D^0-$\overline{D}^0$ Mixing at *BABAR*

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A selection of the most statistically significant measurements of D^0-$\overline{D}^0$mixing performed by the *BABAR* experiment operating at the SLAC National Accelerator Laboratory is presented. We present evidence for charm meson (D^0-$\overline{D}^0$) mixing using a sample of 384 fb^{-1} of e^+e^- colliding beam data recorded near $\sqrt{s} = 10.6$ GeV at the SLAC PEP-II asymmetric-energy B Factory. We measure the rate of mixing with the observable $y_{CP} = (\tau_{K\pi}/\tau_{KK}) - 1$, where τ_{KK} and $\tau_{K\pi}$ are respectively the mean lifetimes of CP-even $D^0 \to K^+K^-$ and CP-mixed $D^0 \to K^-\pi^+$ decays. A new *BABAR* measurement of the mixing parameter y_{CP} is presented for the first time in this conference. This new result is in good agreement with a previous *BABAR* measurement, obtained from a sample of $D^{*+} \to D^0\pi^+$ events, where the D^0 decays to $K^-\pi^+$, K^+K^-, and $\pi^+\pi^-$, which is disjoint with the untagged D^0 events. By combining these two measurements, the no-mixing hypothesis is excluded at 4.1σ level. Finally, by measuring the wrong-sign decay $D^0 \to K^+\pi^-$, we exclude the no-mixing hypothesis with a significance of 3.9 standard deviations.

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1. Introduction

Originally devoted for testing *CP* violation in the *b*-quark sector, the *BABAR* experiment (described elsewhere [1]) has also obtained important results in charm physics, in particular D^0-$\bar{D}^0$ mixing. Most of *BABAR* data has been collected at the $\Upsilon(4)$ resonance, at this energy the charm production cross-section is approximately $\sigma(e^+e^- \to c\bar{c}) \approx 1.3$ nb, while the cross-section for the production of $b\bar{b}$ pairs is $\sigma(e^+e^- \to c\bar{c}) \approx 1.05$ nb. It is clear that *BABAR* is a very useful laboratory to investigate charm physics and D^0-$\bar{D}^0$ mixing. Here I present two measurements of D^0-$\bar{D}^0$ mixing parameters using the ratios of lifetimes of *CP*-even and *CP*-mixed D^0 decays, and one measurement using the wrong-sign decay $D^0 \to K^+\pi^-$.

The charm sector is the only place where the contributions to *CP* violation of down-type quarks in the mixing diagram can be explored. Several recent results [2, 3, 4, 5] show evidence for non-negligible mixing in the D^0-$\bar{D}^0$ system consistent with predictions of possible Standard Model contributions [6, 7, 8, 9, 10]. These results also constrain many new physics models [11, 12, 13, 14], and increasingly precise D^0-$\bar{D}^0$ mixing measurements will provide even stronger constraints.

The D^0 and $\bar{D}^0$ mesons are produced as flavor eigenstates, but evolve and decay as mixtures of the eigenstates D_1 and D_2 of the Hamiltonian, with masses and widths m_1, Γ_1 and m_2, Γ_2 respectively. Mixing is characterised by the parameters $x \equiv \Delta m/\Gamma$ and $y \equiv \Delta\Gamma/2\Gamma$, where $\Delta m = m_1 - m_2$ and $\Delta\Gamma = \Gamma_1 - \Gamma_2$ are respectively the mass and width differences, and $\Gamma = (\Gamma_1 + \Gamma_2)/2$ is the average width. If either x or y is non-zero, mixing will occur, altering the decay time distribution of D^0 and $\bar{D}^0$ mesons decaying into final states of specific *CP* [16].

2. D^0-$\bar{D}^0$ Mixing from Analysis of Wrong Sign $D^0 \to K^+\pi^-$ Decays

At *BABAR*, the first evidence for D^0-$\bar{D}^0$ mixing was found by studying the right-sign (RS), Cabibbo-favored (CF) decay $D^0 \to K^-\pi^+$ and the wrong-sign (WS) decay $D^0 \to K^+\pi^-$ [2]. The latter can be produced via the doubly Cabibbo-suppressed (DCS) decay $D^0 \to K^+\pi^-$ or via mixing followed by a CF decay $D^0 \to \bar{D}^0 \to K^+\pi^-$ [17]. The DCS decay has a small rate $R_{\rm D}$ of order $\tan^4\theta_{\rm C} \approx 0.3\%$ relative to CF decay with $\theta_{\rm C}$ the Cabibbo angle. We distinguish D^0 and $\bar{D}^0$ by their production in the decay $D^{*+} \to \pi_s^+ D^0$ where the π_s^+ is referred to as the "slow pion". In RS decays the π_s^+ and kaon have opposite charges, while in WS decays the charges are the same. The time dependence of the WS decay rate is used to separate the contributions of DCS decays from D^0-$\bar{D}^0$ mixing.

We approximate the time dependence of the WS decay of a meson produced as a D^0 at time $t = 0$ in the limit of small mixing ($|x|$, $|y| \ll 1$) and *CP* conservation as

$$\frac{T_{\rm WS}(t)}{e^{-\Gamma t}} \propto R_{\rm D} + \sqrt{R_{\rm D}}y'\,\Gamma t + \frac{x'^2 + y'^2}{4}(\Gamma t)^2\,, \tag{2.1}$$

where $x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$, $y' = -x\sin\delta_{K\pi} + y\cos\delta_{K\pi}$, and $\delta_{K\pi}$ is the strong phase between the DCS and CF amplitudes.

Assuming *CP* conservation, we have found evidence for D^0-$\bar{D}^0$ mixing by fitting for the parameters $R_{\rm D}$, x'^2, and y'. We measure $y' = [9.7 \pm 4.4\ (\text{stat.}) \pm 3.1\ (\text{syst.})] \times 10^{-3}$, while x'^2 is consistent with zero. We also measure $R_{\rm D}$ to be $[0.303 \pm 0.016\ (\text{stat.}) \pm 0.010\ (\text{syst.})]\%$. Our result is inconsistent with the no-mixing hypothesis at a significance of 3.9 standard deviations.

3. D^0-$\bar{D}^0$ Mixing from Lifetime Ratio Measurements

One manifestation of D^0-$\bar{D}^0$ mixing is differing D^0 decay time distributions for decays to different *CP* eigenstates [15]. In the limit of small mixing, and no *CP* violation in mixing or in the interference between mixing and decay (assumptions which are consistent with current experimental results), the mean lifetimes of decays to a *CP* eigenstate of a sample of D^0 ($\tau_{hh}^{D^0}$) and $\bar{D}^0$ ($\tau_{hh}^{\bar{D}^0}$), along with the mean lifetime of decays to a state of indefinite *CP* ($\tau_{K\pi}$), can be combined into the quantity

$$y_{CP} = \frac{\langle \tau_{K\pi} \rangle}{\langle \tau_{hh} \rangle} - 1, \tag{3.1}$$

where $\langle \tau_{hh} \rangle = (\tau_{hh}^{D^0} + \tau_{hh}^{\bar{D}^0})/2$. Noting that the untagged $K^-\pi^+$ [17] final state is a mixture of Cabbibo-favoured and doubly Cabbibo-suppressed D^0 and $\bar{D}^0$ decays with a purely exponential lifetime distribution, along with a very small admixture of mixed D^0 decays, an analogous expression also holds for $\langle \tau_{K\pi} \rangle$. Given the current experimental evidence indicating a small mixing rate, the lifetime distribution for all hh and $K\pi$ final states is exponential to a good approximation. If y_{CP} is zero there is no D^0-$\bar{D}^0$ mixing attributable to a width difference, although mixing caused by a mass difference may be present. In the limit of no direct *CP* violation, $y_{CP} = y$.

A new *BABAR* measurement [19] of the mixing parameter y_{CP} is presented for the first time in this conference. We measure the D^0 mean lifetime in the D^0 decay modes $K^-\pi^+$ and K^-K^+, where the initial flavor of the decaying D^0 is not identified (the *untagged* sample). An earlier measurement [18] of the mixing parameter y_{CP} was carried out using a sample of D^0 mesons, produced through the process $D^{*+} \to D^0\pi^+$, that decay to $K^-\pi^+$, K^+K^-, and $\pi^+\pi^-$ (the *tagged* sample), and which is disjoint with the untagged D^0 events. The discussion in this section is focused on the analysis of the untagged sample, unless is explicitly stated.

The invariant mass distributions for the untagged $D^0 \to K^-\pi^+$ and $D^0 \to K^-K^+$ samples are shown in Fig. 1. For the lifetime fits, we use only events within $\pm 10\,\mathrm{MeV}/c^2$ of the D^0 signal peak $1.8545 < M_{D^0} < 1.8745\,\mathrm{GeV}/c^2$ (the *lifetime fit mass region*). The $K^-\pi^+$ and K^-K^+ signal yields within this region and their purity are given in Table 1. Events within the mass sideband regions $1.81 < M_{D^0} < 1.83\,\mathrm{GeV}/c^2$ and $1.90 < M_{D^0} < 1.92\,\mathrm{GeV}/c^2$ are used to determine the combinatorial background decay time distribution within the lifetime fit mass region. In addition to purely combinatorial backgrounds, there are small background contributions from decays of non-signal charm parents where two of the decay products are selected as the daughters of a signal decay and subsequently pass the final event selection. These misreconstructed charm backgrounds are accounted for using simulated events. Their contribution is $\sim 0.7\%$ ($\sim 3.8\%$) of the total number of background events in the $K^-\pi^+$ (K^-K^+) signal region.

To avoid potential bias, we finalised our data selection criteria, fitting methodology, sources of possible systematic uncertainties to be examined, and method of calculating statistical limits for the untagged analysis alone and in combination with the tagged analysis, prior to examining the mixing results from the untagged data. In general, systematic uncertainties related to the reconstruction of signal events cancel in the lifetime ratio. However, uncertainties related to the somewhat differing backgrounds present in the $K^-\pi^+$ and K^+K^- final states lead to larger systematic uncertainties in the untagged analysis compared to those of the tagged analysis, which has much higher signal purity. Table 1 shows signal purities for tagged and untagged samples.

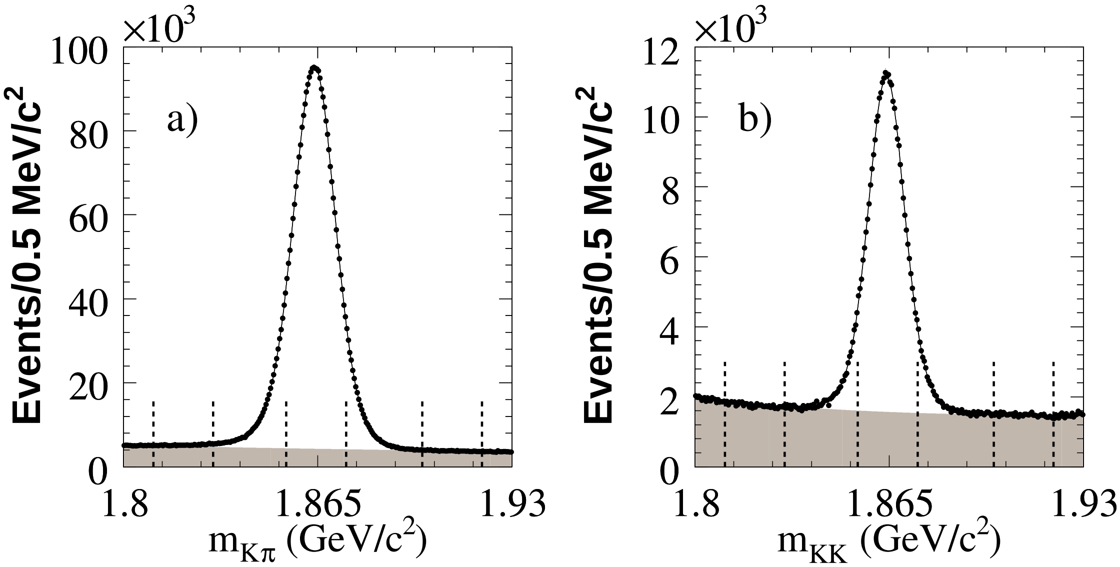

Figure 1: (a) $D^0 \to K^-\pi^+$ and (b) $D^0 \to K^-K^+$ invariant mass distribution with the data (points), total fit (line) and background contribution (solid) overlaid. The innermost dashed lines on either side of the signal peaks delimit the lifetime fit mass region, with lower and upper mass sidebands shown on either side.

Table 1: $D^0 \to K^-\pi^+$, $D^0 \to K^-K^+$ and $D^0 \to \pi^+\pi^-$ signal yield and purity in the lifetime fit mass region.

Sample	Decay	Signal Yield	Purity (%)
Untagged	$K^-\pi^+$	$2,709,949$	94.2
	K^-K^+	$263,602$	80.9
Tagged	$K^-\pi^+$	$730,880$	99.9
	K^-K^+	$69,696$	99.6
	$\pi^-\pi^+$	$30,679$	98.0

The mean D^0 lifetime is determined from an extended unbinned maximum likelihood fit, essentially identical to the one performed in the previous tagged analysis [18], using the reconstructed decay time t and the decay time uncertainty σ_t for events within the lifetime fit mass region. Three categories of events are accounted for in the lifetime fit: signal decays, combinatorial background, and misreconstructed charm events.

The functional form of the probability density function (PDF) for the decay time distribution of signal events is described by an exponential convolved with a resolution function which is taken as the sum of three Gaussian functions with widths proportional to σ_t. The decay time distribution of the combinatorial background is described by a sum of two Gaussians and a modified Gaussian with a power-law tail to account for a small number of events with large reconstructed lifetimes. Events in the lower and upper $K^-\pi^+$ (K^-K^+) mass sidebands are fit separately, and a weighted average of the results of these fits is used to parameterise the PDF for $K^-\pi^+$ (K^-K^+) combinatorial events in the lifetime fit mass region. Misreconstructed charm background events have one or more of the charm decay products either not reconstructed or reconstructed with the wrong particle

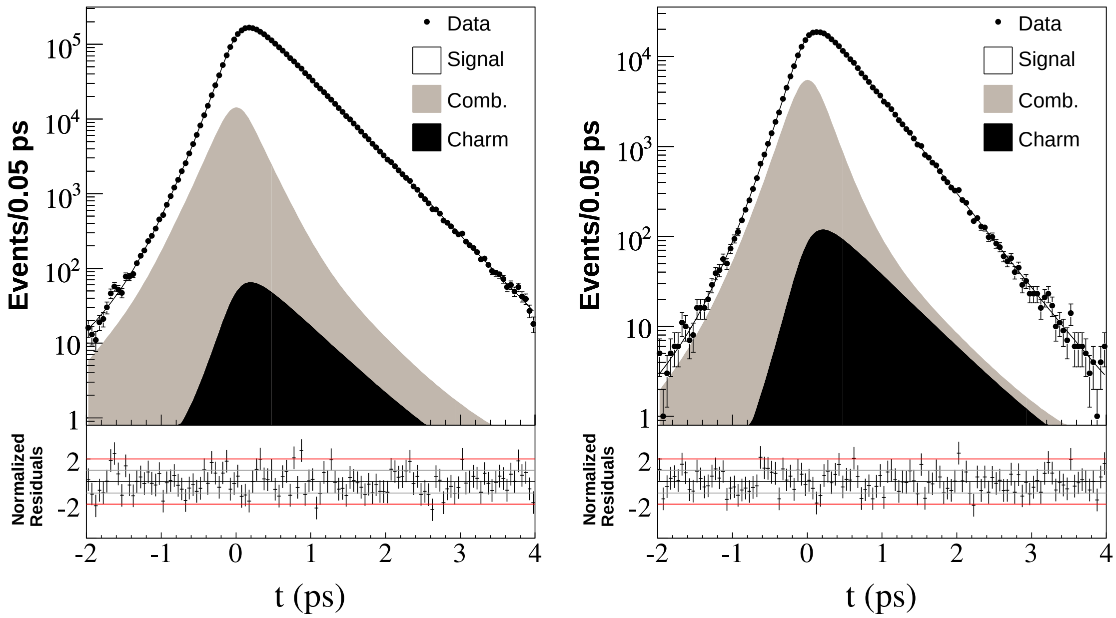

Figure 2: $D^0 \to K^-\pi^+$ (left) and $D^0 \to K^-K^+$ (right) decay time distribution with the data (points), total lifetime fit (line), combinatorial background (gray) and charm background (black) contributions overlaid.

hypothesis. The charm background is long-lived and is described using an exponential convolved with a resolution function consisting of two Gaussians with a shared mean and widths that depend on σ_t. Because the number of these events in the $K^-\pi^+$ (K^-K^+) sample is small relative to the total background, an effective lifetime distribution taken from simulated events and summed over all $K^-\pi^+$ (K^-K^+) charm backgrounds is used in the $K^-\pi^+$ (K^-K^+) lifetime fit.

Many of the systematic uncertainties associated with the individual lifetime measurements cancel to a great extent in the ratio of lifetimes. We consider as possible sources of systematic uncertainty: variations in the signal and background fit models, changes to the event selection, and detector effects that might introduce biases in the lifetime measurements. Numerous cross-checks have been performed to assure the unbiased nature of the fit model and to validate the assumptions used in its construction.

The results of the lifetime fits are shown in Fig. 2. We find the $D^0 \to K^-\pi^+$ mean lifetime $\tau_{K\pi} = 410.39 \pm 0.38$ (stat.) fs and the $D^0 \to K^-K^+$ mean lifetime $\tau_{KK} = 405.85 \pm 1.00$ (stat.) fs, yielding $y_{CP}(\text{untagged}) = [1.12 \pm 0.26\ (\text{stat.}) \pm 0.22\ (\text{syst.})]\%$, which excludes the no-mixing hypothesis at 3.3σ, including both statistical and systematic uncertainties. Our previous tagged result [18] is $y_{CP}(\text{tagged}) = [1.24 \pm 0.39\ (\text{stat.}) \pm 0.13\ (\text{syst.})]\%$. These results contain no events in common, and are thus statistically uncorrelated by construction. However, the degree of correlation in the systematic uncertainties is less clear, and we conservatively assume a 100% correlation in the systematics shared between the two analyses. Combining the tagged and untagged results taking into account both statistical and systematic uncertainties [20], 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 significance of this measurement is 4.1σ.

4. Conclusions

The evidence for D^0-$\bar{D}^0$ mixing at *BABAR* is compelling. We reported on a new measurement of the mixing parameter y_{CP} using a sample of D^0 decays where the flavour of the D^0 is not identified, this measurement excludes the no-mixing hypothesis at 3.3σ [19], including both statistical and systematic uncertainties. The result is consistent with our previous measurement of y_{CP} from a sample of flavour-tagged D^0 decays [18]. Combining these two lifetime ratio measurements, we exclude the no mixing hypothesis with a significance of 4.1 σ. Finally, by measuring the wrong-sign $D^0 \to K^+\pi^-$ decay [2], we exclude the no mixing hypothesis with a significance of 3.9 σ. The results are consistent with SM estimates for mixing.

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