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An overview of D^0-$\bar{D}^0$ mixing and CP violation*

XING Zhi-Zhong(邢志忠)1)

(Institute of High Energy Physics, CAS, Beijing 100049, China)
(Theoretical Physics Center for Science Facilities, CAS, Beijing 100049, China)

Abstract I give a brief overview of D^0-$\bar{D}^0$ mixing and CP violation in the framework of the standard model. I focus on the theoretical estimate of the D^0-$\bar{D}^0$ mixing parameters and the phenomenological description of several types of CP violation in neutral D-meson decays.

Key words D^0-$\bar{D}^0$ mixing, CP violation

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1 Introduction

The phenomenon of meson-antimeson mixing has been of great interest in the long history of particle physics. Four meson-antimeson mixing systems, together with their characteristic parameters x and y which have experimentally been measured or constrained, are listed in Table 1.

Table 1.

system	$\lvert x\rvert$	$\lvert y\rvert$	year
K^0-$\bar{K}^0$	~ 0.47	~ 1.0	1958
B^0_d-$\bar{B}^0_d$	~ 0.78	$< 1\%$	1987
B^0_s-$\bar{B}^0_s$	~ 27	~ 0.1	2006
D^0-$\bar{D}^0$	$\leqslant 1\%$	$\sim 1\%$	2007

Two lessons were learnt in the development of the standard model (SM): (1) theorists speculated the existence of the charm quark and predicted its mass in understanding the observation of K^0-$\bar{K}^0$ mixing; and (2) theorists deduced the correct magnitude of the top quark mass from the observation of B^0_d-$\bar{B}^0_d$ mixing. The measurement of B^0_s-$\bar{B}^0_s$ mixing is consistent with the SM expectation. People feel excited by the preliminary observation of D^0-$\bar{D}^0$ mixing, although current data[1] do not hint at any new physics beyond the SM. The charming sleeping beauty is waking up!

In terms of D^0 and $\bar{D}^0$, the mass states of two neutral D mesons are written as

$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle\,, \qquad |D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle\,, \tag{1}$$

where $|p|^2+|q|^2=1$ holds and CPT invariance has been assumed. Two D^0-$\bar{D}^0$ mixing parameters x and y are defined by

$$x \equiv \frac{M_2 - M_1}{\Gamma}\,, \qquad y \equiv \frac{\Gamma_2-\Gamma_1}{2\Gamma}\,, \tag{2}$$

where $M_{1,2}$ and $\Gamma_{1,2}$ are the mass and width of $D_{1,2}$, and $\Gamma \equiv (\Gamma_1+\Gamma_2)/2$ together with $M\equiv(M_1+M_2)/2$. One has to take care of the definitions of x and y used in different papers.

Why is the D^0-$\bar{D}^0$ system unique? It is the only meson-antimeson system whose mixing (or oscillation) takes place via the intermediate states with down-type quarks. The rate of D^0-$\bar{D}^0$ mixing is expected to be very small in the SM, because the third generation (namely, the bottom quark) plays a negligible role in the corresponding box diagrams: on the one hand, $m^2_b/m^2_W \sim \mathcal{O}(10^{-3})$; on the other hand, $|V_{ub}V_{cb}|^2/|V_{us}V_{cs}|^2 \sim \mathcal{O}(10^{-6})$. The D^0-$\bar{D}^0$ system is also the only meson-antimeson system whose mixing parameters x and y are notoriously hard to be calculated in the SM. The reason is simply that the charm quark mass is neither light enough ($\ll \Lambda_{QCD}$) nor heavy enough ($\gg \Lambda_{QCD}$), and one has no reliable techniques to evaluate x and y in this nonperturbative regime. Therefore, only experimental measurements can reliably tell us how large or how small the rate of D^0-$\bar{D}^0$ mixing is.

Why is the D^0-$\bar{D}^0$ system interesting? It is a sensitive playground to explore possible CP-violating new physics, because the SM effects of CP violation in

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1) E-mail: xingzz@ihep.ac.cn

neutral D-meson decays are typically of $\mathcal{O}(10^{-3})$ or smaller. One may understand this point by considering the charm unitarity triangle of the CKM matrix in the complex plane[2]: $V_{ud}^*V_{cd}+V_{us}^*V_{cs}+V_{ub}^*V_{cb}=0$, in which two sides are comparable in magnitude and much longer than the third one governed by $V_{ub}^*V_{cb}$. The shape of this triangle is too sharp, implying that the CP-violating effects are strongly suppressed in comparison with the CP-conserving effects in the charm sector. On the other hand, The D^0-$\bar{D}^0$ system is a nontrivial playground to test the unitarity of the CKM matrix, quantum coherence of the D^0 and $\bar{D}^0$ mesons at their production thresholds, CPT invariance and $\Delta C=\Delta Q$ rule et al[3]. For example, the CKM unitarity together with current data requires

$$\begin{aligned}|V_{tb}|>|V_{ud}|>|V_{cs}| &\gg |V_{us}|>|V_{cd}| \\ &\gg |V_{cb}|>|V_{ts}| \\ &\gg |V_{td}|>|V_{ub}|>0\,. \end{aligned} \tag{3}$$

More accurate measurements of $|V_{cd}|$ and $|V_{cs}|$ will help test the validity of this hierarchy.

2 D^0-$\bar{D}^0$ mixing

The mixing between D^0 and $\bar{D}^0$ mesons arises from the fact that they couple to a subset of virtual or real intermediate states. In this case, the proper time evolution of two flavor states is described by

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}|D^0(t)\rangle\\|\bar{D}^0(t)\rangle\end{pmatrix}=\left(M-\mathrm{i}\frac{\Gamma}{2}\right)\begin{pmatrix}|D^0(t)\rangle\\|\bar{D}^0(t)\rangle\end{pmatrix}, \tag{4}$$

where M and Γ are 2×2 Hermitian matrices. The CPT invariance implies that $M_{11}=M_{22}$ and $\Gamma_{11}=\Gamma_{22}$ hold. An expansion of the off-diagonal terms M_{12} and Γ_{12} to the second order in the SM perturbation theory is

$$\left(M-\mathrm{i}\frac{\Gamma}{2}\right)_{12}=\frac{1}{2M}\Bigg[\langle D^0|\mathcal{H}_{\rm weak}^{\Delta C=2}|\bar{D}^0\rangle+ \sum_n\frac{\langle D^0|\mathcal{H}_{\rm weak}^{\Delta C=1}|n\rangle\langle n|\mathcal{H}_{\rm weak}^{\Delta C=1}|\bar{D}^0\rangle}{M-E_n+\mathrm{i}\epsilon}\Bigg], \tag{5}$$

where $\mathcal{H}_{\rm weak}^{\Delta C=1}$ and $\mathcal{H}_{\rm weak}^{\Delta C=2}$ are the effective Hamiltonians of $\Delta C=1$ and $\Delta C=2$ processes, respectively. The first term on the right-hand side of Eq. (5) contributes only to M_{12} and is sensitive to new physics, while the second term contributes both to M_{12} and to Γ_{12} and is dominated by the SM contribution.

As the effect of b quark in D^0-$\bar{D}^0$ mixing is negligibly small, it is an excellent approximation to neglect CP violation in this meson-antimeson system. In this case, the mass states $|D_1\rangle$ and $|D_2\rangle$ are just the CP states $|D_+\rangle$ (even) and $|D_-\rangle$ (odd) under the convention $CP|D^0\rangle=|\bar{D}^0\rangle$. One may calculate $\Delta M\equiv M_2-M_1$ and $\Delta\Gamma\equiv\Gamma_2-\Gamma_1$ by using the relations $\Delta M=-2M_{12}$ and $\Delta\Gamma=-2\Gamma_{12}$. In other words,

$$\begin{aligned}x&=\frac{-1}{2M\Gamma}\Bigg[2\langle D^0|\mathcal{H}_{\rm weak}^{\Delta C=2}|\bar{D}^0\rangle+ \\ &\quad\mathcal{P}\sum_n\Bigg(\frac{\langle D^0|\mathcal{H}_{\rm weak}^{\Delta C=1}|n\rangle\langle n|\mathcal{H}_{\rm weak}^{\Delta C=1}|\bar{D}^0\rangle}{M-E_n}+ \\ &\quad\frac{\langle \bar{D}^0|\mathcal{H}_{\rm weak}^{\Delta C=1}|n\rangle\langle n|\mathcal{H}_{\rm weak}^{\Delta C=1}|D^0\rangle}{M-E_n}\Bigg)\Bigg], \\ y&=\frac{-1}{4M\Gamma}\sum_n\Big[\langle D^0|\mathcal{H}_{\rm weak}^{\Delta C=1}|n\rangle\langle n|\mathcal{H}_{\rm weak}^{\Delta C=1}|\bar{D}^0\rangle+ \\ &\quad\langle \bar{D}^0|\mathcal{H}_{\rm weak}^{\Delta C=1}|n\rangle\langle n|\mathcal{H}_{\rm weak}^{\Delta C=1}|D^0\rangle\Big](2\pi)\delta(M-E_n)\,,\end{aligned} \tag{6}$$

where $\mathcal{P}$ denotes the principle value, and the sum is over all intermediate states n with the implicit phase space $(2\pi)^3\delta^3(\boldsymbol{p}-\boldsymbol{p}_n)$.

There are in general two approaches to calculate the values of x and y:

1) to use Eq. (6) at the quark level ($n=d\bar{d}+s\bar{s}+d\bar{s}+s\bar{d}$);

2) to use Eq. (6) at the hadron level ($n=\pi^+\pi^-+K^+K^-+\pi^+K^-+K^+\pi^-+\cdots$).

But neither of them is able to give very reliable results, because the charm quark mass lies in an embarrassing (intermediate or non-perturbative) regime where neither the heavy-quark effective theory nor the chiral perturbation theory can work well.

At the quark level, the lowest-order short-distance calculation of the D^0-$\bar{D}^0$ mixing box diagram yields

$$x_{\rm box}\propto\frac{m_s^2}{m_W^2}\times\frac{m_s^2}{m_c^2}\,,\quad y_{\rm box}\propto\frac{m_s^2}{m_c^2}x_{\rm box}\,, \tag{7}$$

which are of $\mathcal{O}(10^{-5})$ and $\mathcal{O}(10^{-7})$, respectively. The small factor of $y_{\rm box}/x_{\rm box}$ can simply be understood as the helicity suppression. It was first pointed out by Georgi that higher-order contributions to x and y in the operator product expansion have fewer powers of m_s suppression, because the chiral suppression can be lifted by quark condensates instead of mass insertions[4]. The 8-quark operator contributions to D^0-$\bar{D}^0$ mixing are only suppressed by m_s^2, and thus they are the dominant short-distance effects. More explicit estimates[5], which depend on some assumptions and involve large uncertainties in dealing with the hadronic matrix elements, give $x\sim y\sim\mathcal{O}(10^{-3})$ or smaller values.

At the hadron level, one may take the intermediate states n to be the exclusive hadronic states. This long-distance approach is reasonable because m_c (or M) lies in a region populated by the excited light-quark states. It is impossible to sum over all the possible intermediate hadronic multiplets in practice, however. Once the b-quark contribution is neglected, x and y will vanish in the limit of flavor $SU(3)$ symmetry. This point can be illustrated by assuming n to be the two-body charged-pseudoscalar meson states $n = \{\pi^+\pi^-, K^+K^-, \pi^+K^-, K^+\pi^-\}$. Their relative contributions to D^0-$\bar{D}^0$ mixing are proportional to $\{+1,+1,-1,-1\}\cos^2\theta_C \sin^2\theta_C$, as a consequence of flavor $SU(3)$ symmetry. Hence the sum of these dispersive contributions vanishes, implying a perfect realization of the GIM mechanism. But we know that the flavor $SU(3)$ symmetry is badly broken in neutral D-meson decays. Non-vanishing D^0-$\bar{D}^0$ mixing can actually arise as the second-order effect of $SU(3)$ symmetry breaking[6],

$$x \sim y \sim \sin^2\theta_C \times [SU(3) \text{ breaking}]^2 . \tag{8}$$

How to estimate the size of $SU(3)$ breaking effects is a big challenge. One finds that a calculation of y in this exclusive approach is less model-dependent, while the estimate of x involves off-shell hadronic states and thus is less reliable. In this case, one may choose to use the dispersion relation

$$\Delta M = -\frac{1}{2\pi}\mathcal{P}\int_{2m_\pi}^{\infty} \mathrm{d}E \left[\frac{\Delta\Gamma(E)}{E-M} + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{E}\right)\right] , \tag{9}$$

which has been proved in the heavy-quark effective theory[7], to get x from y.

As emphasized by Ligeti[8], the most important long-distance effect is expected to be due to the $SU(3)$ symmetry breaking in phase space. Contrary to the breaking of $SU(3)$ symmetry in hadronic matrix elements, the breaking of $SU(3)$ symmetry in phase space is calculable in a less model-dependent way. A detailed analysis shows that there do exist some exclusive states which can induce large $SU(3)$ symmetry breaking and contribute to y near the 1% level[7]. The dispersion relation implies that the magnitude of x is similar to that of y. With the help of some fair assumptions, one typically gets $x \lesssim y$ and $10^{-3} < |x| < 10^{-2}$. We can therefore draw a preliminary conclusion: the SM predictions for x and y remain quite uncertain, but the above order-of-magnitude estimates seem reasonable.

The BaBar collaboration has obtained the experimental evidence for D^0-$\bar{D}^0$ mixing from a measurement of the time dependence of the doubly-Cabibbo-suppressed decay $D^0 \to K^+\pi^-$ and its CP-conjugate mode[1]. The decay rate of $D^0 \to K^+\pi^-$ can be expressed as

$$\Gamma[D^0(t) \to K^+\pi^-] \propto$$
$$e^{-\Gamma t}\left[R + \sqrt{R}\, y'(\Gamma t) + \frac{x'^2 + y'^2}{4}(\Gamma t)^2\right] , \tag{10}$$

with

$$x' = x\cos\delta + y\sin\delta , \quad y' = y\cos\delta - x\sin\delta , \tag{11}$$

where $A(D^0 \to K^+\pi^-)/A(\bar{D}^0 \to K^+\pi^-) \approx R e^{i\delta}$ and $|q/p| \approx 1$ have been used in the neglect of tiny CP violation. The BaBar measurement yields $y' = (0.97\pm0.54)\times10^{-2}$ and $x'^2 = (-2.2\pm3.7)\times10^{-4}$, which at least indicates $y \sim 1\%$.

The Belle collaboration has used the decay mode $D^0 \to K^+K^-$ to extract the information on D^0-$\bar{D}^0$ mixing[1]. To a good degree of accuracy, the decay rates of $D^0 \to K^+K^-$ and $D^0 \to \pi^+K^-$ can approximate respectively to $\Gamma(D^0 \to K^+K^-) \approx e^{-\Gamma(1+y\cos\phi)t}$ and $\Gamma(D^0 \to \pi^+K^-) \approx e^{-\Gamma t}$, where ϕ is the weak phase of D^0-$\bar{D}^0$ mixing. Hence we have the lifetime ratio

$$\frac{\tau(D^0 \to \pi^+K^-)}{\tau(D^0 \to K^+K^-)} \approx 1 + y\cos\phi , \tag{12}$$

from which the effective mixing parameter

$$y_{CP} \equiv y\cos\phi \approx \frac{\tau(D^0 \to \pi^+K^-)}{\tau(D^0 \to K^+K^-)} - 1 , \tag{13}$$

can be extracted. Current experimental data yield $y_{CP} = (1.31\pm0.32\pm0.25)\times10^{-2}$, consistent with $y \sim 1\%$.

3 *CP* violation

In principle, there may be four different types of CP-violating signals in neutral D-meson decays.

1) CP violation in D^0-$\bar{D}^0$ mixing. This implies $|q/p| \neq 1$. In practice, we have the following CP-violating observable:

$$\Delta_D \equiv \frac{|p|^4 - |q|^4}{|p|^4 + |q|^4} . \tag{14}$$

It is expected that the magnitude of Δ_D should be at most of the order 10^{-3} in the SM[9]. However, a reliable estimation of Δ_D suffers from large long-distance uncertainties.

2) CP violation in the direct decay. For a decay mode $D^0 \to f$ and its CP-conjugate process $\bar{D}^0 \to \bar{f}$, this implies

$$|\langle\bar{f}|\mathcal{H}^{\Delta C=1}_{\rm weak}|\bar{D}^0\rangle| \equiv \left|\sum_n \left[A_n e^{i(\delta_n - \phi_n)}\right]\right| \neq$$
$$|\langle f|\mathcal{H}^{\Delta C=1}_{\rm weak}|D^0\rangle| \equiv \left|\sum_n \left[A_n e^{i(\delta_n + \phi_n)}\right]\right| , \tag{15}$$

where a parametrization of the decay amplitudes with the weak (ϕ_n) and strong (δ_n) phases is also given. We see that $n \geqslant 2$, $\phi_m - \phi_n \neq 0$ or π and $\delta_m - \delta_n \neq 0$ or π are necessary conditions for the above direct CP violation.

3) CP violation from the interplay of decay and mixing. Let us define two rephasing-invariant quan-

tities

$$\lambda_{\rm f} \equiv \frac{q}{p} \cdot \frac{\langle {\rm f}|\mathcal{H}^{\Delta C=1}_{\rm weak}|\bar{\rm D}^0\rangle}{\langle {\rm f}|\mathcal{H}^{\Delta C=1}_{\rm weak}|{\rm D}^0\rangle} \,, \qquad \bar{\lambda}_{\bar{\rm f}} \equiv \frac{p}{q} \cdot \frac{\langle \bar{f}|\mathcal{H}^{\Delta C=1}_{\rm weak}|{\rm D}^0\rangle}{\langle \bar{\rm f}|\mathcal{H}^{\Delta C=1}_{\rm weak}|\bar{\rm D}^0\rangle} \,, \tag{16}$$

where the hadronic states f and $\bar{\rm f}$ are common to the decay of D^0 (or $\bar{D}^0$). Even in the assumption of $|q/p|=1$, indirect CP violation can appear if

$$\mathrm{Im}\lambda_{\rm f} - \mathrm{Im}\bar{\lambda}_{\bar{\rm f}} \neq 0\,. \tag{17}$$

Provided f is a CP eigenstate (i.e., $|\bar{\rm f}\rangle = \pm|{\rm f}\rangle$) and the decay is dominated by a single weak phase, then we have $\bar{\lambda}_{\bar{\rm f}} = \lambda^*_{\rm f}$.

4) CP violation in the CP-forbidden decay. On the ψ(3770) (or ψ(4140)) resonance, a CP-odd (or CP-even) $D^0\bar{D}^0$ pair can be coherently produced:

$$\psi(3770) \rightarrow {\rm D}^0\bar{\rm D}^0\,;$$
$$\psi(4140) \rightarrow {\rm D}^0\bar{D}^{*0} \rightarrow {\rm D}^0\bar{\rm D}^0\pi^0\,, \rightarrow {\rm D}^0\bar{\rm D}^0\gamma\,. \tag{18}$$

The $D^0\bar{D}^0$ pairs produced in the above three processes are CP-odd, CP-odd and CP-even, respectively. Then the decay

$$\left({\rm D}^0\bar{\rm D}^0\right)_{CP=\pm1} \longrightarrow ({\rm f}_1{\rm f}_2)_{CP=\mp1}\,, \tag{19}$$

where f_1 and f_2 are proper CP eigenstates (e.g., $\pi^+\pi^-$, K^+K^- and $K_S\pi^0$), is a CP-forbidden process and can only occur due to CP violation.

Besides these four types of CP-violating effects in neutral D-meson decays, one may expect the effect of CP violation induced by K^0-$\bar{K}^0$ mixing in those decay modes with K_S or K_L in their final states[10]. Its magnitude is typically[11]

$$2\mathrm{Re}(\epsilon_{\rm K}) \approx 3.3\times10^{-3}\,, \tag{20}$$

which may be comparable in magnitude with the charmed CP-violating effects listed in Eqs. (14), (15) and (17). Kaplan emphasized that this kind of known CP-violating asymmetry should be measured in the charm factory as a calibration for the experimental systematics of asymmetries at the 0.1% level[12].

We have pointed out that the SM expectation for CP violation in the charm sector is of $\mathcal{O}(10^{-3})$ or smaller. The reason is simply that the charm unitarity triangle of the CKM matrix, formed by $V^*_{ud}V_{cd} + V^*_{us}V_{cs} + V^*_{ub}V_{cb} = 0$ in the complex plane, is too sharp. In the Wolfenstein phase convention recommended by the PDG[11], we have

$$\mathrm{Im}(V^*_{\rm ub}V_{\rm cb}) \approx -\lambda^6\sin\gamma\,, \tag{21}$$

where $\lambda \equiv \sin\theta_{\rm C} \approx 0.22$, and $\gamma \approx 65^\circ$ is one of the inner angles of the well-known beauty unitarity triangle of the CKM matrix. Hence the imaginary part of $V^*_{ud}V_{cd} + V^*_{us}V_{cs}$ must be $+\lambda^6\sin\gamma$, and the ratio of the CP-violating part to the CP-conserving part in many D-meson decay channels is characterized by

$$\frac{\mathrm{Im}(V^*_{\rm ub}V_{\rm cb})}{|V^*_{\rm ud}V_{\rm cd}|} \approx \frac{\mathrm{Im}(V^*_{\rm ub}V_{\rm cb})}{|V^*_{\rm us}V_{\rm cs}|} \approx A^2\lambda^4\sqrt{\rho^2+\eta^2}\ {\rm e}^{-{\rm i}\gamma} \approx \lambda^6{\rm e}^{-{\rm i}\gamma}\,, \tag{22}$$

which is about 5×10^{-4} in magnitude. This naive but reasonable estimate implies that the magnitudes of CP-violating asymmetries in neutral (and charged) D-meson decays are at most of $\mathcal{O}(10^{-3})$ in the SM, even if there are large final-state interactions. In general, the singly Cabibbo-suppressed D-meson decays may have larger CP-violating effects than those Cabibbo-favored and doubly Cabibbo-suppressed decays[13].

CP violation at the percent level has not been observed in any experiments[13]. But signals of $\mathcal{O}(10^{-3})$ are expected to show up in some neutral D-meson decays within the SM[14], although such theoretical estimates involve large uncertainties. If a CP-violating asymmetry of $\mathcal{O}(10^{-2})$ is observed in the (near) future, it will clearly signify the existence of new physics in the charm sector.

4 Concluding remarks

Now let me make some concluding remarks.

1) The SM predictions for D^0-$\bar{D}^0$ mixing and CP violation have very large uncertainties, and they are very hard to get improved in the foreseeable future.

2) However, D^0-$\bar{D}^0$ mixing up to the 1% level is very likely in the SM, consistent with current experimental evidence. The fact $x \lesssim y$ implies that this meson-antimeson mixing system might not be sensitive to new physics.

3) CP violation up to the 0.1% level is expected in the SM, and thus a signal of CP violation at the 1% level would serve as robust evidence of new physics in the charm sector.

4) But personally, I believe that new physics might essentially be decoupled to the standard flavor physics at low energy scales, just like the physics of massive neutrinos. I hope that I would be wrong.

5) No matter whether there is new physics or not in the charm sector, it is interesting and important to study D^0-$\bar{D}^0$ mixing and CP violation at the BEPC-II collider and other facilities.

Let us see what will happen in the coming years.

Many people in the audience believe that (CP) symmetry is beautiful. My friend, Peter Minkowski, believes that (CP-violating) asymmetry is a sister of (CP) symmetry. So, I have a very good reason to believe that (CP-violating) asymmetry is also beautiful! Then let us look for this sleeping beauty in the charm sector.

Finally, I would like to thank the organizers (in particular, Changchun Zhang and Hanqing Zheng) for inviting me to give this talk at the 2007 Joint BES-Belle-CLEO-BaBar Workshop on Charm Physics.

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