Searching a systematics for nonfactorizable contributions to hadronic decays of D^0 and D^+ mesons

R. C. Verma
Centre for Advanced Study in Physics, Department of Physics,
Panjab University, Chandigarh -160014 **India**

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Abstract

We investigate nonfactorizable contributions to charm meson decays in $D \to \bar{K}\pi/\ \bar{K}\rho\ /\bar{K}^*\pi\ /\ \bar{K}a_1\ /\ \bar{K}^*\rho$ modes. Obtaining the contributions from spectator-quark diagrams for $N_c = 3$, we determine nonfactorizable isospin 1/2 and 3/2 amplitudes required to explain the data for these modes. We observe that ratio of these amplitudes seem to follow a universal value.

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1 Introduction

As precise data [1] on some of the weak hadronic and semileptonic decays of charm mesons is available, it has now become possible to test the validity of the factorization model. Employing isospin formalism, in a strong interaction -phase independent manner, recently, Kamal and Pham [2] has, shown that the naive factorization model fails to account for isospin amplitudes ($A_{1/2}$ and $A_{3/2}$) for $D \rightarrow \bar{K}\pi$, $D \rightarrow \bar{K}\rho$, and $D \rightarrow \bar{K}^*\pi$ modes. It was observed that for $D \rightarrow$ PP (P $\equiv$ pseudoscalar meson), whereas the factorization assumption accounts for branching ratio of $D^+ \rightarrow \bar{K}^0\pi^+$, it overestimates $A_{1/2}$ for D^0 -decays. For $D \rightarrow PV$ ($V \equiv$ vector mesons) modes, it overestimates $A_{3/2}$ for $D \rightarrow \bar{K}\rho$, decays and underestimates $A_{3/2}$ for $D \rightarrow K^*\pi$ decays. One of the ways to remove the discrepancy could be the inelastic final state interaction [2,3] which can feed $\bar{K}^*\pi$ channel at the expense of $\bar{K}^*\rho$ channel. An alternative may be the nonfactorizable contributions [4] arising through the soft gluon exchange, which are generally ignored in the factorization model. Recently, there has been a growing interest [5,6] in exploring such contributions in the hadronic decays of charmed and bottom mesons. Major cause of the concern has been that $N_c \rightarrow \infty$ limit, which is considered to be supported by D-meson phenomenology, fails when carried over to B-meson decays [7]. Therefore, a reinvestigation of the charm decays is called for.

We, in this paper, study the nonfactorizable contributions to $D \to \bar{K}\pi$, $D \to \bar{K}\rho$, $D \to \bar{K}^*\pi$, $D \to \bar{K}a_1$ and $D \to \bar{K}^*\rho$ decays. Employing the isospin formalism in the phase-independent manner, we determine these contributions in respective 1/2 and 3/2 -isospin amplitudes from experiment and search for a systematics in the amplitudes.

In section 2, weak Hamiltonian is discussed. In next sections, we study these decay modes one by one. Summary and discussion are given in the last section.

2 Weak Hamiltonian

The effective weak Hamiltonian for Cabibbo-angle-enhanced decays of the charm hadrons is given by

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

where $\tilde{G}_F = \frac{G_F}{\sqrt{2}} V_{ud} V_{cs}^*$ and $\bar{q}_1 q_2$ represents color singlet V - A current

$$\bar{q}_1 q_2 \equiv \bar{q}_1 \gamma_\mu (1 - \gamma_5) q_2,$$

and the QCD coefficients at the charm mass scale are [8]

$$c_1 = 1.26 \pm 0.04, \qquad c_2 = -0.51 \pm 0.05. \tag{2}$$

Due to the Fierz transformation of the product of two Dirac currents in (1) in N_c-color space, the Hamiltonian takes the following form

$$\begin{aligned} H_w^{CF} &= \tilde{G}_F[a_1(\bar{u}d)(\bar{s}c) + c_2 H_w^8], \\ H_w^{CS} &= \tilde{G}_F[a_2(\bar{s}d)(\bar{u}c) + c_1 \tilde{H}_w^8], \end{aligned} \tag{3}$$

for color favored (CF) and color suppressed (CS) decay amplitudes, and

$$\begin{aligned} a_{1,2} = c_{1,2} &+ \frac{c_{2,1}}{N_c}, \\ H_w^8 &= \frac{1}{2}\sum_{a=1}^{8}(\bar{u}\lambda^a d)(\bar{s}\lambda^a c), \\ \tilde{H}_w^8 &= \frac{1}{2}\sum_{a=1}^{8}(\bar{s}\lambda^a d)(\bar{u}\lambda^a c), \end{aligned} \tag{4}$$

where color-octet currents

$$\bar{q}_1\lambda^a q_2 \equiv \bar{q}_1\gamma_\mu(1-\gamma_5)\lambda^a q_2$$

involve the Gell-Mann matrices, λ^a for color. Matrix element of the first terms of (3) can be calculated using the factorization scheme [9]. In this scheme, nonfactorizable contributions from the second terms in (3) are ignored, so long one restricts to color singlet intermediate states. Due to the neglect of these terms, one usually treats a_1 and a_2 as input parameters instead of using $N_c = 3$ in reality. Empirically $D \to \bar{K}\pi$ data seem to favor $N_c \to \infty$ limit [9] which is justified with the hope that the nonperturbative effects arising due to the soft gluon exchange between the colored-octet current in (4), relative to the factorizable amplitudes arising from the color singlet current in (3), are of the order $\frac{1}{N_c}$ in the large N_c-limit. In fact, in some of the QCD calculations [10], it has been claimed that for $B \rightarrow D\pi$, and $D \rightarrow \bar{K}\pi$ as well, nonfactorizable terms tend to cancel the contributions from $\frac{1}{N_c}$ terms in the first terms of (3). However, B-mesons don't favor this result empirically. Further, this does not guarantee that such cancellations would persist for other decay modes too. In other words, a_1 and a_2 are not universal parameters, these are decay dependent if one is to stick to the factorization model. An alternative is to take $N_c = 3$ and investigate nonfactorizable contributions more seriously. This is what we do in the following sections employing the flavor-isospin framework.

3 $D \rightarrow \bar{K}\pi$ decays

In terms of the isospin amplitudes and final state interactions phases [2],

$$\begin{aligned} A(D^0 \rightarrow K^-\pi^+) &= \frac{1}{\sqrt{3}}[A_{3/2}e^{i\delta_{3/2}} + \sqrt{2}A_{1/2}e^{i\delta_{1/2}}], \\ A(D^0 \rightarrow \bar{K}^0\pi^0) &= \frac{1}{\sqrt{3}}[\sqrt{2}A_{3/2}e^{i\delta_{3/2}} - A_{1/2}e^{i\delta_{1/2}}], \\ A(D^+ \rightarrow \bar{K}^0\pi^+) &= \sqrt{3}A_{3/2}e^{i\delta_{3/2}}. \end{aligned} \tag{5}$$

These lead to the following phase independent quantities:

$$|A(D^0 \to K^-\pi^+)|^2 + |A(D^0 \to \bar{K}^0\pi^0)|^2 = |A_{1/2}|^2 + |A_{3/2}|^2,$$
$$|A(D^+ \to \bar{K}^0\pi^+)|^2 = 3|A_{3/2}|^2. \quad (6)$$

With Experimental [1] values:

$$B(D^0 \to K^-\pi^+) = (4.01 \pm 0.14)\%,$$
$$B(D^0 \to \bar{K}^0\pi^0) = (2.05 \pm 0.26)\%,$$
$$B(D^+ \to \bar{K}^0\pi^+) = (2.74 \pm 0.29)\%,$$

and D-meson lifetimes

$$\tau_{D^0} = 0.415\ ps,$$
$$\tau_{D^+} = 1.057\ ps,$$

decay rate formula

$$\Gamma(D \to PP) = |\tilde{G}_F|^2 \frac{p}{8\pi m_D^2} |A(D \to PP)|^2$$

yields

$$|A_{1/2}|_{exp} = 0.387 \pm 0.011\ GeV^3,$$
$$|A_{3/2}|_{exp} = 0.097 \pm 0.005\ GeV^3 \quad (7)$$

Since the relations (6) are independent of the final state interaction phases, one might well evaluate them without the phases and determine nonfactorizable contributions using experimental values. We separate the factorizable and nonfactorizable parts of the decay amplitude as

$$A(D \to \bar{K}\pi) = A^f(D \to \bar{K}\pi) + A^{nf}(D \to \bar{K}\pi). \tag{8}$$

Using the factorization scheme, factorizable part of the decay amplitudes can be written [9] as

$$\begin{aligned}
A^f(D^0 \to K^-\pi^+) &= a_1 f_\pi (m_D^2 - m_K^2) F_0^{DK}(m_\pi^2), \\
&= 0.351\ GeV^3, \\
A^f(D^0 \to \bar{K}^0\pi^0) &= \frac{1}{\sqrt{2}} a_2 f_K (m_D^2 - m_\pi^2) F_0^{D\pi}(m_K^2), \\
&= -0.030\ GeV^3, \\
A^f(D^+ \to \bar{K}^0\pi^+) &= a_1 f_\pi (m_D^2 - m_K^2) F_0^{DK}(m_\pi^2) \\
&\quad + a_2 f_K (m_D^2 - m_\pi^2) F_0^{D\pi}(m_K^2), \\
&= 0.309\ GeV^3
\end{aligned} \tag{9}$$

Numerical input for these terms is taken as

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

$$f_\pi = 0.132\ GeV, \qquad f_K = 0.161\ GeV,$$

and

$$F_0^{DK}(0) = 0.76, \qquad F_0^{D\pi}(0) = 0.83 \tag{10}$$

from Ref [11]. Using isospin C. G. Coefficients, nonfactorizable part of the decay amplitudes can be expressed as scattering amplitudes for spurion + $D \to \bar{K} + \pi$ process:

$$
\begin{aligned}
A^{nf}(D^0 \to K^-\pi^+) &= \frac{1}{3}c_2(<\bar{K}\pi||H_w^8||D>_{3/2} + 2 <\bar{K}\pi||H_w^8||D>_{1/2}), \\
A^{nf}(D^0 \to \bar{K}^0\pi^0) &= \frac{\sqrt{2}}{3}c_1(<\bar{K}\pi||\tilde{H}_w^8||D>_{3/2} - <\bar{K}\pi||\tilde{H}_w^8||D>_{1/2}), \\
A^{nf}(D^+ \to \bar{K}^0\pi^+) &= c_2 <\bar{K}\pi||\tilde{H}_w^8||D>_{3/2} + c_1 <\bar{K}\pi||\bar{H}_w^8||D>_{3/2}
\end{aligned}
\tag{11}
$$

In order to reduce the number of unknown reduced amplitude, we assume the following

$$
<\bar{K}\pi||H_w^8||D>_{1/2} = <\bar{K}\pi||\bar{H}_w^8||D>_{1/2}, \tag{12}
$$

$$
<\bar{K}\pi||H_w^8||D>_{3/2} = <\bar{K}\pi||\tilde{H}_w^8||D>_{3/2}, \tag{13}
$$

as both H_w^8 and $\tilde{H}_w^8$ behave like $|1,1>$ component of an isovector spurion. In fact, H_w^8 and $\tilde{H}_w^8$ transform into each other under the interchange of u and s quarks. Thus, in the limit of flavor SU(3) symmetry, the constraints given in eqs. (12) and (13) become reliable. From (5), we can write

$$
\begin{aligned}
A_{1/2}^{nf}(D \to \bar{K}\pi) &= \frac{1}{\sqrt{3}}\{\sqrt{2}A^{nf}(D^0 \to K^-\pi^+) - A^{nf}(D^0 \to \bar{K}^0\pi^0)\} \\
A_{3/2}^{nf}(D \to \bar{K}\pi) &= \frac{1}{\sqrt{3}}\{A^{nf}(D^0 \to K^-\pi^+) + \sqrt{2}A^{nf}(D^0 \to \bar{K}^0\pi^0)\} \\
&= \frac{1}{\sqrt{3}}\{A^{nf}(D^+ \to \bar{K}^0\pi^+)\}
\end{aligned}
\tag{14}
$$

Relations (12) and (13) then lead to the following prediction:

$$\frac{A^{nf}_{1/2}(D \to \bar{K}\pi)}{A^{nf}_{3/2}(D \to \bar{K}\pi)} = \frac{c_1^2 + 2c_2^2}{\sqrt{2}(c_2^2 - c_1^2)} = -1.123 \pm 0.112. \tag{15}$$

Experimentally, the nonfactorized isospin amplitudes is determined as

$$A^{nf}_{1/2} = +0.082 \pm 0.032 \, GeV^3,$$
$$A^{nf}_{3/2} = -0.081 \pm 0.023 \, GeV^3, \tag{16}$$

from $A_{1/2} = 0.387 \pm 0.011 \, GeV^3$, and $A_{3/2} = 0.097 \pm 0.005 \, GeV^3$ given in (7). This yields

$$\frac{A^{nf}_{1/2}}{A^{nf}_{3/2}} = -1.011 \pm 0.250, \tag{17}$$

in good agreement with theoretical expectation (15). Such isospin formalism can easily be extended to $D \to \bar{K}\rho$, $D \to \bar{K}^*\pi$, and $D \to \bar{K}a_1$ decays. Since the isospin structure of these decay modes is exactly the same as given in (5) and (11), the same value -1.123 ± 0.112 would follow for the respective ratio of the nonfactorizable isospin amplitudes $A^{nf}_{1/2}$ and $A^{nf}_{3/2}$ in each of these cases. In the following, we determine these amplitudes from experimental values of the branching ratios of these decay modes, and compare their ratio with theoretically expected one.

4 $D \to \bar{K}\rho$ decays

We begin with the definition of the decay amplitude $A(D \to PV)$ through the decay rate formula,

$$\Gamma(D \to PV) = |\tilde{G}_F|^2 \frac{p^3}{2\pi} |A(D \to PV)|^2.$$

$A(D \to PV)$ has the dimension of GeV and is obtained by writing down the standard decay amplitude and removing from it a factor $2m_V(\epsilon^*.P_D)\tilde{G}_F$, where m_V is the vector meson mass and ϵ^* is its polarization vector, P_D is the D-meson four momentum. Factorizable parts of the decay amplitudes $A(D \to \bar{K}\rho)$ can be written as

$$\begin{aligned}
A^f(D^0 \to K^- \rho^+) &= a_1 f_\rho F_1^{DK}(m_\rho^2), \\
&= 0.203\, GeV, \\
A^f(D^0 \to \bar{K}^0 \rho^0) &= \frac{1}{\sqrt{2}} a_2 f_K A_0^{D\rho}(m_K^2), \\
&= -0.0074\, GeV, \\
A^f(D^+ \to \bar{K}^0 \rho^+) &= a_1 f_\rho F_1^{DK}(m_\rho^2) + a_2 f_K A_0^{D\rho}(m_K^2), \\
&= 0.192\, GeV.
\end{aligned}$$

Here, we use

$$\begin{aligned}
f_\rho &= 0.212\, GeV, \\
F_1^{DK}(0) &= F_0^{DK}(0) = 0.76,
\end{aligned}$$

from (10) and

$$A_0^{D\rho}(0) \quad = \quad 0.669$$

is taken from the BSW model [9]. Numerical values given above are calculated by extrapolating $F_1^{DK}(q^2)$ and $A_0^{D\rho}(q^2)$ using a monopole formulae with pole mass 2.11 GeV (D_s^* pole) and 1.865 GeV (D-pole) respectivelly. Experimental [1] values of branching ratios:

$$B(D^0 \to K^- \rho^+) \quad = \quad (10.4 \pm 1.3)\%,$$

$$B(D^0 \to \bar{K}^0 \rho^0) \quad = \quad (1.10 \pm 0.18)\%,$$

$$B(D^+ \to \bar{K}^0 \rho^+) \quad = \quad (6.6 \pm 2.5)\%,$$

yield the total isospin-amplitudes:

$$|A_{1/2}|_{exp} \quad = \quad 0.235 \pm 0.014\, GeV,$$

$$|A_{3/2}|_{exp} \quad = \quad 0.067 \pm 0.013\, GeV \qquad (19)$$

Writing $A^{nf}(D \to \bar{K}\rho)$ analogues to (11) - (13), inturn leads to

$$A_{1/2}^{nf}(D \to \bar{K}\rho) \quad = \quad +0.065 \pm 0.015\, GeV,$$

$$A_{3/2}^{nf}(D \to \bar{K}\rho) \quad = \quad -0.041 \pm 0.013\, GeV, \qquad (20)$$

with positive signs chosen for both $A_{1/2}$ and $A_{3/2}$ in (19). The ratio

$$\frac{A_{1/2}^{nf}(D \to \bar{K}\rho)}{A_{3/2}^{nf}(D \to \bar{K}\rho)} \quad = \quad -1.481 \pm 0.582, \qquad (21)$$

is consistent with (15) within errors.

5 $D \to \bar{K}^*\pi$ decays

Repeating the same procedure used for $D \to \bar{K}\rho$ decays, here the factorizable amplitudes are given by

$$\begin{aligned}
A^f(D^0 \to \bar{K}^{*-}\pi^+) &= a_1 f_\pi A_0^{DK^*}(m_\pi^2), \\
&= 0.100\, GeV, \\
A^f(D^0 \to \bar{K}^{*0}\pi^0) &= \frac{1}{\sqrt{2}} a_2 f_{K^*} F_1^{D\pi}(m_{K^*}^2), \\
&= -0.015\, GeV, \\
A^f(D^+ \to \bar{K}^{*0}\pi^+) &= a_1 f_\pi A_0^{DK^*}(m_\pi^2) + a_2 f_{K^*} F_1^{D\pi}(m_{K^*}^2), \\
&= 0.080\, GeV.
\end{aligned} \tag{22}$$

Here, we use

$$F_1^{D\pi}(0) = F_0^{D\pi}(0) = 0.83, \quad f_{K^*} = 0.221\, GeV,$$

and $A_0^{DK^*}(0)$ is determined from the relation

$$A_0^{DK^*}(0) = A_3^{DK^*}(0) = \frac{1}{2m_{K^*}}\{(m_D + m_{K^*})A_1^{DK^*}(0) - (m_D - m_{K^*})A_2^{DK^*}(0)\}. \tag{23}$$

Semileptonic $D \to K^* e\nu$ data [11] yields

$$A_1^{DK^*}(0) = 0.61 \pm 0.05, \qquad A_2^{DK^*}(0) = 0.45 \pm 0.09.$$

Which gives

$$A_0^{DK^*}(0) = 0.70 \pm 0.09.$$

Experimental [1] values of branching ratios:

$$\begin{aligned} B(D^0 \to K^{*-}\pi^+) &= (4.9 \pm 0.6)\%, \\ B(D^0 \to \bar{K}^{*0}\pi^0) &= (3.0 \pm 0.4)\%, \\ B(D^+ \to \bar{K}^{*0}\pi^+) &= (2.2 \pm 0.4)\%, \end{aligned} \tag{24}$$

yield the total isospin-amplitude:

$$\begin{aligned} |A_{1/2}|_{exp} &= 0.186 \pm 0.009\ GeV, \\ |A_{3/2}|_{exp} &= -0.036 \pm 0.003\ GeV \end{aligned} \tag{25}$$

Choosing positive and negative sign for the $A_{1/2}$ and $A_{3/2}$ terms respectively, we find

$$\begin{aligned} A^{nf}_{1/2}(D \to \bar{K}^*\pi) &= +0.096 \pm 0.009\ GeV, \\ A^{nf}_{3/2}(D \to \bar{K}^*\pi) &= -0.082 \pm 0.008\ GeV, \end{aligned} \tag{26}$$

leading to

$$\frac{A^{nf}_{1/2}(D \to \bar{K}^*\pi)}{A^{nf}_{3/2}(D \to \bar{K}^*\pi)} = -1.171 \pm 0.158, \tag{27}$$

for monopole like extrapolation of $F_1^{D\pi}(q^2)$. This ratio is consistent with theoretical expectation (15) within errors. Also note that

$$|A^{nf}_{1/2}(D \to K^*\pi)| > |A^{nf}_{1/2}(D \to \bar{K}\rho)|, \tag{28}$$

consistent with theoretical expectations that final state having low momentum is likely to be affected more by the soft gluon exchange effects.

6 $D \to \bar{K} a_1$ decays

$D \to \bar{K} a_1$ decays can also be treated in a manner similar to that used for $D \to \bar{K}\rho$ modes; due to the similarity in their Lorentz structure. For $D \to \bar{K} a_1$ decays, factorized amplitudes are (upto the scale factor $\frac{\tilde{G}_F}{\sqrt{2}}(\epsilon^*.p)2m_{a_1}$):

$$\begin{aligned}
A^f(D^0 \to K^- a_1^+) &= a_1 f_{a_1} F_1^{DK}(m_{a_1}^2), \\
&= 0.285\, GeV, \\
A^f(D^0 \to \bar{K}^0 a_1^0) &= \frac{1}{\sqrt{2}} a_2 f_K V_0^{Da_1}(m_K^2), \\
&= 0, \\
A^f(D^+ \to \bar{K}^0 a_1^+) &= a_1 f_{a_1} F_1^{DK}(m_{a_1}^2) + a_2 f_K V_0^{Da_1}(m_K^2), \\
&= 0.285\, GeV. \qquad (29)
\end{aligned}$$

Here, we use

$$f_{a_1} = 0.221\, GeV,$$

and take

$$V_0^{DK}(0) \approx 0$$

due to the orthogonality of the D and a_1 spin-wave functions. The experimental values [1,12] for branching ratios:

$$\begin{aligned}
B(D^0 \to K^- a_1^+) &= (7.9 \pm 1.2)\%, \\
B(D^0 \to \bar{K}^0 a_1^0) &= (0.43 \pm 0.99)\%,
\end{aligned}$$

$$B(D^+ \to \bar{K}^0 a_1^+) \quad = \quad (8.1 \pm 1.7)\%, \tag{30}$$

when used for analogues of relations (6), yield total isospin amplitudes:

$$\begin{aligned} |A_{1/2}|_{exp} &= (0.582^{+0.066}_{-0.055})\ GeV, \\ |A_{3/2}|_{exp} &= (0.338^{+0.077}_{-0.064})\ GeV. \end{aligned} \tag{31}$$

Here we have neglected the small effects arising due to the width of a_1 meson [13]. Choosing positive and negative signs for $A_{1/2}$ and $A_{3/2}$ respectively in (31), we find

$$\begin{aligned} A^{nf}_{1/2}(D \to \bar{K} a_1) &= +0.349 \pm 0.060\ GeV, \\ A^{nf}_{3/2}(D \to \bar{K} a_1) &= -0.221 \pm 0.023\ GeV, \end{aligned} \tag{32}$$

leading to

$$\frac{A^{nf}_{1/2}(D \to \bar{K} a_1)}{A^{nf}_{3/2}(D \to \bar{K} a_1)} \quad = \quad -0.910 \pm 0.165, \tag{33}$$

which is consistent with theoretical expectation (15). Also note that

$$|A^{nf}_{1/2}(D \to PA)| > |A^{nf}_{1/2}(D \to PV)|, \tag{34}$$

again in accordance with theoretical expectation, as in the $D \to \bar{K} a_1$ decays, final state momentum is smaller than that in $D \to PV$ mode.

Thus, we observe that in all the decay modes, considered so far, $D \to \bar{K}\pi$, $D \to \bar{K}\rho$, $D \to \bar{K}^*\pi$, $D \to \bar{K} a_1$, the nonfactorizable isospin amplitude $A^{nf}_{1/2}$ not only have the same sign for these decays, but also bears the same ratio, with in the experimental errors, with $A^{nf}_{3/2}$ amplitude, i.e.,

$$\frac{A^{nf}_{1/2}(D \to \bar{K}a_1)}{A^{nf}_{3/2}(D \to \bar{K}a_1)} \approx \frac{A^{nf}_{1/2}(D \to \bar{K}^*\pi)}{A^{nf}_{3/2}(D \to \bar{K}^*\pi)} \approx \frac{A^{nf}_{1/2}(D \to \bar{K}\rho)}{A^{nf}_{3/2}(D \to \bar{K}\rho)}$$

$$\approx \frac{A^{nf}_{1/2}(D \to \bar{K}\pi)}{A^{nf}_{3/2}(D \to \bar{K}\pi)}. \qquad (35)$$

Further, we notice that the nonfactorized amplitudes show an increasing pattern with decreasing momenta available to the final state particles, i.e.,

$$|A^{nf}(D \to \bar{K}a_1)| \quad > \quad |A^{nf}(D \to \bar{K}^*\pi)| \quad > \quad |A^{nf}(D \to \bar{K}\rho)| \qquad (36)$$

This behaviour is understandable, since low momentum states are likely to be affected more through the exchange of soft gluons and can acquire larger nonfactorizable contributions. If one takes value of the ratio of $A^{nf}_{1/2}$ and $A^{nf}_{3/2}$ in (35) to be -1.123 as obtained in (15), and determine $A^{nf}_{3/2}$ from D^+ decay, one can predict the sum of the branching ratios of D^0 -meson decays in the corresponding mode. Following this procedure, we predict

$$B(D^0 \to K^-\pi^+) + B(D^0 \to \bar{K}^0\pi^0) \quad = 6.30 \pm 0.67\%$$

$$= (6.06 \pm 0.30\% \quad Expt),$$

$$
\begin{aligned}
B(D^0 \to K^-\rho^+) + B(D^0 \to \bar{K}^0\rho^0) \quad &= 10.17 \pm 3.85\% \\
&= (11.50 \pm 1.31\% \quad Expt), \\
B(D^0 \to \bar{K}^{*-}\pi^+) + B(D^0 \to \bar{K}^{*0}\pi^0) &= 6.29 \pm 1.20\% \\
&= (7.9 \pm 2.2\%, \quad Expt) \\
B(D^0 \to K^-a_1^+) + B(D^0 \to \bar{K}^0 a_1^0) \quad &= 10.67 \pm 2.24\% \\
&= (8.33 \pm 1.56\% \quad Expt).
\end{aligned} \tag{37}
$$

All theoretical values match well with experiment. Infact, these relations can be expressed in a general form as

$$
B_{-+} + B_{00} = \frac{\tau_{D^0}}{3\tau_{D^+}} B_{0+}[1 + \{\alpha + \frac{(\sqrt{2}-\alpha)A_{-+}^{fac} - (1+\sqrt{2}\alpha)A_{00}^{fac}}{A_{0+}}\}^2], \tag{38}
$$

with $\alpha \equiv A_{1/2}^{nf}/A_{3/2}^{nf}$, where subscript $-+$, 00, $0+$ denote the charge states of strange and nonstrange mesons emitted in each case. A_{-+}^{fac} and A_{00}^{fac} denote the factorized amplitudes of D^0 decays. A_{0+} is obtained from the D^+ -decay branching ratio B_{0+} ,

$$
A_{0+} \quad = \quad \sqrt{\frac{B_{0+}}{\tau_{D^+} \times (Kinematic factors)}}
$$

7 $D \to \bar{K}^*\rho$ decays

In general, $D \to VV$ modes involve Lorentz structure for three partial waves: S, P, D waves. Therefore, one may expect nonfactorizable contributions to be present in all of them. Experimentally their partial wave structure has been analysed [1,12]. Data indicates that S-wave is dominant in the $D^+ \to \bar{K}^{*0}\rho^+$ decays. For $D^0 \to \bar{K}^{*0}\rho^0$ mode, D-wave component seems to exist which interfere destructively with S-wave. P-wave component of these two modes is negligible. However, for $D^0 \to K^-\rho^+$, data is not clean enough to separate these partial waves, though P-wave component is found to be small here also. Looking at the experimental status, we introduce the nonfactorizable term in S-wave, and relate only the S-wave decay branching ratios. Then $D \to VV$ decays also share the same isospin structure as given in (5) and (11). The factorizable decay amplitudes (in S-wave) are given by (upto the scale factor $\tilde{G}_F \epsilon_1^*.\epsilon_2^*$)

$$\begin{aligned} A^f(D^0 \to \bar{K}^{*-}\rho^+) &= a_1(m_D + m_{K^*})m_\rho f_\rho A_1^{DK^*}(m_\rho^2), \\ &= 0.330\, GeV^3, \\ A^f(D^0 \to \bar{K}^{*0}\rho^0) &= \frac{1}{\sqrt{2}} a_2(m_D + m_\rho) f_{K^*} m_{K^*} A_1^{D\rho}(m_{K^*}^2), \\ &= -0.030\, GeV^3, \\ A^f(D^+ \to \bar{K}^{*0}\rho^+) &= a_1(m_D + m_{K^*}) f_\rho m_{K^*} A_1^{DK^*}(m_\rho^2) \\ &+ a_2(m_D + m_\rho) f_{K*} A_1^{D\rho}(m_{K^*}^2), \\ &= 0.289\, GeV. \end{aligned} \tag{39}$$

Numerical values given above are determined using the form factors $A_1^{DK^*}(0)$ already given and $A_1^{D\rho}(0) = 0.775$ as determined in the BSW model [9].

The decay rate formula [14] reduces to

$$\Gamma(D \to VV) = |\tilde{G}_F|^2 \frac{p}{8\pi m_D^2}(2+(\frac{m_D^2 - m_{V_1}^2 - m_{V_2}^2}{2m_{V_1}m_{V_2}})^2)|A(D \to VV)|^2, \tag{40}$$

for S-wave. Writing

$$A(D \to VV) \quad = \quad A^f(D \to VV) + A^{nf}(D \to VV),$$

we obtain

$$A_{3/2}^{nf}(D \to VV) \quad = \quad +0.114^{+0.021}_{-0.040}, \tag{41}$$

from experimental value of S-wave branching ratio $B_S(D^+ \to \bar{K}^{*0}\rho^+) = (1.7 \pm 1.6)\%$. Extending the apparent universality (35) of the ratio to the $D \to VV$ decay modes,

$$\frac{A_{1/2}^{nf}(D \to VV)}{A_{3/2}^{nf}(D \to VV)} \quad = \quad -1.123 \pm 0.112.$$

We calculate the sum of S-wave branching ratios of $D^0 \to K^{*-}\rho^+$ and $D^0 \to \bar{K}^{*0}\rho^0$ decays,

$$B_S(D^0 \to K^{*-}\rho^+) + B_S(D^0 \to \bar{K}^{*0}\rho^0) \quad = \quad (14.0^{+2.9}_{-1.3})\%. \tag{42}$$

Subtracting the experimentally known value of

$$B_S(D^0 \to \bar{K}^{*0}\rho^0) \quad = \quad (3.0 \pm 0.6)\%,$$

we predict

$$B_S(D^0 \to K^{*-}\rho^0) \quad = \quad (11.0^{+3.5}_{-1.9})\%.$$

It is interesting to remark this value satisfy the following relation:

$$\frac{B_{total}(D^0 \to K^{*-}\rho^+)}{B_S(D^0 \to K^{*-}\rho^+)} \quad = \quad \frac{B_{total}(D^0 \to \bar{K}^{*0}\rho^0)}{B_S(D^0 \to \bar{K}^{*0}\rho^0)},$$

$$0.54 \pm 0.25 \quad = \quad 0.53 \pm 0.17,$$

indicating the destructive interference of S- and D-wave partial waves for $D^0 \to \bar{K}^{*-}\rho^+$ decay also.

8 Summary and Discussion

In this work, we have investigated the nonfactorizable contributions to various decays of D^0 and D^+ mesons $\bar{K}\pi/\bar{K}\rho/\bar{K}^*\pi/\bar{K}a_1/\bar{K}^*\rho$ states involving isospin 1/2 and 3/2 final states. In our analysis, we take the real value of $N_c = 3$. Since the nonfactorizable contributions, being nonperturbative, are difficult to be calculated, we determine their amplitudes in these isospin states required by the experiment. We have ignored the annihilation contributions here as these don't contribute to D^+ decays and for D^0 -decays these are suppressed due to the small value of $a_2(\approx -0.09 \pm 0.05)$. We observe that not only the nonfactorizable isospin amplitudes $A^{nf}_{1/2}$ have the sign for the modes considered, but also bears the same ratio with $A^{nf}_{3/2}$ within experimental errors. The ratio can be understood on the basis of V-spin symmetry, under which nonfactorizable parts H_w^8 and $\tilde{H}_w^8$ of the weak Hamiltonian transform into each other. Further the nonfactorizable contributions also show an increasing pattern with decreasing momentum available to the final state particles emitted in these decays. Extending the apparent universality of the ratio $A_{1/2}^{nf}/A_{3/2}^{nf}$ to $D \to VV$ modes, we predict the S-wave branching ratio for $B_S(D^0 \to K^{*-}\rho^+) = (11.0^{+3.5}_{-1.9})\%$, indicating destructive interference between S-wave and D-wave components for this decay.

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