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Non-Leptonic Decays: a Long Story

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The large $SU(3)_F$ violations in the amplitudes for the D decays into a pair of pseudoscalar mesons are mainly accounted by the final state interaction and by contributions related to the non conservation of the strangeness changing vector currents of the octet.
An approximate selection rule for the contributions proportional to $V_{cb}V_{ub}^*$ allows to predict the CP violating asymmetries in terms of only one parameter depending on the penguin contribution. The enhancement of the octet final states with respect to the 27, larger than expected, may be related to the presence of the nonet of scalar mesons with masses around the one of the D's. A similar mechanism may be responsible for the dominance of the $\Delta I = \frac{1}{2}$ term in K decays related to the large f^0 resonance with a mass near to one of the decaying particles.

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1. Introduction

The non-leptonic decays of hadrons played and is playing a central role in understanding the weak interactions. Here, we will give a very short historical introduction to the non-leptonic decay modes of the hadrons. We will start with the K decays up to consider the two body decays of heavy mesons and CP violation. At the end we will discuss our model to study the non-leptonic two body (pseudoscalar) decays of D mesons. In the model, the large $SU(3)_F$ violation are mainly accounted by the Final State Interactions and by contributions to the amplitude related to the non-conservation of the strangeness changing octect vector currents. In the next section we will give a short historical review of weak interactions and CP violation; then, in the third section, we will discuss non-leptonic decays of D mesons and we will give our conclusions.

2. Historical introduction

The experimental discovery of strange particles, expecially kaons, in the 50's had a decisive impact to understand weak interactions. The oscillation of neutral kaons, produced with opposite strangeness and evolving as a combination of two (almost) CP eigenstates with different lifetime, mass and decay channels, proposed by Gell-Mann and Pais [1] and experimentally verified by Piccioni [2]. This inspired Bruno Pontecorvo [3, 4] to propose neutrino oscillations, which provide, after a long research to confirm them, the bridge towards physics beyond the standard model.
The brilliant solution by C. N. Yang and T. D. Lee [5] of the θ - τ enigma with the opposite parity of the 3π and 2π final states in the decay of the charged kaon lead to the evidence in the experiment conducted by Madame Wu of parity violation in β decay of polarized cobalte and to the $V-A$ theory of weak interactions by R.e. Marshak and E.C.G. Sudarshan [6] and by R.P. Feynman and M. Gell-Mann [7]. Another crucial point in the knowledge of the non-leptonic decays is the, so called, $\Delta I = \frac{1}{2}$ rule [1, 8]. It refers to the fact that the in $K \to \pi\pi$ decays the final state with isospin zero, $I = 0$ is larger than the one with $I = 2$. In particular, in the $K \to \pi\pi$ the $\mathrm{Re}A_0/\mathrm{Re}A_2 = 22.4$ and a similar result in the decays of strange baryons. This rule implies

$$A(K^0 \to \pi^+\pi^-) = A(K^0 \to \pi^0\pi^0)$$

and a selection rule against $A(K^+ \to \pi^+\pi^0)$ which is the main motivation of the fact that K^+ has a longer lifetime than K_S. Regarding the baryon decays, we have

$$\begin{aligned} A(\Lambda \to p+\pi^-) &= -\sqrt{2}A(\Lambda \to n+\pi^0), \\ A(\Xi^- \to \Lambda+\pi^-) &= \sqrt{2}A(\Xi^0 \to \Lambda+\pi^0), \\ A(\Sigma^+ \to p+\pi^0) &= \sqrt{2}\left[A(\Sigma^+ \to n+\pi^+) - A(\Sigma^- \to n+\pi^-)\right]. \end{aligned} \tag{2.1}$$

While the semileptonic and leptonic decays $K^- \to \pi^0 + e^- + \bar{\nu}_e$, $K^- \to \pi^0 + \mu^- + \bar{\nu}_\mu$ show a smaller coupling with respect to $\pi^- \to \pi^0 + e^- + \bar{\nu}_e$ and $\pi^- \to \pi^0 + \mu^- + \bar{\nu}_\mu$ the amplitudes for the $|\Delta S| = 1$ non-leptonic decays of the strange particles are rather large.
The Cabibbo universality for the hadron weak current [9]

$$J_\mu = \bar{u}(x)\gamma_\mu(1-\gamma_5)\left[\cos(\theta_C)d(x) + \sin(\theta_C)s(x)\right]$$

	UT_{fit}
λ	0.22497 ± 0.00069
A	0.833 ± 0.012
ρ	0.157 ± 0.014
η	0.352 ± 0.011

Table 1: Fitted parameters entering in the CKM matrix.

gives rise to the effective lagrangian

$$L_{eff}^{\Delta S=1} = \frac{G_F}{\sqrt{2}} \cos(\theta_C)\sin(\theta_C)\left[\bar{d}(x)\gamma^\mu(1-\gamma_5)u(x)\right]\left[\bar{u}(x)\gamma_\mu(1-\gamma_5)s(x)\right] \tag{2.2}$$

which contains both components with Isospin $I = 1/2$ and $I = 3/2$ involved in the $K \to \pi\pi$ transitions. If we take into account QCD corrections, the transitions with $\Delta I = 1/2$ are enhanced together with a suppression of the $\Delta I = 3/2$ ones. In particular [10, 11]

$$\frac{k^2}{2}[\bar{d}_L\gamma^\mu u_L\bar{u_L}\gamma_\mu s_L - \bar{u_L}\gamma^\mu u_L\bar{d}_L\gamma_\mu s_L] + \frac{1}{2k}[\bar{d}_L\gamma^\mu u_L\bar{u_L}\gamma_\mu s_L + \bar{u_L}\gamma^\mu u_L\bar{d}_L\gamma_\mu s_L] \tag{2.3}$$

For a quite recent review on the subject we will address to Ref. [12].

At the beginning of 1970 S. Glashow, J. Iliopoulos and L. Maiani [13] assumed the existence of a fourth quark, the charm, coupled to the combination:

$$-\sin(\theta_C)d + \cos(\theta_C)s$$

and some years later M. Kobayashi and T. Maskawa [14] wrote the general mixing matrix for six quarks. A possible parameterization of the Cabibbo-Kobayashi-Maskawa matrix was proposed by L. Wolfenstein [15]

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - \imath\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-\imath\eta) & -A\lambda^2 & 1 \end{pmatrix}, \tag{2.4}$$

where $\lambda = \sin(\theta_C)$ and the parameters A, ρ and η were intended to be of the order of unity. Many fit of these parameters can be found in literature, we mention in table 1 the UT fit results [16].

In this parametrization the effects of CP violation are related to the η parameter. More precisely, any observable which violates CP must be proportional to the *so-called* J_{CP} parameter [17]

$$J_{CP} = \Im\left(V_{ai}V_{bj}V_{aj}^*V_{bi}^*\right) = \eta A^2\lambda^6 + \mathscr{O}(\lambda^8). \tag{2.5}$$

The CP violation has been observed experimentally in the K [18] and in the B systems. In the neutral kaon decays the CP violating effects are parameterized in terms of ε, and ε' by means of the ratios:

$$\frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \varepsilon + \varepsilon',$$
$$\frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \varepsilon - 2\varepsilon', \tag{2.6}$$

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where ε is related to the *indirect* CP violation and ε' to the *direct* one. For a recent report on this subject and in particular on $(\varepsilon'/\varepsilon)$ quantity see, for example, [19].

Indeed it has been easier to measure the CP violating asymmetry at the beauty factories (Belle and BaBaR) in the *golden channel* $J/\psi K_S$ in neutral B decays [20, 21]:

$$B^0 \equiv d\bar{b} \to d\bar{c}c\bar{s}$$
$$\bar{B}^0 \equiv \bar{d}b \to \bar{d}cs\bar{c}$$

and the two amplitudes:

$$< J/\psi \overline{K}^0 | \bar{s}_L \gamma^\mu c_L \bar{c}_L \gamma_\mu b_L | B^0 >$$
$$< J/\psi K^0 | \bar{c} \gamma^\mu s_L \bar{b}_L \gamma_\mu c_L | \overline{B}^0 >$$

are equal.

3. The non-leptonic two body decays of D mesons and CP violation

Also in the charm sector there is the possibility to study effects of CP violation. It is interesting, for example, to look for CP violations not accounted by the phase in the CKM matrix in the search for physics beyond the standard model. A possible signal has been the measurement of the difference between the CP violating asymmetries in the neutral D^0 decays ($c\bar{u}$ and $u\bar{c}$) for the final states with two charged kaons or pions [22, 23, 24, 25, 26, 27, 28].

To give theoretical predictions about these asymmetries the first step consists in evaluating the non-leptonic amplitudes starting from the effective hamiltonian. The calculation can be done in the framework of models because it is not reliable the heavy quark effective theory approach due to the fact that $1/m_c$ corrections can be large. An approach weak model dependent and, in principle, capable to include corrections is based on $SU(3)_F$ flavour symmetry. In this framework, one has to evaluate the matrix elements of the $\Delta U = 1$ and $\Delta U = 0$ parts of the effective hamiltonian, proportionally respectively to [29]

$$V_{cs}V_{us}^* - V_{cd}V_{ud}^* \approx \sin(2\theta_C) \approx 2\lambda\,,$$
$$V_{cs}V_{us}^* + V_{cd}V_{ud}^* = -V_{cb}V_{ub}^* = -A^2\lambda^5(\rho + \imath\eta)\,.$$

The moduli of the $\Delta U = 1$ amplitudes may be obtained by the very precisely measured branching ratios of D^0 into charged kaons and pions, but the strong phases, which appear in the expression of the CP violating asymmetries, should be fixed by a theoretical approach able to reproduce the experimental branching ratios for both charged and neutral kaon and pion final states. Indeed strong $SU(3)_F$ violations are present, since the theoretical predictions

$$A(D^0 \to \pi^+\pi^-) = -A(D^0 \to K^+K^-),$$
$$A(D^0 \to K^0\bar{K}^0) = 0,$$

are strongly contradicted by the experimental branching ratios [30]

$$Br(D^0 \to \pi^+\pi^-) < Br(D^0 \to K^+K^-),$$
$$Br(D^0 \to K_SK_S) > 0\,.$$

Channel	Fit ($\times 10^{-3}$)	Exp. ($\times 10^{-3}$)
CF		
BR($D^+ \to \pi^+ K_S$)	15.72 ± 0.41	15.3 ± 0.6
BR($D^+ \to \pi^+ K_L$)	14.27 ± 0.38	14.6 ± 0.5
BR($D^0 \to \pi^+ K^-$)	39.33 ± 0.40	39.3 ± 0.4
BR($D^0 \to \pi^0 K_S$)	12.02 ± 0.35	12.0 ± 0.4
BR($D^0 \to \pi^0 K_L$)	9.48 ± 0.28	10.0 ± 0.7
SCS		
BR($D^0 \to \pi^+ \pi^-$)	1.42 ± 0.03	1.421 ± 0.025
BR($D^0 \to \pi^0 \pi^0$)	0.83 ± 0.04	0.826 ± 0.035
BR($D^+ \to \pi^+ \pi^0$)	1.24 ± 0.06	1.24 ± 0.06
BR($D^0 \to K^+ K^-$)	4.00 ± 0.07	4.01 ± 0.07
BR($D^0 \to K_S K_S$)	0.17 ± 0.04	0.18 ± 0.04
BR($D^+ \to K^+ K_S$)	2.99 ± 0.14	2.95 ± 0.15
DCS		
BR($D^+ \to \pi^0 K^+$)	0.166 ± 0.011	0.189 ± 0.025
BR($D^0 \to \pi^- K^+$)	0.140 ± 0.003	0.1399 ± 0.0027

Table 2: Result of the fit; CF means Cabibbo Favoured, SCS and DCS mean respectively singly and double Cabibbo suppressed decay modes. See text for more details.

It has been understood since a long time that these strong $SU(3)_F$ violations are the consequence of the final state interaction due to the presence in the mass region of the D's of a nonet of scalar positive parity resonances, whose mass splittings imply different phases for the $I = 0, 1/2$ and 1 final states [31]. Such phases are implied by the isospin sum rules for the Cabibbo favoured and single Cabibbo suppressed amplitudes:

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

with large angles in the Gauss plane of the corresponding triangles. In fact

$$A(D^0 \to 2\pi, I = 2) = 0.4\, e^{\imath \delta/2} A(D^0 \to 2\pi, I = 0)\,. \tag{3.1}$$

For the D^0 single Cabibbo suppressed decays we have been able to reproduce the branching ratios into $K\bar{K}$ and $\pi\pi$ with $SU(3)_F$ symmetry for the matrix elements of the non-leptonic weak lagrangian and the $SU(3)_F$ violation are a consequence of the phases of the octet final state interaction in the $I = 1$ channel, δ_1, and in the $I = 0$ channels, for which we have three parameters, the mixing angle ϕ for the singlet and octet states and the two phases δ_0 and δ_0'.

The main contribution to the $\Delta U = 0$ part proportional to $V_{cb} V_{ub}^*$ is expected to come from the penguin contribution due to the operator

$$\bar{u}_L \gamma^\mu \lambda_a c_L [\bar{u} \gamma_\mu \lambda_a u + \bar{d} \gamma_\mu \lambda_a d + \bar{s} \gamma_\mu \lambda_a s] \tag{3.2}$$

which transforms as a representation of dimension **3** of $SU(3)_F$. We assume a selection rule against the final state $K^0\bar{K}^0$, which would correspond to the production at the same time of a $s\bar{s}$ and a $d\bar{d}$ pair, while the operator at lowest order in QCD produces either one or the other pair. So the penguin contribution gives rise to the following combination of states

$$K^+K^- + K^-K^+ + \pi^+\pi^- + \pi^0\pi^0 + \pi^-\pi^+ + \frac{1}{3}\eta_8\eta_8 + \frac{1}{\sqrt{3}}(\pi^0\eta_8 + \eta_8\pi^0). \tag{3.3}$$

The final state interaction provides the large $SU(3)_F$ violations shown by the experimental data on the branching ratios for the Cabibbo first forbidden decays of D^0; these data are known with a precision better than the one expected assuming the $SU(3)_F$ symmetry. This gives us confidence that the strong phases found for the $I = 0$ and $I = 1$ channels are right and that the consequent predictions for the CP violating asymmetries are reliable, in particular we give

$$\frac{a_{CP}(\pi^+\pi^-)}{a_{CP}(K^+K^-)} \approx -2. \tag{3.4}$$

This result is confirmed by extending the study to all the two pseudoscalar mesons non-leptonic decays of the D's, which implies another $SU(3)_F$ invariant amplitude, the final state phase interaction into $I = 1/2$ of the octet and the $SU(3)_F$ violations related to the non-conservation of the strangeness changing vector currents of the octet and slightly different matrix reduced elements for the Cabibbo favoured amplitudes [32]. In table 2 we report the result of our fit to the experimental branching ratios of the Cabibbo favoured, singly and double suppressed decay modes. As one can see the agreement is excellent.

Before to go to the conclusions we want to do some considerations about the role of resonances in the decays of mesons in pions and the possible contribution to the $\Delta I = 1/2$ rule.

It is well known that, within the *naive* factorization approach, the description of the experimental enhancement of the octet with respect to the representation of dimension **27** in non-leptonic D decays requires to assume $1/N_c = 0$. This may depend on the fact that this approximation is unable to account for the enhancement factor for the matrix element of the effective non-leptonic lagrangian related to the presence of the octet resonances responsible for the strong final state interaction [31].

This effect is very large for K decays into two pions due to the f^0 resonance with mass very near to the kaon mass. It implies a stronger than expected enhancement for the $\Delta I = 1/2$ matrix elements of the effective strangeness changing weak non-leptonic lagrangian.

By comparing the contributions of the tree and penguin terms for B and D decays into two pions, we can study the kaon decays by assuming that the enhancement of the $\Delta I = 1/2$ from D to K for the tree and penguin parts are in the same ratio than the ones from B to D and require to agree with the total enhancement [33]. In such a way it is, in principle, possible to describe $\Delta I = 1/2$ dominance in $K \to \pi\pi$ and to study the penguin contribution, which might be useful for the evaluation of ε'.

4. Conclusions

We have proposed a model to describe the non-leptonic decays of D into two pseudoscalar mesons. In this model the strong violation of $SU(3)_F$ are mainly due to the final state interactions which are assumed to be dominated by an octet of scalar resonances. A direct consequences of this approach is the prediction

$$\frac{a_{CP}(\pi^+\pi^-)}{a_{CP}(K^+K^-)} \approx -2\,. \tag{4.1}$$

The experimental data about two pion decays of B, D and K particles suggests that the scalar resonances responsible for the final state interaction (which fixes the strong phases) may give a contribution also to the enhancement of the $\Delta I = 1/2$ in K decays.

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