HADRONIC DECAYS OF CHARMED D^+, D^0 MESONS AND THEIR LIFETIMES

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General discussions on the non-leptonic decays of D^+ and D^0 are presented from the isospin point of view. We point out that the two recent data on τ^{D^+}/τ^{D^0} and $D^0 \to \bar{K}^0\pi^0$ are strongly correlated. We show that the annihilation mechanism for $D^0 \to K\pi$ is not at all suppressed as is usually believed. A mechanism is suggested in which the light quark in the D meson plays a more selective role than its usual spectator one. This mechanism and the annihilation one provide a natural explanation for the recent data without requiring any revision of our usual understanding of weak and strong interactions.

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Very recent data [1, 2] on the decays of charmed D mesons, if confirmed, contradict strongly theoretical expectations [3–5] based on the assumption that the light quark in the D mesons acts simply as a spectator, leaving its charmed partner responsible for the decay mechanism. For the convenience of the discussion, in the following we will call this point of view the "standard" mechanism.

Let us mention the two new measurements that motivate this work. The first one [1] concerning the inclusive semi-leptonic decay of D mesons, that gives

$$B^+_{SL} \equiv \frac{\Gamma(D^+ \to e^+\nu_e+\text{hadrons})}{\Gamma^{D^+}_{tot}} = (23\pm6)\%,$$

$$B^0_{SL} \equiv \frac{\Gamma(D^0 \to e^+\nu_e+\text{hadrons})}{\Gamma^{D^0}_{tot}} < 4\%. \quad (1)$$

For the semi-leptonic decay modes $\Delta C = \Delta S = 1$, the hadronic weak current is of the form $\bar{s}\gamma_\mu(1-\gamma_5)c$ obeying the $\Delta I = 0$ rule, then by isospin symmetry one would expect

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that semi-leptonic rates of D^+ and D^0 are equal. This point does not seem to raise any objections. If so, then the lifetimes of D^+ and D^0 are very different [6], their ratio becomes

$$\frac{\tau^{D^+}}{\tau^{D^0}} = \frac{\Gamma_{tot}^{D^0}}{\Gamma_{tot}^{D^+}} > 5.8 \pm 1.5 \tag{2}$$

while standard expection predicts lifetimes of all charmed particles to be the same [3–5].

The next new data [2] concerns the two body decay mode $D^0 \to \bar{K}^0\pi^0$, its branching ratio is found to be very similar to those of two other modes $D^0 \to K^-\pi^+$ and $D^+ \to \bar{K}^0\pi^+$ measured repeatedly some time ago by different groups [7]. Their respective branching ratios are:

$$B(D^0 \to \bar{K}^0\pi^0) = (2 \pm 0.9)\%,$$

$$B(D^0 \to K^-\pi^+) = (2.8 \pm 0.6)\%,$$

$$B(D^+ \to \bar{K}^0\pi^+) = (2.1 \pm 0.4)\%. \tag{3}$$

The ratio $\varrho = \dfrac{B(D^0 \to K^-\pi^+)}{B(D^0 \to \bar{K}^0\pi^0)}$ in "standard" mechanism is predicted to be 18 in the free quark limit [3–5]. When renormalization QCD effects due to hard gluons exchange are incorporated, the ratio ϱ becomes [3, 4] as large as 40.

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Facing such spectacular disagreement with standard theoretical expectations, a prudent attitude of wait and see further experimental confirmations is usually adopted. We point out that this attitude might be too prudent and that the data are probably correct. Our argument is quite simple and based only on the isospin consideration. For the Cabibbo favored decays $D \to \bar{K}\pi$ that we are discussing, the effective Hamiltonian (see Eq. (7) below) $H_{eff} \sim (\bar{s}c)(\bar{u}d) \pm (\bar{u}c)(\bar{s}d)$ acts like a spurion with both $I = I_z = 1$.

Then the decay amplitudes $D \to \bar{K}\pi$ can be decomposed as follows

$$A(D^0 \to K^-\pi^+) = \tfrac{1}{3}a_{3/2} + \tfrac{2}{3}a_{1/2},$$

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

$$A(D^+ \to \bar{K}^0\pi^+) = a_{3/2}, \tag{4}$$

where the amplitudes $a_{3/2}$ and $a_{1/2}$ denote respectively those with isospin $\frac{3}{2}$ and $\frac{1}{2}$ of the final state $\bar{K}\pi$ system. From (4) one deduces [8]:

$$\sqrt{2}\, A(D^0 \to \bar{K}^0\pi^0) + A(D^0 \to K^-\pi^+) = A(D^+ \to \bar{K}^0\pi^+). \tag{5}$$

A similar relation between three body decay amplitudes $D \to K\pi\pi$ can also be obtained. As a consequence of the $\Delta I = 1$ rule, the relation (5) is general and must be satisfied by all detailed mechanisms of the D disintegrations. Translated into measurable quantities, the relations (5) is now written under the constraint:

$$\frac{\sqrt{B(D^0 \to K^-\pi^+)}-\sqrt{2B(D^0 \to \bar{K}^0\pi^0)}}{\sqrt{B(D^+ \to \bar{K}^0\pi^+)}} \leqslant \sqrt{\frac{\tau^{D^0}}{\tau^{D^+}}}$$

$$\leqslant \frac{\sqrt{B(D^0 \to K^-\pi^+)}+\sqrt{2B(D^0 \to \bar{K}^0\pi^0)}}{\sqrt{B(D^+ \to \bar{K}^0\pi^+)}}. \quad (6)$$

We observe that the data as given by (2) and (3) are perfectly consistent with the inequalities (6). Taking for sure the two "old" measurements $B(D^0 \to K^-\pi^+)$ and $B(D^+ \to \bar{K}^0\pi^+)$, let us ask whether or not the two new data $\tau^{D^+}/\tau^{D^0} > 5.8 \pm 1.5$ $\frac{B(D^0 \to K^-\pi^+)}{B(D^0 \to \bar{K}^0\pi^0)} = 1.4 \pm 0.7$ might be "wrong", compared respectively to the "standard" theoretical values 1 and 18 (or 40).

Let us denote the first measurement τ^{D^+}/τ^{D^0} as (A) and the second one $\frac{B(D^0 \to K^-\pi^+)}{B(D^0 \to \bar{K}^0\pi^0)}$ as (B). Then by examination of the bounds of inequality (6), the following statement is found to be true: If (A) is right then (B) *must* be right or if (B) is wrong then (A) *must* be wrong. In a more quantitative form, our statement is: if $\tau^{D^+}/\tau^{D^0} > 5.8 \pm 1.5$ is correct, then $\varrho \equiv \frac{B(D^0 \to K^-\pi^+)}{B(D^0 \to \bar{K}^0\pi^0)}$ is smaller than 2.4 and certainly cannot be as big as theoretical estimates (18 or 40). Conversely, if the data (B) is wrong (the ratio ϱ is not 1.4 ± 0.7 but is 18 or 40), then τ^{D^+}/τ^{D^0} is very near to 1 and cannot be greater than 5.8 ± 1.5.

Emulsion experiments (through some events) also indicate that lifetimes of D^+ and D^0 are very dissimilar [9]. From these considerations, we conclude that both the new measurements are very likely correct, and the problem is now on the theoretical side, why they fail so badly to account for the data?

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Two opposite points of view have been recently proposed to accommodate them. Either the decay mechanism of D^0 is "standard" and only that of D^+ must be changed [10], or vice versa [11].

Before examining the two extreme models, let us remind the effective Hamiltonian relevant for the Cabibbo favored non leptonic decay of charmed particles [5, 12]

$$H_{eff} = \frac{G}{\sqrt{2}} \cos\theta_{ud} \cos\tilde{\theta}_{cs} \left\{ \frac{f_+ + f_-}{2} (\bar{s}c)(\bar{u}d) + \frac{f_+ - f_-}{2} (\bar{u}c)(\bar{s}d) \right\}, \quad (7)$$

where γ matrices and color index summations are understood in the four quark fields c, s, u, d. The coefficients f_+ and f_- embody the QCD hard gluons effects ($f_+ = f_- = 1$

in the limit of free quarks)

$$f_- = (f_+)^{-2} = \left[\frac{\alpha(m_c)}{\alpha(M_W)}\right]^d$$

and

$$\alpha(m) = \frac{\pi d}{\ln \frac{m^2}{\Lambda^2}} = \frac{12\pi}{(33-2F)\ln \frac{m^2}{\Lambda^2}}. \tag{8}$$

With $F = 6$, $\Lambda = 0.5$ GeV, $m_c = 1.5$ GeV, $M_W = 84$ GeV, one gets $f_- = 2.41$ and $f_+ = 0.64$.

In models where the decay mechanism of D^0 is "standard", one must have [3, 4], because of the relation (5), for each decay mechanism of D^+

$$\frac{\Gamma(D^0 \to K^-\pi^+)}{\Gamma(D^+ \to \bar{K}^0\pi^+)} = \frac{\tau^{D^+}}{\tau^{D^0}} \frac{B(D^0 \to K^-\pi^+)}{B(D^+ \to \bar{K}^0\pi^+)} = \left(\frac{2f_+ + f_-}{4f_+}\right)^2. \tag{9}$$

Putting experimental values on the left-hand side one sees that this relation (9) can only be satisfied if $f_-/f_+ > 10$. In such a model, [3, 4] the ratio $\varrho = 2\left(\frac{2f_+ + f_-}{2f_+ - f_-}\right)^2$ is strictly greater than two, for $f_-/f_+ = 10$ the ratio $\varrho = 4.5$ to be compared with the experimental value 1.4 ± 0.7. Moreover, in order to take into account the semi-leptonic branching ratio of D^0 as given by $(2+f_-^2+2f_+^2)^{-1}$ in the standard model [3], the absolute value of f_- must be taken as big as 5. Even with this price (both f_- and f_-/f_+ are quite large), the ratio ϱ obtained differs by 4 standard deviations with the data. For this reason, we believe that the decay mechanism of D^0 should be somehow modified. As for the second point of view in which the decay mechanism of D^+ is "normal", the difficulty is that one cannot explain why its semi-leptonic branching ratio can be bigger than 25% unless f_+ and f_- are now considerably reduced, which is very unlikely.

This brief survey of the two opposite models suggests that Nature is somehow between.

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Now we come to a more model dependent "explanation" of the two experimental puzzles. For the exclusive channel $D \to K\pi$, it is straightforward to derive different decay amplitudes from the effective Hamiltonian, Eq. (7):

$$A^0_{-+} \equiv A(D^0 \to K^-\pi^+) = \frac{f_+ + f_-}{2} f_\pi[(m_D^2 - m_K^2)g_+^{D\to K}(m_\pi^2) + m_\pi^2 g_-^{D\to K}(m_\pi^2)]$$

$$- \frac{f_+ - f_-}{2} f_D[(m_K^2 - m_\pi^2)g_+^{K\to\pi}(m_D^2) + m_D^2 g_-^{K\to\pi}(m_D^2)], \tag{10}$$

$$A^0_{00} \equiv A(D^0 \to \overline{K}^0\pi^0) = \frac{f_+ - f_-}{2} f_K \frac{1}{\sqrt{2}} [(m_D^2 - m_\pi^2) g_+^{D\to\pi}(m_K^2) + m_K^2 g_-^{D\to\pi}(m_K^2)]$$

$$+ \frac{f_+ - f_-}{2} f_D \frac{1}{\sqrt{2}} [(m_K^2 - m_\pi^2) g_+^{K\to\pi}(m_D^2) + m_D^2 g_-^{K\to\pi}(m_D^2)], \tag{11}$$

$$A^+_{0+} \equiv A(D^+ \to \overline{K}^0\pi^+) = \frac{f_+ + f_-}{2} f_\pi [(m_D^2 - m_K^2) g_+^{D\to K}(m_\pi^2) + m_\pi^2 g_-^{D\to K}(m_\pi^2)]$$

$$+ \frac{f_+ - f_-}{2} f_K [(m_D^2 - m_\pi^2) g_+^{D\to\pi}(m_K^2) + m_K^2 g_-^{D\to\pi}(m_K^2)]. \tag{12}$$

The decay width is given by:

$$\Gamma(D \to K\pi) = \frac{G^2 \cos^2\theta_{ud} \cos^2\theta_{cs}}{32\pi m_D} \frac{\lambda^{1/2}(m_D^2, m_K^2, m_\pi^2)}{m_D^2} |A|^2, \tag{13}$$

where $\lambda(a, b, c)$ is the Källén symbol $a^2+b^2+c^2-2ab-2ac-2bc$. The coupling constants f_π, f_K, f_D are those entering in the pure leptonic decays of π, K, D mesons respectively. The form factors $g_+^{a\to b}$, $g_-^{a\to b}$ enter in the semi-leptonic decay $a \to b + l + \nu_l$. We remark the opposite sign of the Clebsch-Gordan coefficients of terms proportional to f_D in the amplitudes $D^0 \to K^-\pi^+$ and $D^0 \to \overline{K}^0\pi^0$.

Although starting from the same effective Hamiltonian (Eq. (7)), our amplitudes $A(D \to K\pi)$ are different from those of the standard model by two main aspects:

(*i*) the annihilation terms proportional to f_D in Eqs (10), (11) are absent in the standard model;

(*ii*) The Fierz rearrangement is not operated here, thus we have always $\frac{f_+ \pm f_-}{2}$ coefficients instead of the usual $\frac{2f_+ \pm f_-}{3}$ one. Physically, the Fierz transformation is necessary only when the light antiquark in D mesons acts as spectator, because it can couple indifferently with the s and u quarks that come from the decay $c \to sud$ to form different hadronic final states. Here in our model, the light antiquark is no longer spectator, it couples selectively with the s quark with the weight $\frac{f_+ + f_-}{2}$ and the u quark with the weight $\frac{f_+ - f_-}{2}$, as given by the effective Hamiltonian (Eq. (7)). In this model, the light antiquark of the D mesons follows always its charmed c partner, letting the two currents $(u\bar{d})$ and $(s\bar{d})$ play spectator role.

An important remark here is in order. For the total inclusive channel $D^0 \to$ hadrons, the annihilation mechanism is believed to be negligible compared to the standard one. This point seems correct, because the total hadronic amplitude in the annihilation mechanism is governed by the amplitude $D^0 \to s\bar{d}$, its rate is calculated to be $\Gamma(D^0 \to \text{hadrons}) = 3\times 24\pi^2 \frac{f_D^2 m_s^2}{m_c^4}\Gamma_{st} \simeq 10^{-1}\left(\frac{f_D}{f_\pi}\right)^2 \Gamma_{st}$ where $\Gamma_{st} = \Gamma_\mu \left(\frac{m_c}{m_\mu}\right)^5 h\left(\frac{m_s^2}{m_c^2}\right)$ with $h(\varepsilon) = 1 -8\varepsilon+8\varepsilon^3-\varepsilon^4-12\varepsilon^2 \ln \varepsilon$. The factor 3 comes from color. This rate is to be compared with the one calculated in the standard mechanism as given by $(2f_+^2+f_-^2)\Gamma_{st}$.

However, for the two body decay mode $D^0 \to \bar{K}\pi$, the annihilation is not negligible at all. When comparing the annihilation contribution (terms proportional to f_D) in Eqs. (10), (11) with the c quark decay one (terms proportional to f_π or f_K), we observe that they are comparable. Indeed, firstly the form-factor $g_-^{a\to b}$ which is suppressed in the semi--leptonic decays by the lepton mass, contributes with full strength in the hadronic decays. Secondly $g_-^{K\to\pi}(m_D^2)$ is enhanced by the $\kappa(1450)$ pole, where κ is the $K\pi$ S-wave $J^P = 0^+$ resonance. Since the κ mass is not far from the D mass, the enhancement is by a factor two. Thirdly from $K_{\mu 3}$ experiments [13], one knows that the ξ parameter defined as $g_-^{K\to\pi}(0)/g_+^{K\to\pi}(0)$ is about 1/3. All these points show that $g_-^{K\to\pi}(m_D^2)$ is comparable with $g_+^{D\to K}(m_\pi^2)$ or $g_+^{D\to\pi}(m_K^2)$, and the annihilation terms are not negligible in $D^0 \to \bar{K}\pi$.

Writing:

$$A_{-+}^0 = \frac{f_+ + f_-}{2}\alpha - \frac{f_+ - f_-}{2}\beta, \tag{14}$$

$$A_{00}^0 = \frac{f_+ - f_-}{2\sqrt{2}}(\beta+\gamma), \tag{15}$$

$$A_{0+}^+ = \frac{f_+ + f_-}{2}\alpha + \frac{f_+ - f_-}{2}\gamma, \tag{16}$$

where (neglecting the pion mass):

$$\begin{aligned}
\alpha &= f_\pi(m_D^2 - m_K^2) g_+^{D\to K}(m_\pi^2)\cos\theta_{ud}\cos\tilde{\theta}_{cs},\\
\beta &= f_D[m_K^2 g_+^{K\to\pi}(m_D^2) + m_D^2 g_-^{K\to\pi}(m_D^2)]\cos\theta_{ud}\cos\tilde{\theta}_{cs},\\
\gamma &= f_K[m_D^2 g_+^{D\to\pi}(m_K^2) + m_K^2 g_-^{D\to\pi}(m_K^2)]\cos\theta_{ud}\cos\tilde{\theta}_{cs},
\end{aligned} \tag{17}$$

we observe that, without forcing the f_-, f_+ values, there exists a domain of α, β, γ which allows to satisfy the new data

$$\frac{B(D^0 \to K^-\pi^+)}{B(D^0 \to \bar{K}^0\pi^0)} = 1.4\pm 0.7 \quad \text{and} \quad \frac{\Gamma(D^0 \to K^-\pi^+)}{\Gamma(D^+ \to \bar{K}^0\pi^+)} > 7.74\pm 2.70.$$

For example with $\beta/\alpha \simeq 0.75$ and $\gamma/\alpha \simeq 1.25$ the data can be accommodated.

In the SU(4) symmetry limit where $\alpha = \beta = \gamma$, the amplitude $A(D^0 \to K^-\pi^+)$ is proportional to f_- while that of $A(D^+ \to \bar{K}^0\pi^+)$ is proportional to f_+. We will come back to this observation later.

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We now discuss the total inclusive decay D → hadrons. For the D^+ case, we adhere to the point of view of Guberina et al. [10]: the non leptonic decay of D^+ is highly suppressed because of the strong color clustering. In this model, the non leptonic rates of D^+ is $\Gamma(D^+ \to \text{hadrons}) = 4f_+^2\Gamma_{st}$. We remark that in the D^+ decay, the hadronic final states, whatever in details they are, have a pure isospin 3/2. The mode $D^+ \to \bar{K}^0\pi^+$ is only one example. This is so because D^+ has $I = I_z = 1/2$ and the Hamiltonian behaves like $I = I_z = 1$. This fact gives a hint that f_+ is associated with the $I = 3/2$ hadronic final state of D decay products, while f_- is somehow strongly associated with the $I = 1/2$ final state.

We then propose a heuristic argument that the non leptonic decay width of D^0 is $3f_-^2\Gamma_{st}$ which becomes $3\Gamma_{st}$ in the free quark limit as it should be. As noted before, it is interesting to observe that in the SU(4) symmetry limit, the decay width $\Gamma(D^0 \to K^-\pi^+)$ is proportional to f_-^2 while $\Gamma(D^+ \to \bar{K}^0\pi^+)$ is proportional to f_+^2. If this tendency is to be generalized for the total inclusive case, and because $\Gamma(D^+ \to \text{hadrons}) = 4f_+^2\Gamma_{st}$ in the Guberina et al. model, our Ansatz $\Gamma(D^0 \to \text{hadrons}) = 3f_-^2\Gamma_{st}$ seems to be natural. It should be emphasized here that we are unable to show why $\Gamma(D^0 \to \text{hadrons})$ is $3f_-^2\Gamma_{st}$. The proposition we made is simply a naive guess. Accepting this assumption, we have

$$B_{SL}^+ = \frac{1}{2+4f_+^2} = 27\%, \quad B_{SL}^0 = \frac{1}{2+3f_-^2} = 4.5\%,$$

in agreement with experimental data.

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We list some immediate consequences of the decay mechanism proposed here: the rate $\Gamma(D^0 \to K^-\pi^+)$ is similar to the semi-leptonic rate $\Gamma(D^0 \to K^-e^+\nu_e)$ as also obtained by Gavela et al. [14], but $\Gamma(D^+ \to \bar{K}^0\pi^+)$ is much smaller than $\Gamma(D^+ \to \bar{K}^0e^+\nu_e)$.

Predictions about three body decay modes $D \to K\pi\pi$ as well as on F^+ decays can also be made.

Concerning now the Cabibbo suppressed two body decay modes of D^+ and D^0, some interesting features emerge. Let us write down explicitly the different amplitudes:

$$A(D^+ \to \bar{K}^0K^+) = A(D^0 \to K^-K^+) = \sin\theta_{ud}\cos\tilde{\theta}_{cs}\frac{f_+ + f_-}{2}\alpha', \tag{18}$$

$$A(D^+ \to \pi^0\pi^+) = A(D^0 \to \pi^-\pi^+) = \cos\theta_{ud}\sin\tilde{\theta}_{cs}\frac{f_+ + f_-}{2}\beta', \tag{19}$$

where (the pion mass is neglected here):

$$\alpha' = f_K[(m_D^2 - m_K^2)g_+^{D\to K}(m_K^2) + m_K^2 g_-^{D\to K}(m_K^2)], \quad \beta' = f_\pi m_D^2 g_+^{D\to\pi}(m_\pi^2). \tag{20}$$

The relative enhancement of the $D^0 \to \bar{K}K$ mode against the $D^0 \to \pi\pi$ one, as observed experimentally [15], can be easily accommodated. The model proposed here predicts moreover the same enhancement for $D^+ \to \bar{K}K$ against $D^+ \to \pi\pi$.

Another point is worth mentioning [16]: for D^+ decay, the ratio Cabibbo suppressed/Cabibbo favored modes $\frac{B(D^+ \to \bar{K}K)}{B(D^+ \to \bar{K}\pi)}$ must be much larger than $\tan^2 \theta_{ud}$ (see Eq. (18) for the numerator and Eq. (16) for the denominator), while this is not the case for D^0.

We conclude that, without requiring any revision of our usual understanding of weak and strong interactions, new data can be accounted for, provided the light quark plays a more active role and the annihilation mechanism is kept.

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