P_c^m P_b^b)H_{(b,c)}^a \]
\[ + e_2(P_m^b P_a^c P_m^m)H_{(b,c)}^a + f_2(P_m^b P_a^c P_m^m)H_{(b,c)}^a \]

Since the C.G. coefficients appearing in the eqs. (11) and (17) are the same, the unknown reduced amplitudes get combined as

\[ b = b_1 + b_2, \quad d = d_1 + d_2, \quad e = e_1 + e_2, \quad f = f_1 + f_2, \]

when the matrix elements are substituted in eq.(6).
There exists a straight correspondence between the terms appearing in (11) and (17) and various quark level processes. The first two terms, involving the coefficients $b'$s and $d'$s, represent W-annihilation or W-exchange diagrams. Notice that unlike factorizable W-exchange or W-annihilation diagrams, these diagrams are not suppressed on the basis of the helicity arguments due to the involvement of gluons. The third term, having coefficient $e'$s, represents spectator quark like diagram where the uncharmed quark in the parent D-meson flows into one of the final state mesons. The last term is like a hair-pin diagram, where $q\bar{q}$ generated in the process hadronizes to one of the final state mesons. Thus obtained nonfactorizable contributions to various $D \to PP$ decays are given in Table II.

Now we proceed to determine the SU(3) reduced amplitudes $b, d, e, f$. First, we calculate the factorizable contributions to various decays using $N_c = 3$, which yields

$$a_1 = 1.09, \quad a_2 = -0.09$$

(19)

For the form factors, we use

$$F_0^{DK}(0) = 0.76, \quad F_0^{D\pi}(0) = 0.83,$$

(20)

as guided by the semileptonic decays [8, 12], and

$$F_0^{D\eta}(0) = 0.68, \quad F_0^{D\eta'}(0) = 0.65,$$

$$F_0^{D_s\eta}(0) = 0.72, \quad F_0^{D_s\eta'}(0) = 0.70,$$

(21)

from the BSW model [1]. Numerical values of the factorizable amplitudes are given in col (iii) of Table I.

$D \to K\pi$ decays involve elastic final state interactions (FSI) whereas the remaining decays are not affected by them. As a result, the isospin amplitudes...
1/2 and 3/2 appearing in $D \to \bar{K}\pi$ decays develop different phases;

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

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

$$A(D^+ \to \bar{K}^0\pi^+) = \sqrt{3}A_{3/2}e^{i\delta_{3/2}}. \quad (22)$$

which yield the following phase independent [7,11] expressions:

$$|A(D^0 \to K^-\pi^+)|^2 + |A(D^0 \to \bar{K}^0\pi^0)|^2 = |A_{1/2}|^2 + |A_{3/2}|^2;$$

$$|A(D^+ \to \bar{K}^0\pi^+)|^2 = 3|A_{3/2}|^2. \quad (23)$$

These relations allow one to work without the phases. Writing the total decay amplitude as sum of factorizable and nonfactorizable parts

$$A(D \to \bar{K}\pi) = A^f(D \to \bar{K}\pi) + A^{nf}(D \to \bar{K}\pi), \quad (24)$$

we obtain

$$A^{nf}_{1/2} = \frac{1}{\sqrt{3}}\{\sqrt{2}A^{nf}(D^0 \to K^-\pi^+) - A^{nf}(D^0 \to \bar{K}^0\pi^0)\}, \quad (25)$$

$$A^{nf}_{3/2} = \frac{1}{\sqrt{3}}\{A^{nf}(D^0 \to K^-\pi^+) + \sqrt{2}A^{nf}(D^0 \to \bar{K}^0\pi^0)\},$$

$$= \frac{1}{\sqrt{3}}\{A^{nf}(D^+ \to \bar{K}^0\pi^+)\}. \quad (26)$$

The last relation (26) leads to the following constraint:

$$\frac{b + d}{e} = \frac{c_1 + c_2}{c_2 - c_1} = -0.424 \pm 0.042. \quad (27)$$

Experimental value $B(D^+ \to \bar{K}^0\pi^+) = 2.74 \pm 0.29\%$ yields, up to a scale factor $\tilde{G}_F$,

$$e = -0.094 \pm 0.027 \text{GeV}^3. \quad (28)$$

This in turn predicts sum of the branching ratios of $D^0 \to \bar{K}\pi$ decay modes,

$$B(D^0 \to K^-\pi^+) + B(D^0 \to \bar{K}^0\pi^0) = 6.30 \pm 0.67\% \quad (6.06 \pm 0.30\% \text{ Expt.}) \quad (29)$$
in good agreement with experiment. Using the experimental value of $B(D_s^+ \to \bar{K}^0 K^+) = 3.5 \pm 0.7\%$, we find (in GeV$^3$)

\begin{align*}
b &= +0.080 \pm 0.026, \\
d &= -0.040 \pm 0.026.
\end{align*}

Note that the unknown reduced amplitude $f$ appears only in decays involving $\eta$ and $\eta'$ in the final state. We find that experimental values of these decay rates require (in GeV$^3$):

\begin{align*}
f &= -0.145 \pm 0.077 \quad \text{for} \quad D^0 \to \bar{K}^0 \eta, \\
f &= -0.115 \pm 0.012 \quad \text{for} \quad D^0 \to \bar{K}^0 \eta', \\
f &= -0.104 \pm 0.163 \quad \text{for} \quad D_s^+ \to \eta \pi^+, \\
f &= -0.081 \pm 0.073 \quad \text{for} \quad D_s^+ \to \eta' \pi^+.
\end{align*}

In Tables III, we calculate branching ratios for all the four $\eta, \eta'$ emitting decay modes for different choice of $f$, for $\phi = -10^o$ and $-19^o$. It is clear that for $f = -0.12$ and $\phi = -10^o$, all the branching ratios match well with experiment. For the sake of comparison with factorizable terms, nonfactorizable contributions to various modes for $f = -0.12$ are given in column (iii) of the Table II. Color-suppressed decays obviously require large nonfactorizable contributions.

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Table I

| Process | Amplitude | $\phi = -10^0$ | $\phi = -19^0$ |
|---------|-----------|---------------|---------------|
| $D^+ \rightarrow K^0 \pi^+$ | $a_1 f_{21}(m_D^2 - m_K^2)F_{0}^{DK}(m_{\pi}^2)$ $+ a_2 f_{21}(m_D^2 - m_{\pi}^2)F_{0}^{D\pi}(m_{K}^2)$ | +0.311 | +0.311 |
| $D^0 \rightarrow K^- \pi^+$ | $a_1 f_{21}(m_D^2 - m_K^2)F_{0}^{DK}(m_{\pi}^2)$ | +0.354 | +0.354 |
| $D^0 \rightarrow \bar{K}^0 \pi^0$ | $\frac{1}{\sqrt{2}} a_2 f_{K}(m_D^2 - m_{\pi}^2)F_{0}^{D\pi}(m_{K}^2)$ | -0.030 | -0.030 |
| $D^0 \rightarrow \bar{K}^0 \eta$ | $\frac{1}{\sqrt{2}} a_2 \sin \theta f_{K}(m_D^2 - m_{\eta}^2)F_{0}^{D\eta}(m_{K}^2)$ | -0.016 | -0.019 |
| $D^0 \rightarrow \bar{K}^0 \eta'$ | $\frac{1}{\sqrt{2}} a_2 \cos \theta f_{K}(m_D^2 - m_{\eta'}^2)F_{0}^{D\eta'}(m_{K}^2)$ | -0.013 | -0.010 |
| $D_s^+ \rightarrow \bar{K}^0 K^+$ | $a_2 f_{K}(m_D^2 - m_K^2)F_{0}^{DK}(m_{K}^2)$ | -0.035 | -0.035 |
| $D_s^+ \rightarrow \pi^0 \pi^+$ | $0$ | $0$ | $0$ |
| $D_s^+ \rightarrow \eta \pi^+$ | $a_1 \cos \theta f_{\pi}(m_D^2 - m_{\eta}^2)F_{0}^{D\eta}(m_{\pi}^2)$ | -0.261 | -0.216 |
| $D_s^+ \rightarrow \eta' \pi^+$ | $a_1 \sin \theta f_{\pi}(m_D^2 - m_{\eta'}^2)F_{0}^{D\eta'}(m_{\pi}^2)$ | +0.213 | +0.243 |

Table II

| Process | Amplitude | $\phi = -10^0$ | $\phi = -19^0$ |
|---------|-----------|---------------|---------------|
| $D^+ \rightarrow \bar{K}^0 \pi^+$ | $2(c_1 + c_2) e$ | -0.141 | -0.141 |
| $D^0 \rightarrow K^- \pi^+$ | $c_2 (b + d + e)$ | +0.028 | +0.028 |
| $D^0 \rightarrow \bar{K}^0 \pi^0$ | $\frac{1}{\sqrt{2}} c_1 (-b - d + e)$ | -0.119 | -0.119 |
| $D^0 \rightarrow \bar{K}^0 \eta$ | $c_1 \left[ \frac{\sin \theta}{\sqrt{2}} (b + d + e + 2f) - \cos \theta (b + d + f) \right] + \cos \theta (b + d + f) + \sin \theta (b + d + f)$ | -0.256 | -0.235 |
| $D^0 \rightarrow \bar{K}^0 \eta'$ | $c_1 \left[ \frac{\cos \theta}{\sqrt{2}} (b + d + e + 2f) + \sin \theta (b + d + f) \right] - \sin \theta (b + d + f) + \cos \theta (b + d + f)$ | -0.268 | -0.268 |
| $D_s^+ \rightarrow \bar{K}^0 K^+$ | $c_1 (-b + d + e)$ | 0 | 0 |
| $D_s^+ \rightarrow \pi^0 \pi^+$ | $0$ | 0 | 0 |
| $D_s^+ \rightarrow \eta \pi^+$ | $c_2 \left[ \sqrt{2} \sin \theta (b + d + f) - \cos \theta (e + f) \right] + \cos \theta (e + f) + \sin \theta (e + f)$ | +0.046 | +0.076 |
| $D_s^+ \rightarrow \eta' \pi^+$ | $c_2 \left[ \sqrt{2} \cos \theta (b + d + f) + \sin \theta (e + f) \right] - \sin \theta (e + f) + \cos \theta (e + f)$ | +0.199 | +0.189 |
Table III

Branching (%) of $\eta/\eta'$ emitting decays including nonfactorization terms

| Decay            | $\phi = -10^\circ$ | $\phi = -19^\circ$ | Expt.         |
|------------------|---------------------|---------------------|---------------|
|                  | $f = -0.10$, -0.12, -0.14 | $f = -0.10$, -0.12, -0.14 |               |
| $D^0 \to \eta K^0$ | 0.53 0.59 0.66       | 0.86 1.02 1.19       | 0.68±0.11     |
| $D^0 \to \eta' K^0$ | 1.28 1.81 2.43      | 1.04 1.51 2.06       | 1.66±0.29     |
| $D_s^+ \to \eta\pi^+$ | 1.93 1.87 1.82     | 0.86 0.80 0.73       | 1.9±0.4       |
| $D_s^+ \to \eta'\pi^+$ | 5.17 5.64 6.13    | 5.73 6.22 6.72       | 4.7±1.4       |
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