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D^0-$\bar{D}^0$ mixing and search for CP violation in D^0 decays using T-odd correlations at BaBar

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We report on D^0 mixing and searches for *CP* violation in charm meson decays using the large sample of charm anti-charm produced in e^+e^- annihilation data collected with the BaBar detector at the PEP-II asymmetric-energy B-Factory near a center-of-mass energy of 10.58 GeV/c^2. A direct measurement of D^0-$\bar{D}^0$ mixing parameters through a time-dependent amplitude analysis of the Dalitz plots of $D^0 \to K_S\pi^+\pi^-$ and, for the first time, $D^0 \to K_S K^+ K^-$ decays is reported. We measure the mixing parameters x and y and provide the best measurement to date of x. We also report on a measurement of the D^0-$\bar{D}^0$ mixing parameter y_{CP}, obtained in a lifetime ratio analysis using untagged samples of $D^0 \to K^+K^-$ and $D^0 \to K^-\pi^+$. In addition, we report on a search for *CP* violation in Cabibbo-suppressed $D^0 \to K^+K^-\pi^+\pi^-$ decays, which is signaled by the difference between the T-odd asymmetries, obtained using triple product correlations, measured for $D^0$and $\bar{D}^0$decays.

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1. INTRODUCTION

Mixing and *CP* violation in neutral *D* mesons were discussed in 1975 [1], but it was not until 2007 that the BaBar and Belle collaborations made the first mixing measurements [2, 3]. Since then, this result has been confirmed by the same collaborations in multiple D^0 decay modes, [4, 5, 6] as well as by the CDF experiment. [7]

Mixing in neutral mesons occurs through either box diagram amplitudes (short-range effects) or through a sum over intermediate states accessible to both the meson and anti-meson (long-range effects). In D^0-$\bar{D}^0$ mixing, the box diagrams consist of amplitudes involving d, s and b quarks. If these three quarks had the same mass, these amplitudes would completely cancel one another out, and this accounts for the small contribution from the amplitudes involving d and s quarks. The b quark has the most different mass and could potentially contribute significantly to mixing. However, its couplings to u and c are suppressed relative to the decay rate of the D meson, and so we find minimal contributions from any of the box diagrams. In the standard model then, D^0-$\bar{D}^0$ mixing is dominated by the long-range diagrams. However, these are difficult to compute reliably [8, 9, 10, 11].

1.1 Notation and Formalism

While D^0 and $\bar{D}^0$ mesons are produced in flavour eigenstates, they propagate in time t and decay as mixtures of eigenstates D_1 and D_2, with masses and widths $M_{1,2}$ and $\Gamma_{1,2}$. We write the relationship between the flavour and mass eigenstates as follows:

$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle \qquad\qquad |D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle \tag{1.1}$$

with the requirement that $|p|^2 + |q|^2 = 1$. We make use of the canonical mixing parameters x, y, and ϕ_M and a decay parameter λ_f:

$$x = \frac{M_1 - M_2}{\Gamma} \;\; ; \;\; y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \;\; ; \;\; \phi_M = \mathrm{Arg}\left\{\frac{q}{p}\right\} \;\; ; \;\; \lambda_f = \frac{q\bar{\mathscr{A}}_f}{p\mathscr{A}_f} \propto e^{i(\delta_f + \phi_f)} \tag{1.2}$$

where M and Γ are averages for the two mass eigenstates and δ_f, ϕ_f are strong and weak relative phases, respectively, for the amplitudes $\mathscr{A}_f(\bar{\mathscr{A}}_f)$ for the decays of $D^0(\bar{D}^0)$ to the final state f. In the absence of *CP* violation in mixing $p = q = 1/\sqrt{2}$ and ϕ_M (the mixing phase) is zero, D_1 is *CP*-even and D_2 is *CP*-odd. If there is no direct *CP* violation in the decay, then either ϕ_f or $\delta_f = 0$.

In the standard model, the mixing parameters x and y are on the order of 1%, in good agreement with observation. *CP*violation is predicted to be less than 0.1% and has yet to be observed. Measuring a larger value for the mixing parameters or the observation of *CP* violation in the D^0 system with the present statistics would be an indication of new physics. [9, 10, 11, 12]. For a more complete discussion of neutral meson mixing in general and D^0-$\bar{D}^0$in particular, we direct the reader to the respective reviews in the *"Review of particle physics"* from the Particle Data Group [13]. In the following sections, we discuss recent experimental results from the *BABAR* collaboration on the mixing parameters x, y and y_{CP}, as well as a search for *CP* violation using T-odd asymmetries.

2. RECENT BABAR RESULTS

2.1 MEASUREMENT OF x AND y IN SELF-CONJUGATE FINAL STATES

In general the extraction of mixing parameters from observables in D^0 decays is complicated by terms that include the strong phase, δ_f, which arises from hadronization of the quarks in the final state. However, the analysis of self-conjugate D^0final states is insensitive to the strong phase and allows measuring x and y directly. A time-dependent Dalitz analysis is performed using the decays $D^0 \to K_S h^+ h^-$ where the h is a π or K. Let the position in the Dalitz plot be indicated by $s_+ = m^2(K_S h^+)$ and $s_- = m^2(K_S h^-)$. Assuming no *CP* violation in the decay, then $\mathscr{A}(s_+,s_-) = \bar{\mathscr{A}}(s_-,s_+)$, where $\mathscr{A}$ and $\bar{\mathscr{A}}$ are the respective decay amplitudes for a D^0 and a $\bar{D}^0$. The time-dependent decay amplitudes are then defined as

$$\mathscr{M}(s_+,s_-,t) = \mathscr{A}(s_+,s_-)g_+(t) + \frac{q}{p}\mathscr{A}(s_-,s_+)g_-(t) \quad (2.1)$$

$$\overline{\mathscr{M}}(s_+,s_-,t) = \frac{q}{p}\overline{\mathscr{A}}(s_+,s_-)g_+(t) + \overline{\mathscr{A}}(s_-,s_+)g_-(t) \quad (2.2)$$

where $g_\pm = \frac{1}{2}\left[e^{i(m_1-i\Gamma_1/2)t} \pm e^{i(m_2-i\Gamma_2/2)t}\right]$. If there is no *CP* violation in the mixing amplitude then $q/p = 1$. The decay rates are calculated by squaring $\mathscr{M}$ and $\overline{\mathscr{M}}$ and we find that the process is a function of (s_-,s_+) and proportional to $\cosh(y\Gamma t)$, $\sinh(y\Gamma t)$, $\cos(x\Gamma t)$, $\sin(x\Gamma t)$, and modulated by $e^{-\Gamma t}$. By assuming some model for the intermediate two-body resonances, we can extract x and y, which are the same in both the $K_S\pi^+\pi^-$ and $K_S K^+ K^-$ topologies. The mixing parameters are extracted by measuring the changes in the Dalitz plot distributions as a function of time,

We report on the use of this technique in a recent publication by the *BABAR* collaboration [14]. The analysis is performed using a data sample of 468.5 fb^{-1} of e^+e^- collisions, which corresponds to about 609M $c\bar{c}$ pairs. To measure the time-dependence, we reconstruct D^{*+} candidates in $D^{*+} \to D^0\pi^+$ and use the charge of the "slow" pion to tag the flavour of the D^0 at $t = 0$. After all cuts, we are left with a sample of 540,800$\pm$800 signal events (98.5% pure) for the $D^0 \to K_S\pi^+\pi^-$ decay mode, and 79,900$\pm$300 signal events (99.2% pure) for the $D^0 \to K_S K^+ K^-$ decay mode. The Dalitz plot amplitudes are modeled with a coherent sum of quasi-two-body amplitudes. Various models are used to describe the intermediate state resonances. The parameters in these models are varied, as is the choice of model for some line shapes, in order to estimate the uncertainties arising from these parameterizations. The final values from the fit to the data are $x = [1.6 \pm 2.3(\text{stat.}) \pm 1.2(\text{sys.}) \pm 0.8(\text{model})] \times 10^{-3}$ and $y = [5.7 \pm 2.0(\text{stat.}) \pm 1.3(\text{sys.}) \pm 0.7(\text{model})] \times 10^{-3}$. This is the most precise single measurement of x to date.

2.2 MEASUREMENT OF y_{CP} USING LIFETIME RATIO

By measuring the lifetime of D^0 using both *CP*-even and *CP*-mixed final states, we find another path to determining the D^0-$\bar{D}^0$ mixing rate. We first note that K^+K^- is a *CP*-even final state and $K^-\pi^+$ is a *CP*-mixed final state. We define the observable $y_{CP} = (\tau_{K\pi}/\tau_{KK}) - 1$ where τ_{KK} is the mean lifetime for $D^0 \to K^+K^-$ decays and $\tau_{K\pi}$ is the mean lifetime for $D^0 \to K^-\pi^+$. The mean lifetime for one of these decays is defined as $\langle\tau_{hh}\rangle = (\tau_{hh}^{D^0} + \tau_{hh}^{\bar{D}^0})/2$, where hh represents either the K^+K^- or $K^-\pi^+$ final state. A non-zero value for y_{CP} indicates D^0-$\bar{D}^0$ mixing arising from a width difference $(\Gamma_1 - \Gamma_2)$. If there is no direct *CP* violation, $y_{CP} = y$.

We report on the use of this technique in a recent publication by the *BABAR* collaboration [15]. Using a sample of 384 fb^{-1}, which roughly corresponds to 500M $c\bar{c}$ pairs, the D^0 and $\bar{D}^0$ are reconstructed without determining the initial flavour of the meson. We reconstruct $2710.2 \pm 3.4 \times 10^3$ signal events in the $D^0 \to K^-\pi^+$ decay mode with 94.2% purity and $263.6 \pm 1.0 \times 10^3$ signal events in the $D^0 \to K^+K^-$ decay mode with 80.9% purity. There are two main backgrounds: combinatorial and contributions from decays of non-signal charm mesons where two of the decay products are reconstructed as the daughters of a signal decay and pass the final event selection. We measure the lifetimes for the two decay modes to be $\tau_{K\pi} = 410.39 \pm 0.38(\text{stat.})$ps and $\tau_{KK} = 405.85 \pm 1.00(\text{stat.})$ps.

We calculate $y_{CP} = [1.12 \pm 0.26(\text{stat.}) \pm 0.22(\text{syst.})]\%$ and with this measurement alone, we exclude the no-mixing hypothesis at 3.3σ. We combine this result with a previously published tagged analysis [5], where we assume 100% correlated systematic uncertainties, and we find $y_{CP}(\text{correlated}) = [1.16 \pm 0.22(\text{stat}) \pm 0.18(\text{syst})]\%$. Summing statistical and systematic uncertainties in quadrature, the no-mixing hypothesis is excluded at 4.1σ.

2.3 SEARCH FOR *CP* VIOLATION USING *T*-ODD CORRELATIONS

In the standard model, *CP* violation is accommodated by a complex phase in the CKM quark mixing matrix. The predicted *CP* asymmetries in charm meson decays are $\mathcal{O}(10^{-3})$ or below, about one order of magnitude lower than current experimental limits[16]. Following a suggestion by I.I. Bigi [17], we search for *CP* violation in the decay $D^0 \to K^+K^-\pi^+\pi^-$ using a kinematic triple product correlation of the form $C_T = \mathbf{p_1} \cdot (\mathbf{p_2} \times \mathbf{p_3})$, where each $\mathbf{p_i}$ is a momentum vector of one of the particles in the decay [18]. The product is odd under time-reversal (T) and, assuming the *CPT* theorem, T violation is a signal for *CP* violation. Let Γ represent the decay rate and define the asymmetry

$$A_T \equiv \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}, \tag{2.3}$$

Strong interaction dynamics can produce a non-zero value of the A_T asymmetry, even if the weak phases are zero. The true T-violating asymmetry [19] is given as $\mathscr{A}_T = \frac{1}{2}(A_T - \overline{A_T})$, where A_T is the asymmetry for D^0 decays and $\overline{A_T}$ is the asymmetry for $\bar{D}^0$ decays. At least four particles are required in the final state so that the three used to define the triple product are independent [20] of each other. The analysis reduces to counting the D^0 and $\bar{D}^0$ candidates for which the C_T is either positive or negative.

The analysis is performed using a data sample of 470 fb^{-1} of e^+e^- collisions, which corresponds to about 611M $c\bar{c}$ pairs. The flavour of the D meson is tagged using the "slow" pion in the decay $D^{*+} \to D^0\pi^+$. Backgrounds come from four main sources: D^0 decays where the incorrect "slow" pion is used in the reconstruction, D^0 candidates where one or more of the final state K or π has been reconstructed with the incorrect particle hypothesis, combinatorial candidates where the final state K or π do not come from a signal D^0, and D_S^+ decays. We extract the number of candidates for C_T using a PDF that models the signal and these four backgrounds. Using the extracted signal yields, we calculate $A_T = [-68.5 \pm 7.3(\text{stat.}) \pm 5.8(\text{sys.})] \times 10^{-3}$, $\overline{A_T} = [-70.5 \pm 7.3(\text{stat.}) \pm 3.9(\text{sys.})] \times 10^{-3}$, and $\mathscr{A}_{\mathscr{T}} = [1.0 \pm 5.1(\text{stat.}) \pm 4.4(\text{sys.})] \times 10^{-3}$ We find that these values are consistent with a lack of a T asymmetry and therefore consistent with a lack of *CP* violation.

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