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# $D^0\bar{D}^0$ Quantum Correlations, Mixing, and Strong Phases*

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## Abstract

Due to the quantum correlation between the pair-produced $D^0$ and $\bar{D}^0$ from the decay of the $\psi(3770)$, the time-integrated single and double tag decay rates depend on charm mixing amplitudes, doubly-Cabibbo-suppressed amplitudes, and the relative strong phase $\delta$ between $D^0$ and $\bar{D}^0$ decays to identical final states. Using 281 pb$^{-1}$ collected with the CLEO-c detector on the $\psi(3770)$ resonance, we measure the absolute branching fractions of $D^0$ decays to hadronic flavored states, $CP$ eigenstates, and semileptonic final states to determine the relative strong phase, $\cos\delta$, of the $K^-\pi^+$ final state and to limit the mixing amplitude $y$. The results presented in this document are preliminary.

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|  | $f$ | $\ell^+$ | $S_+$ | $S_-$ |
|---|---|---|---|---|
| $f$ | $\mathcal{N}\mathcal{B}_f^2 R_M[1 + r_f^2(2 - z^2) + r_f^4]$ |  |  |  |
| $\bar{f}$ | $\mathcal{N}\mathcal{B}_f^2[1 + r_f^2(2 - z^2) + r_f^4]$ |  |  |  |
| $\ell^-$ | $\mathcal{N}\mathcal{B}_f\mathcal{B}_\ell$ | $\mathcal{N}\mathcal{B}_\ell^2$ |  |  |
| $S_+$ | $\mathcal{N}\mathcal{B}_f\mathcal{B}_{S_+}(1 + r_f^2 + r_f z_f)$ | $\mathcal{N}\mathcal{B}_\ell\mathcal{B}_{S_+}$ | 0 |  |
| $S_-$ | $\mathcal{N}\mathcal{B}_f\mathcal{B}_{S_-}(1 + r_f^2 - r_f z_f)$ | $\mathcal{N}\mathcal{B}_\ell\mathcal{B}_{S_-}$ | $4\mathcal{N}\mathcal{B}_{S_+}\mathcal{B}_{S_-}$ | 0 |
| $X$ | $\mathcal{N}\mathcal{B}_f(1 + r_f^2 + r_f z_f y)$ | $\mathcal{N}\mathcal{B}_\ell$ | $2\mathcal{N}\mathcal{B}_{S_+}(1 - y)$ | $2\mathcal{N}\mathcal{B}_{S_-}(1 + y)$ |

TABLE I: ST and DT yields for $C = -1$ $D^0\bar{D}^0$ events, to leading order in $x$ and $y$.

When $D^0$ and $\bar{D}^0$ mesons are pair-produced in $e^+e^-$ collisions with no accompanying particles (such as through the $\psi(3770)$ resonance), they are in a quantum-coherent $C = -1$ state. Because the initial state (the virtual photon) has $J^{PC} = 1^{--}$, there follows a set of selection rules for the decays of the $D^0$ and $\bar{D}^0$ [1–4]. For example, both $D^0$ and $\bar{D}^0$ cannot decay to $CP$ eigenstates with the same eigenvalue. On the other hand, decay rates to $CP$ eigenstates of opposite eigenvalue are enhanced by a factor of two. More generally, final states that can be reached by both $D^0$ and $\bar{D}^0$ are subject to similar interference effects. As a result, the apparent $D^0$ branching fractions in this $D^0\bar{D}^0$ system differ from those of isolated $D^0$ mesons. Moreover, using time-independent rate measurements, it is possible to probe the $D^0$-$\bar{D}^0$ mixing parameters $x \equiv \Delta M/\Gamma$ and $y \equiv \Delta\Gamma/2\Gamma$, which are the mass and width differences between $D_{CP+}$ and $D_{CP-}$, as well as the relative strong phases between $D^0$ and $\bar{D}^0$ decay amplitudes to any given final state.

We implement the technique presented in Ref. [5], where four types of final states are considered: flavored (labeled by $f$ and $\bar{f}$), $CP+$ eigenstates ($S_+$), $CP-$ eigenstates ($S_-$), and semileptonic ($\ell^+$ and $\ell^-$). Event yields are functions of the number of $D^0\bar{D}^0$ pairs produced (denoted by $\mathcal{N}$, branching fractions (denoted by $\mathcal{B}$), the mixing parameters $y$ and $R_M \equiv (x^2 + y^2)/2$, and the amplitude ratio $\langle f|\bar{D}^0\rangle/\langle f|D^0\rangle$, whose magnitude and phase are denoted by $r_f$ and $-\delta_f$, respectively. We define $z_f \equiv 2\cos\delta_f$ and give expressions for these yields in Table I, to leading order in $x$ and $y$.

Our analysis uses 281 pb$^{-1}$ of $e^+e^-$ collisions, taken on the $\psi(3770)$ resonance, with $\sqrt{s} =$ 3773 MeV. The data were collected with the CLEO-c detector, which is a modification of CLEO III [6–9], in which the silicon-strip vertex detector was replaced with a six-layer vertex drift chamber, whose wires are all at small stereo angles to the beam axis [10]. The hadronic final states we reconstruct are $K^-\pi^+$ ($f$), $K^+\pi^-$ ($\bar{f}$), $K^-K^+$ ($CP+$), $\pi^+\pi^-$ ($CP+$), $K^0_S\pi^0\pi^0$ ($CP+$), and $K^0_S\pi^0$ ($CP-$). In the case of the two flavored final states, $K^-\pi^+$ and $K^+\pi^-$, both of these can be reached via Cabibbo-favored (CF) or doubly-Cabibbo-suppresssed (DCS) transitions. The strong phase between the CF and DCS decay amplitudes, $\delta_{K\pi}$, is a source of ambiguity in some previous studies of $D^0$-$\bar{D}^0$ mixing [11]. We measure yields of both single tags (ST), which are single fully-reconstructed $D^0$ or $\bar{D}^0$ candidates, and double tags (DT), which are events where both the $D^0$ and $\bar{D}^0$ are reconstructed. We identify hadronic $D$ candidates by their beam-constrained mass, $M \equiv \sqrt{E^2_{\text{beam}} - \mathbf{p}^2_D}$, and by $\Delta E \equiv E_D - E_{\text{beam}}$.

We also measure semileptonic DT yields, where one $D$ is fully reconstructed in one of the above hadronic modes and the other $D$ is required to be semileptonic. We do not reconstruct semileptonic single tags because of the undetected neutrino. We also omit the DT modes where both $D^0$ and $\bar{D}^0$ decay semileptonically. To maximize efficiency, we use inclusive, partial reconstruction of the semileptonic $D$, demanding that only the electron be found. When the electron is accompanied by a flavor tag ($K^-\pi^+$ or $K^+\pi^-$), we further require that the electron and kaon charges be the same, forming a Cabibbo-favored DT sample. Doing so reduces the dominant electron backgrounds, $\gamma \to e^+e^-$ and $\pi^0 \to e^+e^-\gamma$, which are charge-symmetric. Such a requirement is unavailable for $CP$-eigenstate tags because they are unflavored.

Efficiencies, backgrounds, and crossfeed among signal modes, are determined from Monte Carlo (MC) simulations. Following the least-squares procedure described in Ref. [12], we perform a fit to these efficiency-corrected yields to extract the free parameters listed above. We assume that $K^0_S$ is a purely $CP$-even eigenstate and that $CP$ violation in $D^0$ decays is negligible. In Table II, we show the *preliminary* results of the data fit. Because the precision of the world average for $r^2_{K\pi}$ far exceeds our determination [13–15], we constrain this parameter to be $(3.74 \pm 0.18) \times 10^{-3}$ in the fit. The $\chi^2$ is 15.7 for 20 degrees of freedom, and only statistical uncertainties have been included. Systematic uncertainties are being evaluated, and it is expected that they will be of similar size. The value of $\mathcal{B}(D^0 \to K^0_S\pi^0)$ shown in Table II is equivalent to and correlated with the so-called "single tag" measurement in Ref. [16] of $(1.212 \pm 0.016 \pm 0.039)\%$, which is based on the same dataset as the current analysis but makes use of independently-performed measurements of $y$ [13] and $\mathcal{N}$ [17], whereas we allow both of these parameters to be determined by our fit.

As discussed in Ref. [5], systematic effects that are correlated by final state, such as mismodeling of tracking or $\pi^0$ reconstruction efficiency, cancel in the DCS and mixing parameters. However, one important source of uncertainty is the quantum-number purity of the reconstructed $CP$ eigenstates. Peaking backgrounds to $CP$ eigenstates may come from flavored decays or $CP$ eigenstates of the opposite eigenvalue. Therefore, the size of the simulated background, which assumes uncorrelated decay, may differ from reality because the quantum correlation modifies the rates of each of these processes in a different way, and a systematic uncertainty can be assigned based on the fit results.

Also, the purity of the $C = -1$ initial state may be diluted by radiated photons, which would reverse the $C$ eigenvalue. We limit this effect by searching for DT modes with same-sign $CP$ eigenstates (such as $K^-K^+$ vs. $\pi^+\pi^-$). These decays are forbidden for $C = -1$ but are maximally enhanced for $C = +1$. Including these yield measurements (all of which are consistent with zero) and fitting all the other yields to a sum of $C = -1$ and $C = +1$ contributions, we find no evidence for $C = +1$ contamination — the $C = +1$ fraction of the sample is $0.06 \pm 0.05$ (stat.) — and we observe no significant shifts in the fitted parameters.

In summary, using 281 $\mathrm{pb}^{-1}$ of $e^+e^-$ collisions produced on the $\psi(3770)$ at CLEO-c, we have searched for $D^0$-$\bar{D}^0$ mixing and made a first measurement of the strong phase, $\delta_{K\pi}$. We expect future improvements with the addition of more $CP$ eigenstate modes, more $\psi(3770)$ data, and higher-energy data with $D^0\bar{D}^0\gamma$ events, where the $D^0\bar{D}^0$ pair is a $C = +1$ eigenstate.

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[1] M. Goldhaber and J. L. Rosner, Phys. Rev. D **15**, 1254 (1977).

| Parameter | Fitted Value | PDG [13] |
|---|---|---|
| $\mathcal{N}$ | $(1.09 \pm 0.04) \times 10^6$ | — |
| $y$ | $-0.058 \pm 0.066$ | $0.008 \pm 0.005$ |
| $R_M$ | $(1.7 \pm 1.5) \times 10^{-3}$ | $< \mathcal{O}(10^{-3})$ |
| $\cos \delta_{K\pi}$ | $1.09 \pm 0.66$ | — |
| $\mathcal{B}(D^0 \to K^-\pi^+)$ | $0.0367 \pm 0.0012$ | $0.0380 \pm 0.0009$ |
| $\mathcal{B}(D^0 \to K^-K^+)$ | $0.00354 \pm 0.00028$ | $0.00389 \pm 0.00012$ |
| $\mathcal{B}(D^0 \to \pi^-\pi^+)$ | $0.00125 \pm 0.00011$ | $0.00138 \pm 0.00005$ |
| $\mathcal{B}(D^0 \to K^0_S\pi^0\pi^0)$ | $0.0095 \pm 0.0009$ | $0.0089 \pm 0.0041$ |
| $\mathcal{B}(D^0 \to K^0_S\pi^0)$ | $0.0127 \pm 0.0009$ | $0.0155 \pm 0.0012$ |
| $\mathcal{B}(D^0 \to Xe^+\nu_e)$ | $0.0639 \pm 0.0018$ | $0.0687 \pm 0.0028$ |

TABLE II: Preliminary results from the data fit, with $r^2_{K\pi}$ constrained to be $(3.74 \pm 0.18) \times 10^{-3}$. Uncertainties on the fit results are statistical only.

[2] Z. Z. Xing, Phys. Rev. D **55**, 196 (1997). [arXiv:hep-ph/9606422].

[3] M. Gronau, Y. Grossman and J. L. Rosner, Phys. Lett. B **508**, 37 (2001). [arXiv:hep-ph/0103110].

[4] D. Atwood and A. A. Petrov, Phys. Rev. D **71**, 054032 (2005). [arXiv:hep-ph/0207165].

[5] D. M. Asner and W. M. Sun, arXiv:hep-ph/0507238.

[6] Y. Kubota *et al.*, Nucl. Instrum. Meth. A **320**, 66 (1992).

[7] T. S. Hill, Nucl. Instrum. Meth. A **418**, 32 (1998).

[8] D. Peterson *et al.*, Nucl. Instrum. Methods Phys. Res., Sec. A **478**, 142 (2002).

[9] M. Artuso *et al.*, Nucl. Instrum. Methods Phys. Res., Sec. A **502**, 91 (2003).

[10] R.A. Briere *et al.* (CLEO-c/CESR-c Taskforces & CLEO-c Collaboration), Cornell LEPP preprint CLNS 01/1742 (2001).

[11] See, for instance, D. Asner, *$D^0$-$\bar{D}^0$ Mixing* in Review of Particle Physics, *Phys. Lett.*, **B592**, 1 (2004) and references therein.

[12] W. M. Sun, Nucl. Instrum. Meth. A **556**, 325 (2006) [arXiv:physics/0503050].

[13] Particle Data Group, S. Eidelman *et al.*, Phys. Lett. B **592**, 1 (2004).

[14] K. Abe *et al.* [BELLE Collaboration], Phys. Rev. Lett. **94**, 071801 (2005) [arXiv:hep-ex/0408125].

[15] J. M. Link *et al.* [FOCUS Collaboration], Phys. Lett. B **618**, 23 (2005) [arXiv:hep-ex/0412034].

[16] Q. He *et al.* [CLEO Collaboration], CLEO-CONF-06-11, contributed to ICHEP06 [arXiv:hep-ex/0607068].

[17] Q. He *et al.* [CLEO Collaboration], "Measurement of absolute hadronic branching fractions of D mesons and e+ e- Phys. Rev. Lett. **95**, 121801 (2005) [Erratum-ibid. **96**, 199903 (2006)] [arXiv:hep-ex/0504003].