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Yu.L.Kalinovsky,[1] W.Kallies, V.N.Pervushin,
N.A.Sarikov[2]

NONLEPTONIC DECAYS OF CHARMED MESONS $D \to 0^- 0^-$ AND MIXING ANGLES IN SU(4)

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[1] Gomel Polytechnical Institute, Gomel
[2] NPI AS Uz.SSR, Tashkent

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The experimental fact /1/ that for the Cabibbo-suppressed decays $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ we have $\Gamma(D^0 \to K^+K^-)/\Gamma(D^0 \to \pi^+\pi^-) > 1$ is a subject of the investigation of several theoretical models. The matter is that the standard theory $SU_3 \times SU_2 \times U_1$, in the spectator approximation, gives for the ratio $\lesssim 1$ /2/. To explain the observed pattern, certain phenomenological approaches have been proposed in which one includes such effects as the SU_3 breaking /3/, penguin diagrams /4/, right-handed currents /4/, final-state interactions /6,7/, soft gluons /8/.

At the same time, there is also another traditional approach to the Cabibbo-suppressed decays well describing the $\Delta I = 3/2$ transitions for the kaons, the phenomenological chiral Lagrangian method (PCLM) /9,11/. In this method, one takes the weak interaction Lagrangian in the Sakurai form /12/ with the chiral hadronic currents and the violation of the $\Delta I = 1/2$ rule is realized by the Oakes scheme /13/. Remind, the idea of Oakes is the rotation of both the currents and the SU_3 -chiral-symmetry breaking term around the $7th$ axis in SU_3 -space about the same Cabibbo angle, sin $\theta_c \approx m_\pi / m_K$.

The aim of the present paper is to extend this method to the Cabibbo-suppressed decays of charmed hadrons. An application of the method to the Cabibbo-favored decays is considered in refs. /13,15/. Specifically, to see how the approach does work in the case of Cabibbo-suppressed decays, we consider only the $D \to 0^- 0^-$ decays neglecting the final-state interaction effects (the form factors).

In the charmed case, besides the above rotation in SU_3 --subspace, an additional rotation around the $10th$ axis in SU_4 -space is possible*). It is natural to expect that the new angle is smaller than θ_c but additional rotation may appreciably affect the Cabibbo-suppressed decays, particularly, $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$.

Let us start with the weak nonleptonic interaction Lagrangian (when $\theta_c = 0$)

*) Other rotations are suppressed by the charge conservation law.

$$L_W = L_W\,(\Delta I=0) + L_W^{\Delta S}\,(\Delta I=\tfrac{1}{2}) + L_W^{\Delta C}\,(\Delta I=1). \qquad (1)$$

The first term

$$L_W\,(\Delta I=0) = \frac{G_F}{\sqrt{2}}\, J_\mu^{1+i2}\, J_\mu^{1-i2}.$$

Describes the $\Delta I = \Delta S = \Delta C = 0$ -transitions. Here G_F is the Fermi constant, $J_\mu^{a+ib} \equiv J_\mu^a + i J_\mu^b$ is the hadronic current associated with the chiral symmetry /10,11/

$$i\lambda_a J_\mu^a = \exp(i\xi)\,\partial_\mu \exp(-i\xi),$$

where $\xi = \lambda_i \varphi_i / F$, $F \approx$ 94 MeV, $\lambda_i \varphi_i$ is the 15-plet of pseudoscalar mesons. The second term describing the $\Delta I = 1/2$, $\Delta S = 1$, $\Delta C = 0$ -transitions is the Sakurai Lagrangian /12/,

$$L_W^{\Delta S}\,(\Delta I=\tfrac{1}{2}) = \sqrt{2}\,G_F\, d_{6ab}\, J_\mu^a J_\mu^b. \qquad (2)$$

For the Lagrangian of $\Delta I = \Delta S = \Delta C = 1$ -transitions we suppose the explicit 20-plet (or sextet) dominance /14-16/

$$L_W^{\Delta C}\,(\Delta I=1) = \frac{G_F}{\sqrt{2}}\left(J_\mu^{1-i2} J_\mu^{13-i14} - J_\mu^{6+i7} J_\mu^{9-i10} + h.c.\right). \qquad (3)$$

As the first step, we rotate the currents. The rotation of the currents around the 7th axis in SU_3- subspace about the angle θ_7 is defined by

$$\lambda_a J_\mu^a(\theta_7) = \exp(i\lambda_7\theta_7)(\lambda_a J_\mu^a)\exp(-i\lambda_7\theta_7).$$

Then for the $\Delta I = 3/2$, $\Delta S = 1$, $\Delta C = 0$ -transition from (1) we arrive at

$$L_W^{\Delta S}\,(\Delta I=\tfrac{3}{2}) = \frac{G_F}{\sqrt{2}}\,\epsilon\left(J_\mu^{1+i2} J_\mu^{4-i5} + h.c.\right)$$

satisfactorily describing the data on the Cabibbo-suppressed decays of kaons when $\theta_7 \approx \theta_c$, $\epsilon \equiv \cos\theta_c \sin\theta_c - 2\sin^2\theta_c$ = 0.113 is close to its experimental value /17/ 0.111±0.007.

The charmed part of the rotated Lagragian is given by

$$L_W^{\Delta C}(\theta_7) = \frac{G_F}{\sqrt{2}}\Big\{ c^2\left[J_\mu^{1-i2} J_\mu^{13-i14} - J_\mu^{6+i7} J_\mu^{9-i10}\right]$$
$$+\, cs\left[J_\mu^{1-i2} J_\mu^{11-i12} - J_\mu^{4-i5} J_\mu^{13-i14} + (J_\mu^3 - \sqrt{3}J_\mu^8) J_\mu^{9-i10}\right]$$
$$-\, s^2\left[J_\mu^{4-i5} J_\mu^{11-i12} - J_\mu^{6-i7} J_\mu^{9-i10}\right] + h.c.\Big\},$$

where $c \equiv \cos\theta_7$, $s \equiv \sin\theta_7$. Notice, this charmed part has the same structure as that of the effective unnormalized Lagrangian of the standard theory (for example, see ref. /7/, when $|a_1| = |a_2| = 1$). However, the Lagrangian $L_W^{\Delta C}(\theta_7)$ for the interesting ratio $\Gamma(D^0 \to K^+K^-)\,/\,\Gamma(D^0 \to \pi^+\pi^-)$ gives [*] 0.75 far from the experimental value, ~ 3.7 /1/.

Let us now turn to the additional rotation acting on the current as

$$\lambda_a J_\mu^a(\theta_7, \theta_{10}) = \exp(i\lambda_{10}\theta_{10})(\lambda_a J_\mu^a(\theta_7))\exp(-i\lambda_{10}\theta_{10}).$$

Then we have

$$L_W^{\Delta C}(\theta_7, \theta_{10}) = \frac{G_F}{\sqrt{2}}\Big[\xi_1 J_\mu^{1-i2} J_\mu^{13-i14} - \xi_2 J_\mu^{6+i7} J_\mu^{9-i10}$$
$$+\,\xi_3 J_\mu^{1-i2} J_\mu^{11-i12} - \xi_4 J_\mu^{4-i5} J_\mu^{13-i14} + \xi_5 (J_\mu^3 - \sqrt{3}J_\mu^8) J_\mu^{9-i10}$$
$$+\,\xi_6 J_\mu^{6-i7} J_\mu^{9-i10} - \xi_7 J_\mu^{4-i5} J_\mu^{11-i12} + h.c.\Big].$$

Here

$$\begin{aligned}
\xi_1 &\equiv \tilde{c}^2 c^2 + \tilde{c}\tilde{s}\,(cs - c^2 + s^2) + \tilde{s}^2 s^2 = 0.895\ (0.927) \qquad (4)\\
\xi_2 &\equiv \tilde{c}^2 c^2 + \tilde{c}\tilde{s}\,(c^2 - s^2) + \tilde{s}^2 s^2 = 0.968\ (0.927)\\
\xi_3 &\equiv \tilde{c}^2 cs - \tilde{c}\tilde{s}\,(c^2 + 2cs) - \tilde{s}^2 cs = 0.186\ (0.256)\\
\xi_4 &\equiv \tilde{c}^2 cs + \tilde{c}\tilde{s}\,(s^2 - 2cs) - \tilde{s}^2 cs = 0.236\ (0.256)
\end{aligned}$$

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[*] That result would be expected from the factorization approximation, but in ref. /7/ for some reason that ratio equals 1.4.

$$\xi_5 \equiv \tilde{c}^2 cs + 2\tilde{c}\tilde{s}cs - \tilde{s}^2 cs = 0.285 \quad (0.256)$$

$$\xi_6 \equiv \tilde{c}^2 s^2 - \tilde{c}\tilde{s}(c^2 - s^2) + \tilde{s}^2 c^2 = 0.032 \quad (0.073)$$

$$\xi_7 \equiv \tilde{c}^2 s^2 + \tilde{c}\tilde{s}(-cs + c^2 - s^2) + \tilde{s}^2 c^2 = 0.105 \quad (0.073)$$

$$\tilde{c} \equiv \cos\theta_{10}, \quad \tilde{s} \equiv \sin\theta_{10},$$

in the parentheses ξ_i is indicated when $\theta_{10} = 0$.

As for the Cabibbo angle, the requirement that the rotated currents must describe the semileptonic decays of hadrons leads to

$$\theta_c = \theta_7 - \theta_{10}. \tag{5}$$

As the second step, we define the angles through the mass ratios. The symmetry breaking mass term in the $(4,4^*) + (4^*, 4)$ – model has the $SU_3 \times SU_3$ -symmetry form [18]

$$L_{SB} = F^2 \left(c_0 S_0 + c_8 S_8 + c_{15} S_{15} \right). \tag{6}$$

This is the generalized GMOR model [19] . Here S_i are defined by

$$\sum_{i=0}^{15} \lambda_i s_i = Re \exp\left(i \lambda_K \frac{\varphi^K}{F} \right)$$

whereas the constants C_i are fixed from the physical masses of hadrons (see ref. [11]). In ref. [11] the further violation of the remaining symmetry was realized by the rotation of (6) around the 7th axis in SU_3-subspace, the same scheme as that of Oakes.

Let us rotate (6) around the 10th axis too. The additional mass relations thus obtained lead to the definitions:

$$\sin\theta_7 = \left(m_{D^+}^2 - m_{D^0}^2 + m_{\pi^+}^2 \right)^{\frac{1}{2}} / \sqrt{2}\, m_{K^0} = 0.27 \tag{7}$$

$$\sin\theta_{10} = \left(m_{K^+}^2 - m_{K^0}^2 + m_{\pi^+}^2 \right)^{\frac{1}{2}} / \sqrt{2}\, m_{D^0} = 0.05.$$

Then

$$\sin\theta_c = \sin(\theta_7 - \theta_{10}) = 0.22$$

is slightly different from the earlier value $\sin\theta_7 = m_\pi / m_K = 0.28$.

With these angles in the Lagrangian (4) we calculated the partial width ratios for the decays $D \to O^- O^-$ which are listed in the

table [x)] I. As one sees from the table, the rotation around the 10th axis about the angle θ_{10} indeed increases the ratio $\Gamma(D^0 \to K^+K^-)/\Gamma(D^0 \to \pi^+\pi^-)$ from 0.75 (θ_{10} =0) to 1.2, due to $\xi_4^2/\xi_3^2 = 1.6$. For other available D^0 decay data [1], $\Gamma(D^0 \to K^+K^-)/\Gamma(D^0 \to K^-\pi^+) = (11.3 \pm 3)\%$ and $\Gamma(D^0 \to \pi^+\pi^-)/\Gamma(D^0 \to K^-\pi^+) = (3.3 \pm 1.5)\%$, we can see that our results, 5.5 and 4.6 respectively, agree with the data up to ~ 50%. It is interesting that for the recently observed [20] wrong-signed decay $D^0 \to K^+\pi^-$ for that one has $\Gamma(D^0 \to K^+\pi^-)/\Gamma(D^0 \to K^-\pi^+) < 4\%$, we predict 1.06%. Today there are few experimental data for $D^+ \to O^-O^-$ decays and no ones for $D_s^+ \to O^-O^-$ decays. For the data [xx)] $\Gamma(D^+ \to K^+\bar{K}^0)/\Gamma(D^+ \to \bar{K}^0\pi^+) = (31.7 \pm 10)\%$ and $\Gamma(D^+ \to \pi^+\pi^0)/\Gamma(D^+ \to \bar{K}^0\pi^+) < 21\%$ from the table one has $\Gamma(D^+ \to K^+K_S)/\Gamma(D^+ \to K_S\pi^+) = 77\%$ and $\Gamma(D^+ \to \pi^+\pi^0)/\Gamma(D^+ \to K_S\pi^+) = 18\%$, respectively. Here there is an agreement again on a level, $\lesssim 50\%$. As to the dominant decay modes of D^+ and D$^+$,. they fastly decay to $\pi^+\eta$. So, the Cabibbo-suppressed decay $D^+ \to \pi^+\eta$ can in our scheme dominate even over the Cabibbo--favored $D^+ \to K^+\pi^0$ decay. Future experimental as well as theoretical tests are needed.

To summarize, in the Oakes scheme, when extended to the charmed case, the additional rotation around the 10th axis in SU_4- space is possible. This rotation slightly changes the Cabibbo angle-hadron mass relation, but can considerably affect the Cabibbo-suppresed decay rates. Agreement between the theoretical and experimental partial width ratios, in general, is reasonable within the experimental and theoretical errors. The remaining discrepancies ($\lesssim 50\%$) are probably due to the symmetry breaking [3] or/and final-state interactions effects [6,7] (i.e. form factors). For an explicit test of our approach future theoretical and experimental investigations are needed.

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x) For completeness, both the Cabibbo-favoured and the Cabibbo--suppresed decays are presented.

xx) Experimentally, K^0 is identified through $K_S \to \pi^+\pi^-$ decay.

Table I.

The $D\to 0^-0^-$ decay amplitudes, $M(D\to 0^-0^-)$, and the partial width ratios, where $\sin\theta_7 = 0.27$, $\sin\theta_{10} = 0.05$. From (4) one has $M(D^0\to K^-\pi^+) = \frac{G_F}{\sqrt{2}} F\,(4.572\,\xi_1 + 0.317\,\xi_2)$, $\Gamma(D^0\to K^-\pi^+) = 17\cdot 10^{10}\,s^{-1}$ (or $2.\ 10^{10}\,s^{-1}$ when $\theta_{10}=0$); $M(D^+\to K_S\pi^+) = \frac{G_F}{\sqrt{2}} F\,[-3.246\,\xi_1 + 3.475\,(\xi_2+\xi_6) - 0.228\,\xi_7]$, $\Gamma(D^+\to K_S\pi^+) = 0.61\cdot 10^{10}\,s^{-1}$ (or $0.33\cdot 10^{10}\,s^{-1}$ when $\theta_{10}=0$); $M(D_s^+\to K_S K^+) = \frac{G_F}{\sqrt{2}} F\cdot 3.639\,(\xi_2+\xi_6-\xi_7)$, $\Gamma(D_s^+\to K_S K^+) = 9.88\ 10^{10}\,s^{-1}$ (or $9.35\ 10^{10}\,s^{-1}$ when $\theta_{10} = 0$).

$D^0\to 0^-0^-$	$\frac{\Gamma(D^0\to 0^-0^-)}{\Gamma(D^0\to K^-\pi^+)}$ %	Amplitudes: $\frac{G_F}{\sqrt{2}} F\times$
$D^0\to \bar{K}^0\pi^0$	65.7	$-3.688\,\xi_2$
$D^0\to \bar{K}^0\eta$	16	$-1.926\,\xi_2$
$D^0\to K^+K^-$	5.5	$-4.572\,\xi_4$
$D^0\to \pi^+\pi^-$	4.6	$4.889\,\xi_3$
$D^0\to \pi^0\pi^0$	2.7	$2.446\,\xi_5$
$D^0\to \pi^0\eta$	3.6	$-2.940\,\xi_5$
$D^0\to \eta\eta$	1.9	$-2.246\,\xi_5$
$D^0\to K^0\pi^0$	0.06	$3.229\,\xi_6$
$D^0\to K^0\eta$	0.18	$2.263\,\xi_7 - 0.522\,\xi_6$
$D^0\to K^+\pi^-$	1.06	$-4.255\,\xi_7 - 0.317\,\xi_6$
$D^+\to 0^-0^-$	$\frac{\Gamma(D^+\to 0^-0^-)}{\Gamma(D^+\to K_S\pi^+)}$ %	
$D^+\to \pi^+\pi^0$	18	$3.514\,\xi_5 - 3.551\,\xi_3$
$D^+\to \pi^+\eta$	267	$-6.018\,\xi_5 + 1.843\,\xi_3$
$D^+\to K^+K_S$	77	$-3.246\,\xi_4$
$D^+\to K^+K_L$	77	$-3.246\,\xi_4$
$D^+\to K^+\eta$	5	$-1.744\,\xi_7$
$D^+\to K^+\pi^0$	16.4	$3.250\,\xi_7$
$D^+\to K_L\pi^+$	0.4	$3.246\,\xi_1 + 3.476\,(\xi_6 - \xi_2) - 0.228\,\xi_7$
$D_s^+\to 0^-0^-$	$\frac{\Gamma(D_s^+\to 0^-0^-)}{\Gamma(D_s^+\to K_S K^+)}$ %	
$D_s^+\to \pi^+\pi^0$	~ 0	$0.003\,\xi_1$
$D_s^+\to \pi^+\eta$	114	$-4.136\,\xi_1$
$D_s^+\to K^+\pi^0$	13.1	$-4.145\,\xi_3 - 0.244\,\xi_4$
$D_s^+\to K^+\eta$	5	$4.235\,\xi_4 - 6.303\,\xi_5$
$D_s^+\to K_S\pi^+$	32.5	$3.635\,\xi_3 - 0.228\,\xi_4$
$D_s^+\to K_L\pi^+$	32.5	$3.635\,\xi_3 - 0.228\,\xi_4$
$D_s^+\to K_L K^+$	94.7	$3.639\,(\xi_2 - \xi_6 - \xi_7)$

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Калиновский Ю.Л. и др. E2-87-300
Нелептонные распады очарованных мезонов
($D \to 0^-0^-$) и углы SU(4)-смешивания

В рамках метода киральных лагранжианов с нарушенной SU(4)xSU(4) симметрией рассмотрены кабиббовски подавленные распады очарованных мезонов $D \to 0^-0^-$. Для нарушения симметрии схема Оакса расширена на случай SU(4) при помощи дополнительного поворота вокруг десятой оси в SU(4)-пространстве. Получены следующие значения для углов поворота θ_7 и θ_{10}: $\sin\theta_7 = 0{,}27$, $\sin\theta_{10} = 0{,}05$. Для отношения $\Gamma(D^\circ \to K^+K^-)/\Gamma(D^\circ \to \pi^+\pi^-)$ дополнительный поворот привел к значению 1,2 вместо 0,75 при $\theta_{10} = 0$. Сделано сравнение полученных результатов с имеющимися данными по распадам $D \to 0^-0^-$.

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Kalinovsky Yu.L. et al. E2-87-300
Nonleptonic Decays of Charmed Mesons $D \to 0^-0^-$
and Mixing Angles in SU(4)

The Cabibbo-suppressed charmed meson decays $D \to 0^-0^-$ are considered in the framework of the chiral Lagrangian method with broken SU(4)xSU(4). To break the symmetry, the scheme of Oakes is extended to SU(4) by taking into account an additional rotation around the 10th axis in the SU(4) space. We obtained for the rotation angles θ_7 and θ_{10} the following values; $\sin\theta_7 = 0.27$, $\sin\theta_{10} = 0.05$. For the ratio $\Gamma(D^\circ \to K^+K^-)/\Gamma(D^\circ \to \pi^+\pi^-)$ an additional rotation leads to the values 1.2 instead of 0.75 when $\theta_{10} = 0$. The results are compared to the available data on the decays $D \to 0^-0^-$.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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