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Search for *CP* Violation in Neutral *D* Meson Cabibbo-suppressed Three-body Decays

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Using 385 fb^{-1} of e^+e^- collision data collected at center-of-mass energies around 10.6 GeV, we search for time-integrated CP violation in the Cabibbo-suppressed decays $D^0/\overline{D}^0 \to \pi^-\pi^+\pi^0$ and $D^0/\overline{D}^0 \to K^-K^+\pi^0$ with both model-independent and model-dependent methods. Measurements of the asymmetries in amplitudes of flavor states and CP eigenstates provide constraints on theories beyond the Standard Model, some of which predict CP violation in amplitudes at the 1% level or higher. We find no evidence of CP violation and hence no conflict with the Standard Model.

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CP violation (CPV) in charmed particle decays [1], manifested as an asymmetry between the decay rates of a particle and its *CP*-conjugate antiparticle, requires at least two interfering quantum mechanical amplitudes with different phases. In the Standard Model (SM), CPV is due to *CP*-odd relative weak phases that typically enter as a difference in phase between "tree level" and "penguin" SM amplitudes. The penguin amplitudes in charm decays are of $\mathcal{O}(0.1\%)$ [2]. Extensions of the SM introduce additional amplitudes of $\mathcal{O}(1\%)$ [2–4] that can produce CPV. Current experimental searches [5–10] are approaching this level of sensitivity. Observation of CPV would provide strong evidence of new physics.

Singly Cabibbo-suppressed (SCS) D (meaning either D^0 or $\overline{D}{}^0$) decays are uniquely sensitive to CPV in $c \to u\bar{d}d, u\bar{s}s$ transitions and probe contributions from supersymmetric gluonic penguins [2]. Such transitions do not affect the Cabibbo-favored ($c \to s\bar{d}u$) or doubly Cabibbo-suppressed ($c \to d\bar{s}u$) decays. Time-integrated *CP* asymmetries in D decays can have three components [2]: direct CPV in decays to specific states, indirect CPV in D^0–$\overline{D}{}^0$ mixing, and indirect CPV in interference of decays with and without mixing. Indirect CPV is predicted to be universal for amplitudes with final *CP* eigenstates, but direct CPV can be non-universal depending on the specifics of the new physics [2].

We search for time-integrated CPV in the three-body SCS decays $D \to \pi^-\pi^+\pi^0, K^-K^+\pi^0$. These decays proceed via *CP* eigenstates (*e.g.,* $\rho^0\pi^0$, $\phi\pi^0$) and also via flavor states (*e.g.,* $\rho^\pm\pi^\mp$, $K^{*\pm}K^\mp$), thus making it possible to probe CPV in both types of amplitudes and in the interference between them. Measuring interference effects in a Dalitz plot (DP) probes asymmetries in both the magnitudes and phases of the amplitudes, not simply in the overall decay rates. We adopt four approaches in our search for evidence of CPV, three of which are model-independent. First, we quantify differences between the D^0 and $\overline{D}{}^0$ DPs in two dimensions. Second, we look for differences in the angular moments of the D^0 and $\overline{D}{}^0$ intensity distributions. Third, in a model-dependent approach, we look for CPV in the amplitudes describing intermediate states in the D^0 and $\overline{D}{}^0$ decays. Finally, we look for a phase-space-integrated asymmetry. The first two methods are sensitive to differences in the shapes of the D^0 and $\overline{D}{}^0$ DPs, allowing regions of phase space with CPV to be identified. The third method associates any CPV observed using the first two methods with specific intermediate amplitudes. The last method is insensitive to differences in the DP shapes, so complements the other methods. To minimize bias, we finalize the analysis procedure without looking at the data.

We perform the present analysis using 385 fb^{-1} of e^+e^- collision data collected at 10.58 GeV and 10.54 GeV center-of-mass (CM) energies with the *BABAR* detector [11] at the PEP-II storage rings. The event selection criteria are those used in our measurement of the branching ratios of the decays $D \to \pi^-\pi^+\pi^0$ and $D \to K^-K^+\pi^0$ [12]. In particular, we study D mesons produced in $D^{*+} \to D^0\pi^+$ and $D^{*-} \to \overline{D}{}^0\pi^-$ decays that distinguish between D^0 and $\overline{D}{}^0$. We require the D candidate CM momentum > 2.77 GeV/c and $|m_{D^{*\pm}} - m_D - 145.4 \text{ MeV}/c^2| < 0.6 \text{ MeV}/c^2$. Here, m refers to a reconstructed invariant mass. Around ±1 standard deviation of the nominal D mass, we find 82468 ± 321 $\pi^-\pi^+\pi^0$ and 11278 ± 110 $K^-K^+\pi^0$ signal events with purities of about 98%. We determine the signal reconstruction efficiency as a function of the position in the DP using simulated D^0 and $\overline{D}{}^0$ decays [12] from $e^+e^- \to c\bar{c}$ events, subjected to the same selection procedure that is applied to the data.

A direct comparison of the efficiency-corrected and background-subtracted DPs for D^0 and $\overline{D}{}^0$ events is the simplest way to look for CPV. Figure 1 shows the normalized residuals Δ in DP area elements, where

$$\Delta = (n_{\overline{D}{}^0} - R \cdot n_{D^0}) \,/ \sqrt{\sigma^2_{n_{\overline{D}{}^0}} + R^2 \cdot \sigma^2_{n_{D^0}}}\,, \qquad (1)$$

and n denotes the number of events in a DP element and σ its uncertainty. The factor R, equal to 0.983 ± 0.006 for $\pi^-\pi^+\pi^0$ and 1.020 ± 0.016 for $K^-K^+\pi^0$, is the ratio of the number of efficiency-corrected $\overline{D}{}^0$ to D^0 events. This is introduced to allow for any asymmetry in the production cross section due to higher order QED corrections or in the branching fractions for D^0 and $\overline{D}{}^0$ decay to the same final state.

We calculate $\chi^2/\nu = (\sum_{i=1}^{\nu} \Delta_i^2)/\nu$, where ν is the number of DP elements: 1429 for $\pi^-\pi^+\pi^0$ and 726 for $K^-K^+\pi^0$. In an ensemble of simulated experiments with no CPV, we find the distribution of χ^2/ν values to have a mean of 1.012 (1.021) and an r.m.s. of 0.018 (0.036) for $\pi^-\pi^+\pi^0$ ($K^-K^+\pi^0$). The measured value in the data is 1.020 for $\pi^-\pi^+\pi^0$ and 1.056 for $K^-K^+\pi^0$, so we obtain a one-sided Gaussian confidence level (CL) for consistency with no CPV of 32.8% for $\pi^-\pi^+\pi^0$ and 16.6% for $K^-K^+\pi^0$. The same analysis procedure, when applied to simulated samples with either 1% fractional change in magnitude or 1° change in phase between the D^0 and $\overline{D}{}^0$ amplitudes for decay to any of the main resonant states, gives a χ^2/ν that is about 2σ away from the no CPV hypothesis. Systematic uncertainties are small (as will be clear from the model-dependent results of Tables I–II) and have not been included in the CL calculation.

The angular moments of the cosine of the helicity angle of the D decay products reflect the spin and mass structure of intermediate resonant and nonresonant amplitudes [13]. We define the helicity angle θ_H for decays of the type $D \to r(AB)\; C$ as the angle between the mo-

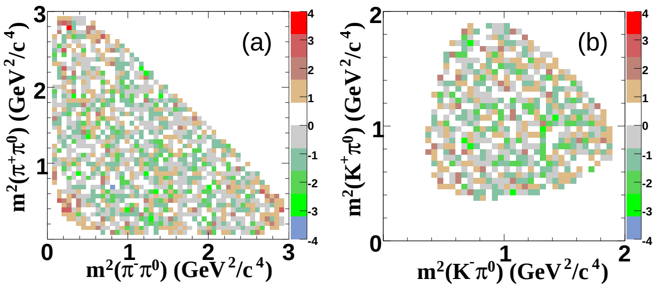

FIG. 1: Normalized residuals in Dalitz plot elements, defined in Eq. 1, for (a) $D \to \pi^-\pi^+\pi^0$ and (b) $D \to K^-K^+\pi^0$.

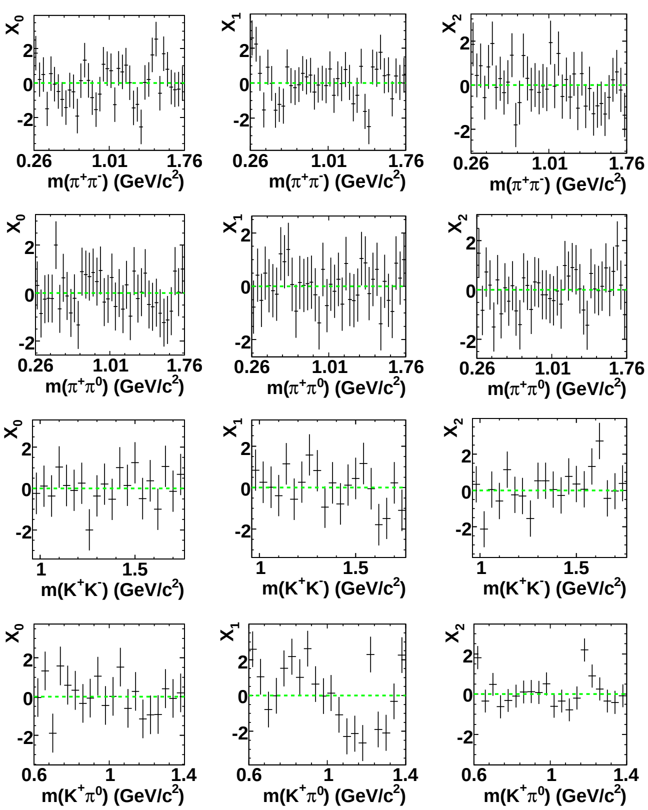

FIG. 2: Normalized residuals for the first three Legendre polynomial moments of the $\pi^-\pi^+$ (row 1), $\pi^+\pi^0$ (row 2), K^-K^+ (row 3), and $K^+\pi^0$ (row 4) sub-systems. The confidence level for no CP violation (dashed line) is obtained from the first eight moments. The error bars represent $\pm 1\sigma$.

mentum of A in the AB rest frame and the direction opposite to the D momentum in that same frame. The angular moments [14] of order l are defined as the efficiency-corrected invariant mass distributions of events weighted by spherical harmonics $Y_l^0(\theta_H) = \sqrt{1/2\pi}\ P_l(\cos\theta_H)$. Here P_l are the Legendre polynomials of order l. To study differences between the D^0 and $\overline{D}^0$ amplitudes, we calculate the quantities X_l for $l = 0-7$, where

$$X_l = \left(\overline{P_l} - R \cdot P_l\right) / \sqrt{\sigma^2_{\overline{P_l}} + R^2 \cdot \sigma^2_{P_l}}\,, \qquad (2)$$

and P_l ($\overline{P_l}$) are obtained from D^0 ($\overline{D}^0$) events. Higher moments are zero within errors in both data and simulation. For illustration, we show the X_l distributions for $l = 0-2$, in Fig. 2.

We then calculate χ^2/ν summed over all intervals in invariant mass as $\chi^2/\nu = (\sum_0^k \sum_{i=0}^7 \sum_{j=0}^7 X_i\ \rho_{ij}\ X_j)/\nu$, where $\nu = 8k$, k is the number of intervals, and ρ_{ij} is the correlation coefficient between X_i, X_j. We determine the ρ_{ij} in each mass interval by simulating experiments with no CPV. We test the method by randomly assigning real events as D^0 or $\overline{D}^0$, and then calculating χ^2/ν for the difference in their angular moments. We repeat this experiment 500 times and find the resulting χ^2/ν distribution to be consistent with no CPV, validating our calculation of ρ_{ij}. We then look at the D flavor in the data and calculate the χ^2/ν values for the two-body channels with charge combinations $+,-$ and $+,0$. Finally, we obtain a one-sided Gaussian CL for consistency with no CPV using the reference value and r.m.s. deviation from simulation. We find the CL for no CPV to be 28.2% for the $\pi^+\pi^-$, 28.4% for the $\pi^+\pi^0$, 63.1% for the K^+K^-, and 23.8% for the $K^+\pi^0$ sub-systems. Again, a 1% fractional change in magnitude or 1° change in phase of any of the main resonant amplitudes gives a χ^2/ν that is about 2σ away from the no CPV hypothesis.

The Dalitz plot amplitude $\mathcal{A}$ can be parametrized as a sum of amplitudes $A_r(s_+, s_-)$ for all relevant intermediate states r, each with a complex coefficient, i.e., $\mathcal{A} = \sum_r\ a_r\ e^{i\phi_r}\ A_r(s_+, s_-)$, where a_r and ϕ_r are real. Here s_+ and s_- are the squared invariant masses of the pair of final state particles with charge combinations $+,0$ and $-,0$. The fit fraction for each process r is defined as $f_r \equiv \int |a_r A_r|^2\, ds_+ ds_- / \int |\mathcal{A}|^2\, ds_+ ds_-$. We model incoherent, CP-symmetric background empirically [13, 15]. In the absence of CPV, we expect the values of a_r and ϕ_r (and hence f_r) to be identical for D^0 and $\overline{D}^0$ decay. The results obtained with this assumption are listed in Ref. [15] for $D \to \pi^-\pi^+\pi^0$ and in Ref. [13] for $D \to K^-K^+\pi^0$. To allow the possibility of CPV in the present analysis, we let a second process – not necessarily of SM origin – contribute to each of the amplitudes A_r, thus permitting the a_r, ϕ_r, f_r for D^0 and $\overline{D}^0$ to differ. We summarize the results of the fit to the data in terms of the differences $\Delta a_r = a_r^{\overline{D}^0} - a_r^{D^0}$, $\Delta\phi_r = \phi_r^{\overline{D}^0} - \phi_r^{D^0}$, and $\Delta f_r = f_r^{\overline{D}^0} - f_r^{D^0}$ in Table I for $\pi^-\pi^+\pi^0$ and in Table II for $K^-K^+\pi^0$. The CP asymmetry in any amplitude, relative to that of the whole decay, is no larger than a few percent.

Systematic uncertainties in the quantities describing CP asymmetries, reported in Tables I–II, arise from experimental effects, and also from uncertainties in the models used to describe the data. We determine these separately, as described in Refs. [13, 15], and add them in quadrature. For all variations described below, we assign the maximum deviation from the central value

TABLE I: Model-dependent CP asymmetry in the $D \to \pi^-\pi^+\pi^0$ Dalitz plots. The first and second errors are statistical and systematic, respectively. For details on the Dalitz plot parametrization and the a_r, ϕ_r, and f_r values, see Ref. [15]. As explained in text, Δf_r is closely related to Δa_r and $\Delta\phi_r$

State	f_r (%)	Δa_r (%)	$\Delta\phi_r$ (°)	Δf_r (%)
$\rho^+(770)$	68	-3.2±1.7±0.8	-0.8±1.0±1.0	-1.6±1.1±0.4
$\rho^0(770)$	26	2.1±0.9±0.5	0.8±1.0±0.4	1.6±1.4±0.6
$\rho^-(770)$	35	2.0±1.1±0.8	-0.6±0.9±0.4	0.7±1.1±0.5
$\rho^+(1450)$	0.1	2±11±8	-30±25±9	0.0±0.1±0.1
$\rho^0(1450)$	0.3	13±8±6	-1±14±3	0.1±0.2±0.1
$\rho^-(1450)$	1.8	-3±6±5	8±7±3	-0.2±0.3±0.1
$\rho^+(1700)$	4	19±27±9	9±7±3	0.4±1.0±0.4
$\rho^0(1700)$	5	-31±20±12	-7±6±2	-1.3±0.8±0.3
$\rho^-(1700)$	3	-3±14±11	-3±8±3	-0.5±0.6±0.3
$f_0(980)$	0.2	0.0±0.1±0.2	-3±7±4	0.0±0.1±0.1
$f_0(1370)$	0.4	-0.3±1.3±1.2	7±14±5	-0.2±0.1±0.1
$f_0(1500)$	0.4	0.4±1.1±0.7	-1±12±1	0.0±0.1±0.1
$f_0(1710)$	0.3	-3±3±2	-25±13±11	0.0±0.1±0.1
$f_2(1270)$	1.3	8±4±5	2±5±2	0.1±0.1±0.1
$\sigma(400)$	0.8	-0.3±0.7±2.0	-4±7±3	-0.1±0.1±0.1
Nonres	0.8	12±7±8	11±9±4	0.2±0.3±0.2

TABLE II: Model-dependent CP asymmetry in the $D \to K^-K^+\pi^0$ Dalitz plots. The errors are statistical and systematic, respectively. We show the $a_0(980)$ contribution, when it is included in place of the $f_0(980)$, in square brackets. For details on the Dalitz plot parametrization and the a_r, ϕ_r, and f_r values, see Ref. [13]. We use Model-I of Ref. [13] to obtain central values and Model-II for study of systematic errors.

State	f_r (%)	Δa_r (%)	$\Delta\phi_r$ (°)	Δf_r (%)
$K^*(892)^+$	45	2±3±2	10±12±3	0.8±1.1±0.4
$K^*(1410)^+$	4	101±65±37	1±21±6	1.7±1.8±0.6
$K^+\pi^0(S)$	16	-130±64±51	-9±10±6	-2.3±4.7±1.0
$\phi(1020)$	19	-1±2±1	-10±20±5	-0.4±0.8±0.2
$f_0(980)$	7	14±16±6	-12±25±8	0.4±2.6±0.2
$[a_0(980)^0]$	[6]	[19±16±6]	[-7±16±8]	[0.6±1.9±0.2]
$f_2'(1525)$	0.1	-38±74±8	6±36±12	0.0±0.1±0.3
$K^*(892)^-$	16	1±3±1	-7±4±2	1.7±1.3±0.4
$K^*(1410)^-$	5	133±93±68	-23±13±9	1.7±2.8±0.7
$K^-\pi^0(S)$	3	8±68±36	32±39±14	0.4±2.4±0.5

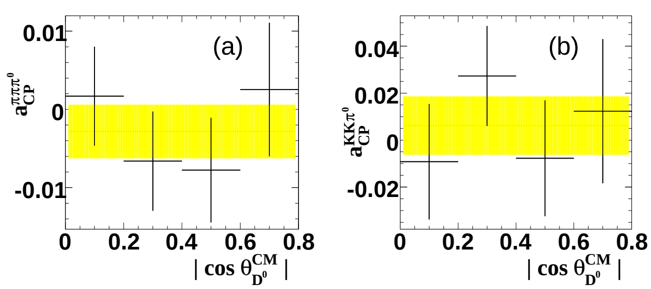

FIG. 3: Phase-space-integrated CP asymmetry as a function of the cosine of the polar angle of the reconstructed D candidate CM momentum for (a) $D \to \pi^-\pi^+\pi^0$ and (b) $D \to K^-K^+\pi^0$ decays. The dashed lines represent the central values, and the shaded regions the 1σ intervals.

as a systematic uncertainty, accounting for correlations among parameters. For resonance lineshapes and form-factors, we vary the parameters [16] by $\pm 1\sigma$. Similarly, we vary the signal efficiency parameters for separately for D^0 and $\overline{D}^0$ events by $\pm 1\sigma$, the ratios of particle-identification rates in data and simulation by $\pm 1\sigma$, and the background shapes by using simulation rather than data sidebands. We include uncertainties from D^0–$\overline{D}^0$ misidentification, estimated from simulation, in the experimental systematic uncertainty.

To this point, we have described the investigation of time-integrated CP asymmetry in neutral D meson decays using information from the DP distributions. Differences in the overall branching fractions for the D^0 and $\overline{D}^0$ decays to $\pi^-\pi^+\pi^0$, $K^-K^+\pi^0$ would also indicate time-integrated CPV. This information is not captured by the differential comparisons of the DP structures already described, and is complementary to them. To correct for any production asymmetry in D^0-flavor assignment, we weight each event by the relative efficiency for flavor assignment, as described in Ref. [5]. Since there is an asymmetry [5] between the number of events reconstructed at forward and backward polar angles ($\theta_{D^0}^{CM}$) of the D candidate CM momentum, we extract the CP asymmetry value, $a_{CP} \equiv \frac{N_{\overline{D}^0} - N_{D^0}}{N_{\overline{D}^0} + N_{D^0}}$, in intervals of $|\cos\theta_{D^0}^{CM}|$. Here, N denotes the number of signal events. Any forward-backward asymmetry is canceled by averaging over symmetric intervals in $\cos\theta_{D^0}^{CM}$, as shown in Eqs. 3–5 of Ref. [5]. In Fig. 3 we show the a_{CP} for events in the D mass window used in the DP analysis. We perform χ^2 minimization to obtain the central values: $[-0.31 \pm 0.41$ (stat) ± 0.17 (syst)] % for $\pi^-\pi^+\pi^0$ and $[1.00 \pm 1.67$ (stat) ± 0.25 (syst)] % for $K^-K^+\pi^0$ final states. The systematic uncertainties result from signal efficiency, particle-identification, background treatment, and D^0–$\overline{D}^0$ misidentification. As a consistency check, we repeat the analysis with a larger D mass window ($\pm 2.5\sigma$) and find consistent results: $[-0.28 \pm 0.34$ (stat) ± 0.19 (syst)] % for $\pi^-\pi^+\pi^0$ and $[0.62 \pm 1.24$ (stat) ± 0.28 (syst)] % for $K^-K^+\pi^0$.

In summary, our model-independent and model-dependent analyses show no evidence of CPV in the SCS decays $D \to \pi^-\pi^+\pi^0$ and $D \to K^-K^+\pi^0$. The intermediate amplitudes include well-defined flavor states (*e.g.*, $\rho^\pm\pi^\mp$, $K^{*\pm}K^\mp$) and CP-odd eigenstates (*e.g.*, $\rho^0\pi^0$, $\phi\pi^0$). With the null results of Ref. [5–8] for CP-even eigenstates $D \to K^+K^-$ and $D \to \pi^+\pi^-$, we conclude that any CPV in the SCS charm decays occurs at a rate which is not larger than a few percent. These results are in accord with the SM predictions, and provide constraints on some models beyond the SM [2].

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