D^0-$\overline{D}^0$ mixing at BaBar

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Abstract. This article reviews the recent measurement of D^0-$\overline{D}^0$ mixing with the $D^0 \to K\pi$ decay channel from the *BABAR* experiment at the PEP-II B-Factory. Averages from the Heavy Flavor Averaging Group btween this result and a previous result from BELLE are also presented.

Introduction

Evidence for charm-meson (D^0-$\overline{D}^0$) mixing is presented. This work complements results in the neutral K [1, 2], B [3, 4], and B_s [5, 6] systems. Although precise predictions are difficult, D^0-$\overline{D}^0$ mixing in the Standard Model (SM) is expected at the 1% level or less [7, 8, 9, 10, 11, 12]. This result is consistent with this expectation and previous experimental limits [13, 14, 15, 16, 17, 18]. By observing the wrong-sign decay $D^0 \to K^+\pi^-$ [19], R_D, the ratio of doubly Cabibbo-suppressed to Cabibbo-favored decay rates, and the mixing parameters x'^2 and y' are determined.

The right-sign (RS), Cabibbo-favored (CF) decay $D^0 \to K^-\pi^+$ and the wrong-sign (WS) decay $D^0 \to K^+\pi^-$ are studied. 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 $D^0 \to \overline{D}^0 \to K^+\pi^-$. The DCS decay has a small rate R_D of order $\tan^4\theta_C \approx 0.3\%$ relative to CF decay. D^0 and $\overline{D}^0$ are distinguished by their production in the decay $D^{*+} \to \pi_\mathrm{s}^+ D^0$ 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-$\overline{D}^0$ mixing.

The D^0 and $\overline{D}^0$ 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 characterized by the mass and lifetime differences $\Delta M = M_1 - M_2$ and $\Delta\Gamma = \Gamma_1 - \Gamma_2$. Defining the parameters $x = \Delta M/\Gamma$ and $y = \Delta\Gamma/2\Gamma$, where $\Gamma = (\Gamma_1 + \Gamma_2)/2$, 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 is approximated as

$$\frac{T_\mathrm{WS}(t)}{e^{-\Gamma t}} \propto R_\mathrm{D} + \sqrt{R_\mathrm{D}}y'\,\Gamma t + \frac{x'^2 + y'^2}{4}(\Gamma t)^2\,, \tag{1}$$

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.

Both CP-conserving and CP-violating cases are studied. For the CP-conserving case, the parameters R_D, x'^2, and y' are extracted. To search for CP violation, Eq. (1) is applied to D^0 and $\overline{D}^0$ samples separately, fitting for the parameters $\{R_\mathrm{D}^\pm,\ x'^{\pm 2},\ y'^\pm\}$ for D^0 (+) decays and $\overline{D}^0$ (−) decays.

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Measurement Of D^0-$\overline{D}^0$ Mixing In The Decay $D^0 \rightarrow K^+\pi^-$

We use 384 fb^{-1} of e^+e^- colliding-beam data recorded near $\sqrt(s) = 10.6$ GeV with the *BABAR* detector at the PEP-II asymmetric-energy storage rings. D^0 candidates are selected by pairing oppositely-charged tracks with a $K^\pm\pi^\pm$ invariant mass m($K\pi$) between 1.81 and 1.92 GeV/c^2. Each pair is identified as $K^\pm\pi^\pm$ using a likelihood-based particle identification algorithm.

The proper decay time t and its error δt for each D^0 candidate is obtained from a fit to a common vertex for both the $K^\pm$ $\pi^\pm$ tracks. The D^0 and the π_s are also required to originate from a common vertex, constrained to e^+e^- interaction region in both size and position. The π_s is required to have a momentum in the laboratory frame greater than 0.1 GeV/c and below 0.45 GeV/c in the e^+e^- center of mass frame. The χ^2 probability of the vertex constrained, combined fit $P(\chi^2)$ must be at least 0.1%, and the mass difference m_{D^*}-$m_{K\pi}$ (Δm) to satisfy $0.14 < \Delta m < 0.16\,\text{GeV}/c^2$.

To eliminate D^0 candidates from B-meson decays and to reduce combinatorial backgrounds, each D^0 is required to have a momentum in the CM frame greater than 2.5 GeV/c, and requirements of $-2 < t < 4$ ps and $\sigma_t < 0.5$ ps are imposed (the most probable value of σ_t) for signal events is 0.16 ps). For D^* candidates sharing one or more tracks with other D^*candidates, only the candidate with the highest $P(\chi^2)$ is retained. After applying all criteria, approximately 1,299,000 RS and 64,000 WS D^0 and $\overline{D}^0$ candidates are kept. To avoid potential bias, our data selection criteria and the procedures for fitting and extracting the statistical limits are finalized without examining the mixing results.

The mixing parameters are determined in an unbinned, extended maximum-likelihood fit to the RS and WS data samples over the four observables $m_{K\pi}$, Δm, t and σ_t. The fit is performed in several stages. First, RS and WS signal and background shape parameters are determined from a fit to $m_{K\pi}$ and Δm, and are not varied in subsequent fits. Next the D^0 proper-time resolution function and lifetime are determined in a fit to the RS data using $m_{K\pi}$ and Δm to separate the signal and the background components. The WS data sample is fit using three different models. The first model assumes both *CP* conservation and the absence of mixing, and only measures R_D. The second model allows for mixing, but assumes no *CP* violation, while the third model allows for both mixing and *CP* violation.

The RS and WS ($m_{K\pi}$, Δm) distributions are described by four components: signal, random π_s^+, mis-reconstructed D^0 and combinatorial background. The signal component has a characteristic peak in both $m_{K\pi}$ and Δm. The random π_s^+ component models reconstructed D^0 decays combined with a random slow pion and has the same shape in $m_{K\pi}$ as signal events, but does not peak in Δm. Mis-reconstructed D^0 events have one or more of the D^0 decay products either not reconstructed or reconstructed with the wrong particle hypothesis. They peak in Δm, but not in $m_{K\pi}$. For RS events, most of these are semileptonic decays $D^0 \rightarrow K^-\ell^+\nu$ with the charged lepton misidentified as a pion. For WS events, the main contributor is RS $D^0 \rightarrow K^-\pi^+$ decays where the K^- and the π^+ are misidentified as π^- and K^+, respectively. Combinatorial background events are those not described by the above components; they do not exhibit any peaking structure in $m_{K\pi}$ or Δm.

The functional forms of the probability density functions (PDFs) for the signal and background components are chosen based on studies of Monte Carlo (MC) samples. However, all parameters are determined from two-dimensional likelihood fits to data over the full $1.81 < m_{K\pi} < 1.92\,\text{GeV}/c^2$ and $0.14 < \Delta m < 0.16\,\text{GeV}/c^2$ region.

The RS and WS data samples are fit simultaneously with shape parameters describing the signal and random π_s^+ components shared between the two data samples. We find $1,141,500 \pm 1,200$ RS signal events and $4,030 \pm 90$ WS signal events. The dominant background component is the random π_s^+ background.

The fit to the RS proper-time distribution is performed over all events in the full $m_{K\pi}$ and Δm region. The PDFs for signal and backgrounds in $m_{K\pi}$ and Δm are used in the proper-time fit with all parameters fixed to their previously determined values. The fitted D^0 lifetime is found to be consistent with the world-average lifetime [20].

The measured proper-time distribution for the WS signal is modeled by Eq. (1) convolved with the resolution function determined in the RS proper-time fit. The random π_s^+ and mis-reconstructed D^0 backgrounds are described by the RS signal proper-time distribution since they are real D^0 decays. The proper-time distribution for WS data is shown in Fig. 1. The fit results with and without mixing are shown as the overlaid curves.

The fit with mixing provides a substantially better description of the data than the fit with no mixing. The significance of the mixing signal is evaluated based on the change in negative log likelihood with respect to the minimum. The likelihood maximum is at the unphysical value of $x'^2 = -2.2 \times 10^{-4}$ and $y' = 9.7 \times 10^{-3}$. The value of $-2\Delta \ln \mathcal{L}$ at the most likely point in the physically allowed region ($x'^2 = 0$ and $y' = 6.4 \times 10^{-3}$) is 0.7 units. The value of $-2\Delta \ln \mathcal{L}$ for no-mixing is 23.9 units. Including systematic uncertainties, this corresponds to a significance equivalent to 3.9 standard deviations ($1 - \mathrm{CL} = 1 \times 10^{-4}$) and thus constitutes evidence for mixing.

Allowing for the possibility for *CP* violation, the values for D^0 and $\overline{D}^0$ decay-time dependence are fit separately.No evidence for *CP* violation is seen. The best fit in each case is more than three standard deviations away from the no mixing hypothesis.

As a cross-check for the mixing signalthe fitted WS branching fractions are are extrapolated and are seen to increase as a function of time. The slope is consistent with the measured mixing parameters and inconsistent with the no-mixing hypothesis

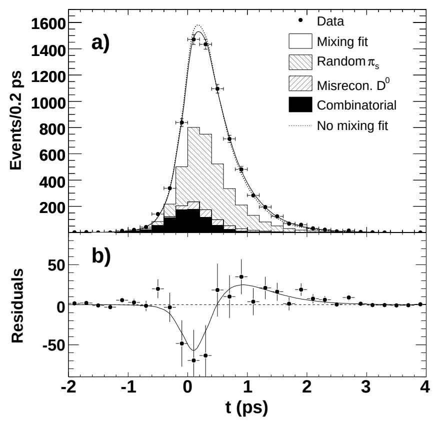

Figure 1. a) The proper-time distribution of combined D^0 and $\overline{D}^0$ WS candidates. b) The points represent the difference between the data and the no-mixing fit. The solid curve shows the difference between fits with and without mixing.

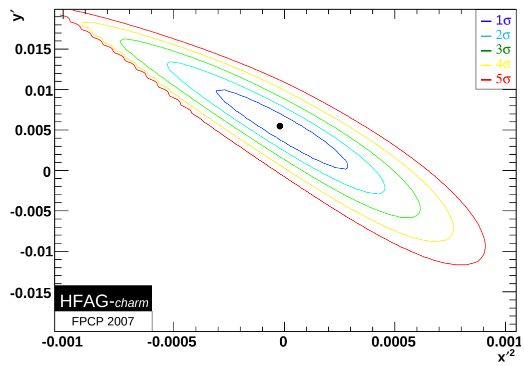

Figure 2. *BABAR* and BELLE combined average of the (x'^2, y') projection mapped liklehood $\rightarrow$ (x, y), assuming *CP* conservation.

To evaluate the systematic uncertainties in R_D and the mixing parameters, variations in the fit model and the selection criteria have been considered. Alternative forms of the $m_{K\pi}$, Δm, t, and Δt PDF's are also considered. The t and Δt requirements were varied. In addition, variations that keep or reject all D^{*+} candidates sharing tracks with other candidates were considered.

Summary

Evidence is presented for D^0-$\overline{D}^0$ mixing, and is inconsistent with the no mixing at 3.9 standard deviations from zero ($stat. + syst.$). This analysis measures $y = [9.7 \pm 4.4(stat.) \pm 3.1(syst.)] \times 10^{-3}$, $x^2 = [-0.22 \pm 0.30(stat.) \pm 0.219(syst.)] \times 10^{-3}$ and is consistent with zero, with a value of $R_D = [0.303 \pm 0.016(stat.) \pm 0.010(syst.)]\%$ [21] No evidence has been seen for CP violation. Our results are consistent with a similar analysis from Belle [14] the combination of these from the Heavy Flavor Averaging Group [22], gives the following world averages for the mixing parameters assuming CP conservation:

$$R_D = 3.30^{+0.14}_{-0.12} \times 10^{-3}, x^2 = -0.01 \pm 0.20 \times 10^{-3}, y = 5.5^{+0.28}_{-0.37} \times 10^{-3}. \tag{2}$$

The confidence-level contours are shown in Fig 2. These results are consistent with the Standard Model estimates for mixing, and also provide strong constraints on new physics models [23].

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