- to some of their salient dynamical features.

Details can be found in the ample literature on that subject.

8 Oscillations and CP Violation in Charm Decays – The Underdog's Chance for Fame

It is certainly true that

- $D^0 - \bar{D}^0$ oscillations proceed very slowly in the Standard Model and
- CP asymmetries in D decays are small or even tiny within the KM ansatz.

Yet the relevant question quantitatively is: how slow and how small?

8.1 $D^0 - \bar{D}^0$ Oscillations

Bounds on $D^0 - \bar{D}^0$ oscillations are most cleanly expressed through 'wrong-sign' semileptonic decays:

$$r_D = \frac{\Gamma(D^0 \to l^- X)}{\Gamma(D^0 \to l^+ X)} \simeq \frac{1}{2}\left(x_D^2 + y_D^2\right) \tag{251}$$

with $x_D = \Delta m_D/\Gamma_D$, $y_D = \Delta\Gamma_D/2\Gamma_D$. It is often stated that the Standard Model predicts

$$r_D \leq 10^{-7} \;\hat{=}\; x_D,\, y_D \leq 3 \cdot 10^{-4} \tag{252}$$

I myself am somewhat flabbergasted by the boldness of such predictions. For one should keep the following in mind for proper perspective: there are quite a few channels that can drive $D^0 - \bar{D}^0$ oscillations – like $D^0 \Rightarrow K\bar{K},\ \pi\pi \Rightarrow \bar{D}^0$ or $D^0 \Rightarrow K^-\pi^+ \Rightarrow \bar{D}^0$ – and they branching ratios on the (few) $\times\, 10^{-3}$ level [21]. In the limit of $SU(3)_{Fl}$ symmetry all these contributions have to cancel of course. Yet there are sizeable violations of $SU(3)_{Fl}$ invariance in D decays, and one should have little confidence in an imperfect symmetry to ensure that a host of channels with branching ratios of order few$\times 10^{-3}$ will cancel as to render $x_D,\, y_D \leq 3 \cdot 10^{-4}$. To say it differently: The relevant question in this context is *not* whether $r_D \sim 10^{-7} \div 10^{-6}$ is a possible or even reasonable Standard Model estimate, but whether $10^{-6} \leq r_D \leq 10^{-4}$ can *reliably be ruled out*! I cannot see how anyone could make such a claim with the required confidence.

The present experimental bound is

$$r_D|_{exp} \leq 3.4 \cdot 10^{-3} \;\hat{=}\; x_D,\, y_D \leq 0.1 \tag{253}$$

[21] For the $K^-\pi^+$ mode this represents the average of its Cabibbo allowed and doubly Cabibbo suppressed incarnations.

to be compared with a *conservative* Standard Model bound

$$r_D|_{SM} < 10^{-4} \;\hat{=}\; y_D,\, x_D|_{SM} \le 10^{-2} \tag{254}$$

New Physics on the other hand can enhance Δm_D (though not $\Delta\Gamma_D$) very considerably up to

$$x_D|_{NP} \sim 0.1 \;, \tag{255}$$

i.e. the present experimental bound.

8.2 CP Violation involving $D^0 - \bar{D}^0$ Oscillations

One can discuss this topic in close qualitative analogy to B decays. First one considers final states that are CP eigenstates like K^+K^- or $\pi^+\pi^-$ [46]:

$$\begin{aligned}\mathrm{rate}(D^0(t) \to K^+K^-) &\propto e^{-\Gamma_D t}\left(1 + (\sin\Delta m_D t)\cdot \mathrm{Im}\frac{q}{p}\bar{\rho}_{K^+K^-}\right) \simeq \\ &\simeq e^{-\Gamma_D t}\left(1 + \frac{\Delta m_D t}{\Gamma_D}\cdot\frac{t}{\tau_D}\cdot \mathrm{Im}\frac{q}{p}\bar{\rho}_{K^+K^-}\right)\end{aligned} \tag{256}$$

With $x_D|_{SM} \le 10^{-2}$ and $\mathrm{Im}\frac{q}{p}\bar{\rho}_{K^+K^-}|_{KM} \sim \mathcal{O}(10^{-3})$ one arrives at an asymmetry of around 10^{-5}, i.e. for all practical purposes zero, since it presents the product of two very small numbers. Yet with New Physics one conceivably has $x_D|_{NP} \le 0.1$, $\mathrm{Im}\frac{q}{p}\bar{\rho}_{K^+K^-}|_{NP} \sim \mathcal{O}(10^{-1})$ leading to an asymmetry that could be as large as of order 1%. Likewise one should compare the doubly Cabibbo suppressed transitions [47, 48]

$$\begin{aligned}&\mathrm{rate}(D^0(t) \to K^+\pi^-) \propto e^{-\Gamma_{D^0}t}\mathrm{tg}^4\theta_C|\hat{\rho}_{K\pi}|^2\cdot \\ &\cdot\left[1 - \frac{1}{2}\Delta\Gamma_D t + \frac{(\Delta m_D t)^2}{4\mathrm{tg}^4\theta_C|\hat{\rho}_{K\pi}|^2} + \frac{\Delta\Gamma_D t}{2\mathrm{tg}^2\theta_C|\hat{\rho}_{K\pi}|}\mathrm{Re}\left(\frac{p}{q}\frac{\hat{\rho}_{K\pi}}{|\hat{\rho}_{K\pi}|}\right) - \right. \\ &\left. - \frac{\Delta m_D t}{\mathrm{tg}^2\theta_C|\hat{\rho}_{K\pi}|}\mathrm{Im}\left(\frac{p}{q}\frac{\hat{\rho}_{K\pi}}{|\hat{\rho}_{K\pi}|}\right)\right]\end{aligned} \tag{257}$$

$$\begin{aligned}&\mathrm{rate}(\bar{D}^0(t) \to K^-\pi^+) \propto e^{-\Gamma_{D^0}t}\mathrm{tg}^4\theta_C|\hat{\bar{\rho}}_{K\pi}|^2\cdot \\ &\cdot\left[1 - \frac{1}{2}\Delta\Gamma_D t + \frac{(\Delta m_D t)^2}{4\mathrm{tg}^4\theta_C|\hat{\bar{\rho}}_{K\pi}|^2} + \frac{\Delta\Gamma_D t}{2\mathrm{tg}^2\theta_C|\hat{\bar{\rho}}_{K\pi}|}\mathrm{Re}\left(\frac{p}{q}\frac{\hat{\bar{\rho}}_{K\pi}}{|\hat{\bar{\rho}}_{K\pi}|}\right) + \right. \\ &\left. + \frac{\Delta m_D t}{\mathrm{tg}^2\theta_C|\hat{\bar{\rho}}_{K\pi}|}\mathrm{Im}\left(\frac{p}{q}\frac{\hat{\bar{\rho}}_{K\pi}}{|\hat{\bar{\rho}}_{K\pi}|}\right)\right]\end{aligned} \tag{258}$$

where

$$\mathrm{tg}^2\theta_C\cdot\hat{\rho}_{K\pi} \equiv \frac{T(D^0 \to K^+\pi^-)}{T(D^0 \to K^-\pi^+)} \;,\; \mathrm{tg}^2\theta_C\cdot\hat{\bar{\rho}}_{K\pi} \equiv \frac{T(\bar{D}^0 \to K^-\pi^+)}{T(\bar{D}^0 \to K^+\pi^-)} \;; \tag{259}$$

in such New Physics scenarios one would expect a considerably enhanced asymmetry of order $1\%/\mathrm{tg}^2\theta_C \sim 20\%$ – at the cost of smaller statistics.

Effects of that size would unequivocally signal the intervention of New Physics!

8.3 Direct CP Violation

As explained before a direct CP asymmetry requires the presence of two coherent amplitudes with different weak and different strong phases. Within the Standard Model (and the KM ansatz) such effects can occur in Cabibbo suppressed [22], yet not in Cabibbo allowed or doubly Cabibbo suppressed modes. There is a subtlety involved in this statement. Consider for example $D^+ \to K_S\pi^+$. At first sight it appears to be a Cabibbo allowed mode described by a single amplitude without the possibility of an asymmetry. However [49]

- due to $K^0 - \bar{K}^0$ mixing the final state can be reached also through a doubly Cabibbo suppressed reaction, and the two amplitudes necessarily interfere;
- because of the CP violation in the $K^0 - \bar{K}^0$ complex there is an asymmetry that can be predicted on general grounds

$$\frac{\Gamma(D^+ \to K_S\pi^+) - \Gamma(D^- \to K_S\pi^+)}{\Gamma(D^+ \to K_S\pi^+) + \Gamma(D^- \to K_S\pi^+)} \simeq -2\mathrm{Re}\,\epsilon_K \simeq -3.3 \cdot 10^{-3} \simeq$$
$$\simeq \frac{\Gamma(D^+ \to K_L\pi^+) - \Gamma(D^- \to K_L\pi^+)}{\Gamma(D^+ \to K_L\pi^+) + \Gamma(D^- \to K_L\pi^+)}\,; \tag{260}$$

- If New Physics contributes to the doubly Cabibbo suppressed amplitude $D^+ \to K^0\pi^+$ (or $D^- \to \bar{K}^0\pi^-$) then an asymmetry could occur quite conceivably on the few percent scale;
- such a manifestation of New Physics would be unequivocal; against the impact of ϵ_K, Eq.(260) it could be distinguished not only through the size of the asymmetry, but also how it surfaces in $D^+ \to K_L\pi^+$ vs. $D^- \to K_L\pi^-$: if it is New Physics one has

$$\frac{\Gamma(D^+ \to K_S\pi^+) - \Gamma(D^- \to K_S\pi^+)}{\Gamma(D^+ \to K_S\pi^+) + \Gamma(D^- \to K_S\pi^+)} = -\frac{\Gamma(D^+ \to K_L\pi^+) - \Gamma(D^- \to K_L\pi^+)}{\Gamma(D^+ \to K_L\pi^+) + \Gamma(D^- \to K_L\pi^+)} \tag{261}$$

  i.e., the CP asymmetries in $D \to K_S\pi$ and $D \to K_L\pi$ differ in sign – in contrast to Eq.(260).

9 Baryogenesis in the Universe

9.1 The Challenge

One of the most intriguing aspects of big bang cosmology is to 'understand' nucleosynthesis, i.e. to reproduce the abundances observed for the nuclei in the universe as *dynamically* generated rather than merely dialed as input values. This challenge

[22] The effect could well reach the 10^{-3} and exceptionally the 10^{-2} level.