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D^0-$\overline{D}^0$ mixing: recent experimental results and intriguing prospects

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A summary of the present experimental limits on quantities related to D^0-$\overline{D}^0$ mixing is presented, with an emphasis on techniques that may achieve sensitivity to aspects of this phenomenon in the near future. The most stringent constraints on D-mixing parameters to date have been obtained by analyzing the decays $D^0 \to K^+\pi^-$, where the time-integrated rate has been determined to be $R_M < 0.04\%$ with 95% confidence. In the future, analyses of interference effects may be able to distinguish the contributions from x and y to the mixing rate.

1. INTRODUCTION

Although K^0-$\overline{K}^0$ mixing and B^0-$\overline{B}^0$ mixing are well established, D^0-$\overline{D}^0$ mixing is yet to be observed. As this particular mixing phenomenon is sensitive to new physics in a complementary manner to the K and B systems, it is an essential test of the completeness of the Standard Model. However, unlike B-mixing phenomena, which can be accurately calculated in the Standard Model from box diagrams, D-mixing phenomena are difficult to calculate because of dominant contributions from long-distance effects. The importance of these long-distance contributions has long been recognized [1,2], and more recent calculations [3,4] have predicted rates at the level of current experimental sensitivities, $R_M \sim \mathcal{O}(10^{-4})$, where R_M is the time-integrated mixing rate. In particular, the contribution from the mass difference of the mass eigenstates may be as large as that from the width difference [4]. Thus, an observation of D mixing at the current experimental level of sensitivity would not necessarily imply new physics. Nevertheless, mixing phenomena have been historic predictors of new physics, and the possibility of discovering new CP-violating effects in the D system makes its experimental analysis compelling.

A thorough review of D mixing is given in Ref. [5]. The two mass eigenstates

$$|D_{A,B}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle \tag{1}$$

generated by mixing dynamics have different masses ($m_{A,B}$) and widths ($\Gamma_{A,B}$), and we parameterize the mixing process with the quantities

$$x \equiv 2\frac{m_B - m_A}{\Gamma_B + \Gamma_A}, \quad y \equiv \frac{\Gamma_B - \Gamma_A}{\Gamma_B + \Gamma_A}. \tag{2}$$

It is not currently known which of the mass eigenstates is more massive, nor which is longer lived. Also, it is not known whether CP is a conserved quantity in this system. Thus, the labels (A) and (B) are used to denote the two mass eigenstates. If CP is not violated, then $|p/q| = 1$. The time-integrated mixing rate is approximately

$$R_M = (x^2 + y^2)/2. \tag{3}$$

This is a useful quantity that can be compared among different experimental analyses.

Four general experimental techniques which may be able to reveal the characteristics of D mixing in the near future are discussed. The first technique is to measure directly the lifetime difference y by measuring the D^0 lifetime in decays to CP eigenstates. The second technique is to search for evidence of mixing in the decay-time distributions of final states that receive contributions from mixing. This technique is sensitive to the mixing rate R_M. A third technique, recently presented by the CLEO Collaboration [6], involves a time-dependent analysis of the resonant behavior of a multibody final state. To the extent that interference effects can be measured, both of the parameters x and y can be determined. Finally, a fourth technique will use the coherent production of $D^0\overline{D}^0$ pairs accessible to the CLEO-c and BES-III experiments to study mixing phenomena [7]. Ref. [8] dis-

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cusses some additional details of these analyses not included herein.

2. MEASURING $\Delta\Gamma$

It is possible to measure the lifetime difference, y, of the two mass eigenstates directly, without searching for evidence of oscillations in decay-time distributions. In the context of the mixing searches sensitive only to R_M (Sec. 3), an independent measurement of y becomes very valuable, as it is difficult to get an independent handle on the mass difference, x. Assuming CP invariance,

$$y = \frac{\tau}{\tau_{CP+}} - 1, \tag{4}$$

where τ is the D^0 lifetime measured in decays to a non-CP eigenstate, such as $D^0 \to K^-\pi^+$, and τ_{CP+} is the lifetime measured in decays to CP-even eigenstates, such as $D^0 \to K^-K^+$ or $D^0 \to \pi^-\pi^+$. It would also be possible to perform a similar analysis with decays to CP-odd eigenstates, such as $D^0 \to K^0_S\phi$, although such an analysis has not yet been done. For reference, the world-average D^0 lifetime is $\tau = 410.3 \pm 1.5$ fs [9]. At the B factories, this corresponds to a decay length of approximately 200 μm, which is of the same scale as the decay-length resolution for these decays.

In the more general case that allows for possible CP violation in either mixing or interference between decay and mixing, we define the quantities Y and ΔY,

$$Y = \frac{\tau}{\langle\tau_{CP+}\rangle} - 1 \tag{5}$$

$$\Delta Y = \frac{\tau}{\langle\tau_{CP+}\rangle} A_{\tau+}, \tag{6}$$

where $\langle\tau_{CP+}\rangle$ is the average lifetime to the CP-even eigenstate,

$$\langle\tau_{CP+}\rangle = \frac{1}{2}\left(\tau^{D^0}_{CP+} + \tau^{\overline{D}^0}_{CP+}\right), \tag{7}$$

and $A_{\tau+}$ is the asymmetry between the two lifetimes

$$A_{\tau+} = \frac{\tau^{D^0}_{CP+} - \tau^{\overline{D}^0}_{CP+}}{\tau^{D^0}_{CP+} + \tau^{\overline{D}^0}_{CP+}}. \tag{8}$$

Of the lifetime-ratio measurements that have been made to date [10–15], the most precise is from the *BABAR* Collaboration [15]. In addition to the use of $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ tagged samples following from the decay $D^{*+} \to D^0\pi^+$ (+ C.C), this analysis uses a large untagged sample of $D^0 \to K^-K^+$ candidates. The tagged samples are so called because the production flavor of the D^0 ($\overline{D}^0$) is tagged by the charge of the D^{*+} (D^{*-}). The tagged samples are purer and can be used to search for possible CP violation; the untagged sample has more signal events, but with a significantly lower signal-to-background ratio.

The results of the *BABAR* analysis, including 26,000 tagged K^-K^+ candidates from 91 fb^{-1} of e^+e^- collisions, are

$$Y = (0.8 \pm 0.4\,(\text{stat.})\,^{+0.5}_{-0.4}\,(\text{syst.}))\% \tag{9}$$

$$\Delta Y = (-0.8 \pm 0.6\,(\text{stat.}) \pm 0.2\,(\text{syst.}))\%. \tag{10}$$

Assuming CP invariance, this yields the most stringent constraint on y to date. It would be important to improve this measurement using the larger data sets available in the near future if a non-zero mixing rate R_M were to be observed using the techniques described in the next Section.

3. MEASURING THE MIXING RATE R_M

Although the width difference, y, can be measured directly, the mass difference, x, is experimentally accessible only by searching for evidence of oscillations. This evidence manifests itself as a non-zero mixing rate, R_M. If a particular *wrong-sign* final state $|\bar{f}\rangle$ is only accessible through the process $D^0 \to \overline{D}^0 \to |\bar{f}\rangle$, then one simply counts the number of signal events in the final state to determine the time-integrated mixing rate, R_M. This is the motivation for analyzing the semileptonic decays $D^0 \to K^+\ell^-\nu_\ell$ and $D^0 \to K^{*+}\ell^-\nu_\ell$, which are only allowed via mixing. However, inability to separate signal from background due to the unreconstructed ν_ℓ seems thus far to compromise the experimental sensitivity. Of the four analyses of semileptonic modes to date [16–19], the three most sensitive—from *BABAR* [17], CLEO [18], and Belle [19]—report significantly higher limits on R_M than nonleptonic analyses performed using data samples of comparable integrated luminosities.

Nonleptonic wrong-sign decays, such as $D^0 \to K^+\pi^-$, can proceed both through mixing and through