A search for $CP$ violation and a measurement of the relative branching fraction in $D^+ \rightarrow K^-K^+\pi^+$ decays

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We report on a search for the CP asymmetry in the singly Cabibbo-suppressed decays $D^+ \rightarrow K^- K^+ \pi^+$ and in the resonant decays $D^+ \rightarrow \phi \pi^+$ and $D^+ \rightarrow K^{*0} K^+$ based on a data sample of 79.9 fb$^{-1}$ recorded by the BABAR detector. We use the Cabibbo-favored $D_s^+ \rightarrow K^- K^+ \pi^+$ branching fraction as normalization in the measurements to reduce systematic uncertainties. The CP asymmetries obtained are $A_{CP}(K^- K^+ \pi^+) = (1.4 \pm 1.0 \text{(stat.)} \pm 0.8 \text{(syst.)}) \times 10^{-2}$, $A_{CP}(\phi \pi^+) = (0.2 \pm 1.5 \text{(stat.)} \pm 0.6 \text{(syst.)}) \times 10^{-2}$, and $A_{CP}(K^{*0} K^+) = (0.9 \pm 1.7 \text{(stat.)} \pm 0.7 \text{(syst.)}) \times 10^{-2}$. The relative branching fraction $\Gamma(D^+ \rightarrow K^- K^+ \pi^+)/\Gamma(D^+ \rightarrow K^- K^+ \pi^+)$ is also measured and is found to be $(10.7 \pm 0.1 \text{(stat.)} \pm 0.2 \text{(syst.)}) \times 10^{-2}$.

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**INTRODUCTION**

Singly Cabibbo-suppressed (SCS) $D$-meson decays are predicted in the standard model (SM) to exhibit CP-violating charge asymmetries of the order of $10^{-3}$ [1]. Direct CP violation in SCS decays could arise from the interference between tree-level (Fig. 1a) and penguin (Fig. 1b) decay processes. Doubly Cabibbo-suppressed and Cabibbo-favored (CF) decays are expected to be CP invariant in the SM because they are dominated by a single weak amplitude. Measurements of CP asymmetries in SCS processes greater than $\mathcal{O}(10^{-3})$ would be evidence of physics beyond the standard model [2].

We define the CP asymmetry by

$$A_{CP} = \frac{|\mathcal{A}|^2 - |\overline{\mathcal{A}}|^2}{|\mathcal{A}|^2 + |\overline{\mathcal{A}}|^2}, \quad (1)$$

where $\mathcal{A}$ is the total decay amplitude for $D^+$ decays and $\overline{\mathcal{A}}$ is the amplitude for the charge-conjugate decays. $A_{CP}$ is non-zero only if there are at least two different decay amplitudes with a CP-violating relative weak phase and a CP-conserving relative strong phase due to final-state interactions. Eq. (1) can be expressed as an asymmetry of branching fractions. We assume that the total decay rates for $D^+$ and $D^-$ are equal (CPT invariance). Assuming further that CF decays are invariant under CP, we use branching fractions for CF decays as normalization factors to reduce experimental systematics due to particle identification (PID) and tracking:

$$A_{CP} = \frac{\mathcal{B}(D^+ \rightarrow K^+ K^- \pi^+) - \mathcal{B}(D^- \rightarrow K^+ K^- \pi^-)}{\mathcal{B}(D^+ \rightarrow K^+ K^- \pi^+) + \mathcal{B}(D^- \rightarrow K^+ K^- \pi^-)}, \quad (2)$$

(Throughout this paper we assume that the production of $D^+$ and $D_s^+$ mesons is charge symmetric.)

We also measure the CP asymmetry in the resonant decays $D^+ \rightarrow \phi \pi^+$ and $D^+ \rightarrow K^{*0} K^+$, and determine the relative branching fraction $\Gamma(D^+ \rightarrow K^- K^+ \pi^+)/\Gamma(D^+ \rightarrow K^- K^+ \pi^+)$.

**DETECTOR AND DATA SAMPLE**

This analysis is performed with a data sample recorded on and below the $\Upsilon(4S)$ resonance with the BABAR detector at the PEP-II asymmetric-energy $e^+ e^-$ storage rings at the Stanford Linear Accelerator Center.

The BABAR detector is described in detail in Ref. [3]. The silicon vertex tracker (SVT) and the 40-layer cylindrical drift chamber (DCH) embedded in a 1.5-T solenoid measure the momenta and energy loss ($dE/dx$) of charged particles. A ring-imaging Cherenkov detector (DIRC) is used for charged-particle identification. Photons are detected and electrons identified with a CsI(Tl) electromagnetic calorimeter (EMC).

We split the 89.7 fb$^{-1}$ data sample into a randomly selected subsample of 9.8 fb$^{-1}$ to optimize the selection criteria and the remainder (a 79.9 fb$^{-1}$ sample) for the final analysis. This procedure eliminates selection bias. We apply the same selection criteria to the CF and SCS modes whenever possible. We determine selection efficiencies from a sample (145 fb$^{-1}$ equivalent) of Monte Carlo (MC) [4] generated $e^+ e^- \rightarrow \phi \pi^+$ events.

**DATA ANALYSIS**

We reconstruct $D^+$ and $D_s^+$ decays by selecting events containing at least three charged tracks. Tracks
are required to have at least 12 measured DCH coordinates, a minimum transverse momentum of 0.1 GeV/c, and to originate within 1.5 cm in xy (transverse to the beam) and ±10 cm along the z-axis (along the e− beam) of the nominal interaction point. Kaons are identified by a selection on the ratio of likelihood functions derived from dE/dx in the SVT and DCH, and from the Cherenkov angle and number of photons in the DIRC. Pions are identified as tracks that fail a loose kaon identification criterion. The three charged tracks are further constrained to originate at a common vertex, the fit for which is accepted if the χ2 satisfies P(χ2) > 1%. We reject D+ and D0 mesons from B decays, and thereby reduce backgrounds, by requiring that their momenta in the center-of-mass (CM) frame be above 2.4 GeV/c.

In order to reduce the remaining combinatorial background we consider likelihood ratios formed from the probability density functions (PDFs) of the following discriminating variables for the D+ and D0 decays: CM momentum (pCM), vertex-fit probability with a beamspot constraint (PBS(χ2)), and the distance in the xy-plane from the interaction point to the D+ or D0 vertex (dx,y). The quantity PBS(χ2) is the probability that the decay tracks form a vertex within the beam spot region. Most of the D+ mesons decay outside this region, thus the probability PBS(χ2) is small for the D+ signal and is large for combinatorial background. Background distributions are taken from sidebands in the decay modes. We choose the signal region mKKK = [1,944,1,992] GeV/c2, while the sidebands are chosen to be [1,914,1,938] and [1,998,2,022] GeV/c2, respectively [see Fig. 2(b)]. In addition, contamination from D+ → K−π+π+π− decays is removed as follows: for all KKπ candidates, the kaon with the same charge as the pion is treated as a pion and then the Kπ invariant mass is calculated. We observe a D+ peak, indicating that part of the D+ signal is composed of misidentified D+ candidates. Events in the region 1.855 < mKKK < 1.883 GeV/c2 are removed from the D+ sample. Contamination from D+ → D0(→ K−π+,K−π+π+)π− decays is removed by eliminating events for which mK−π− < 1.84 GeV/c2. Candidates for D+ → K−π+π+π− are eliminated if both Kπ combinations satisfy the requirement. Partially reconstructed D+ → D0(→ K−π+π0)π− decays can also be misidentified as K−K+π− candidates if the π0 is missed and the charged pion is misidentified as a kaon. Most of these decays are eliminated by assigning a pion mass to kaon tracks and removing candidates for which the mass difference (mKK−π+π−−mK−π−) lies in the range [0.139,0.150] GeV/c2.

Figure 2 shows the mass distributions obtained after all selection criteria are applied. The yields, listed in Table I, are computed by subtracting from the number of events in the signal region a scaled background estimate, obtained from the sideband mass region.

| Parent Charge | + | - |
|---------------|---|---|
| D± → K−K+π± | 21632 ± 228 | 20940 ± 226 |
| D± → φπ± | 5452 ± 87 | 5327 ± 86 |
| D± → K∗0K± | 5247 ± 96 | 5113 ± 96 |
| D± → K−K+π± | 23066 ± 217 | 22928 ± 214 |

The efficiencies needed for the ACP calculation are obtained from a sample of MC generated CP events to which the same selection criteria are applied. The efficiencies for each decay mode are shown in Table III.

We obtain ACP using Eq. 2 and replacing branching fractions with efficiency-corrected yields. The results are shown in Table III. We also studied the CP asymmetry in 16 bins of the D+ → K−K+π± Dalitz plot.
and found that the asymmetry is consistent with being constant (with a probability of 51%) and zero.

We use the CF sample of $D^+ \to K^{-}\pi^+\pi^+$ decays, obtained using selection criteria identical to the SCS case, to determine the relative branching fraction $\Gamma(D^+\to K^{-}\pi^+\pi^+)/\Gamma(D^+\to K^{+}\pi^+\pi^+)$ as follows. The CF and SCS Dalitz plots are first divided into equally populated bins (16 bins for the SCS mode, 64 for the CF mode). Next, the signal and normalization yields and efficiencies are calculated bin-by-bin. The efficiency-corrected yields are then summed and divided to obtain the ratio. Figure 3 shows the mass distribution in the CF $D^\pm \to K^{\pm}\pi^+\pi^\pm$ mode, for which the average efficiency is 10.03 ± 0.01(stat.)%. We obtain a relative branching fraction of $(10.7\pm0.1\text{(stat.)})\times10^{-2}$.

### TABLE II: Efficiencies for positively ($\varepsilon^+$) and negatively ($\varepsilon^-$) charged $D$ and $D_s$ meson decays. Efficiencies are in percent. The stated uncertainties are due to MC statistics only.

| Decay | $\varepsilon^+$ | $\varepsilon^-$ |
|-------|----------------|----------------|
| $D^\pm \to K^{-}\pi^+\pi^\pm$ | 8.20±0.04 | 8.26±0.04 |
| $D^+ \to \phi\pi^\pm$ | 7.67±0.07 | 7.63±0.07 |
| $D^\pm \to K^{0}\pi^\pm$ | 5.88±0.07 | 5.90±0.07 |
| $D_s^\pm \to K^{-}\pi^+\pi^\pm$ | 3.77±0.02 | 3.79±0.02 |

### TABLE III: Results of the $CP$-asymmetry measurements, $A_{CP}$. Also listed are the values for $A^{(2)}_{CP}$, the asymmetry computed without the normalization mode.

| Decay | $A_{CP}$ [10^{-2}] | $A^{(2)}_{CP}$ [10^{-2}] |
|-------|---------------------|---------------------|
| $K^{-}\pi^+$ | +1.36 ± 1.01 | +2.07 ± 0.84 |
| $\phi\pi^\pm$ | +0.24 ± 1.45 | +0.94 ± 1.33 |
| $K^{0}\pi^\pm$ | +0.88 ± 1.67 | +1.58 ± 1.57 |

### SYSTEMATIC UNCERTAINTIES AND CROSS-CHECKS

The only difference between the final states from $D_s^\pm$ and $D^\pm$ decays considered here is a slightly harder momentum spectrum for the $D_s^\pm$ decay products. In turn, these small differences are corrected for by the efficiencies which come from MC. Any charge asymmetry in the detection of pions thus cancels when $D_s^\pm \to K^{-}\pi^+\pi^\pm$ decays are used as normalization, as in Eq. (2). We estimate the systematic uncertainty on the $CP$ asymmetries by combining estimates of the contributions from various identified sources listed in Table IV.

The uncertainty due to small differences in momentum spectra of $\pi$, $K$ from $D^+$ and $D_s^+$ decays, 0.06%, is estimated as three times the maximum difference in $\pi$, $K$ asymmetries in $D^+$ and $D_s^+$ decays. We evaluate an uncertainty for the background subtraction by changing the widths of the sideband mass regions. The uncertainty is taken to be the difference in the central values of $A_{CP}$.

| Source | $K^{-}\pi^+\pi^\pm$ | $\phi\pi^\pm$ | $K^{0}\pi^\pm$ |
|--------|---------------------|----------------|----------------|
| MC simulation | 0.06 | 0.06 | 0.06 |
| Background estimate | 0.63 | 0.32 | 0.49 |
| Selection criteria | 0.46 | 0.54 | 0.54 |
| Total | 0.78 | 0.63 | 0.73 |

We performed two cross-checks on our measurement of $A_{CP}$. First, we calculated an alternative measure of $CP$ asymmetry without using $D_s^+ \to K^{-}\pi^+\pi^+$ decays as normalization, which we labeled $A^{(2)}_{CP}$ in Table III. We find its values to be consistent with our measurements of $A_{CP}$. Second, we measured the $CP$ asymmetry for a control sample: the CF decays $D_s^+ \to K^{-}\pi^+\pi^+$ (non-resonant as well as resonant). This asymmetry is expected to be zero within the SM. In $D_s^+ \to K^{-}\pi^+\pi^+$ decays, both the $D_s^+$ and the $D_s^-$ decay to two oppositely charged kaons and only the pion charge differs in particle and antiparticle decays. Thus, any detector-induced asymmetry would arise only from a charge asymmetry in pion tracking and is expected to be very small. Indeed the measured value is $(+0.6\pm0.8)\times10^{-2}$.

As a final cross-check, the $CP$ asymmetry has also been studied as a function of the $D^+$ laboratory momentum, as well as by the run period. No significant dependence on momentum or detector operation conditions is observed.

A summary of the systematic uncertainties for the relative branching fraction $\Gamma(D^+\to K^{-}\pi^+\pi^+)/\Gamma(D^+\to K^{+}\pi^+\pi^+)$ is given in Table V. The fractional uncertainty due to PID and tracking has been estimated as 2.1%, computed as the sum in quadrature of 1.1% for PID and 1.8% for tracking. The PID uncertainty is estimated from a comparison of PID efficiencies in data and MC. The tracking uncertainty, which is the uncertainty on the $K/\pi$ efficiency ratio, is conservatively estimated as three times its value obtained using MC.
or light shaded) and sidebands (red or darker shaded) regions are shown for D selected by the B and measured the relative branching fraction of D in Table VI. These results are in agreement with

\[ \text{FIG. 2: } K K \pi \text{ mass distributions for positively charged (left) and negatively charged (right)} \ D \text{ and D, candidates for events satisfying the requirement } r \geq 4.3. \text{ Figures (a) and (b) are for all } K K \pi \text{ candidates, while (c) and (d) are for } \phi \pi \text{ candidates, and (e) and (f) for } K^0 K \text{ candidates. Signal (yellow or light shaded) and sidebands (red or darker shaded) regions are shown for } D^+ \text{ and } D^0_\pi \text{ decays in (a) and (b), respectively.} \]

\[ \text{FIG. 3: Mass distribution for } D^\pm \to K^\mp \pi^\pm \pi^\pm \text{ decays.} \]

**SUMMARY**

We have searched for a CP asymmetry in D → K−K+π+, D → φπ+, and D → K^{00}K^+ decays and measured the relative branching fraction of D → K−K+π+ decays, with a data sample of 79.9 fb^{-1} collected by the BABAR experiment.

The measurements of the CP asymmetries are summarized in Table VI. These results are in agreement with previous published results \[5\], with our results in the resonant modes having significantly smaller uncertainties.

Further, we obtain a branching fraction for D^+ → K^-K^+π^+ decays relative to that for D^+ → K^-π^+π^+ decays of (10.7 ± 0.1(stat.) ± 0.2(syst.)) \times 10^{-2}. This result is a significant improvement over previous measurements \[3\].

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| Source        | Uncertainty [10^{-2}] |
|---------------|------------------------|
| PID + tracking| 0.22                   |
| Background estimate | 0.05               |
| Selection criteria | 0.02               |
| Total         | 0.23                   |

**TABLE VI: Results of the CP asymmetry (ACP) measurements for D^± decays.**

| Decay            | ACP [10^{-2}] |
|------------------|---------------|
| K^-K^+π^±        | +1.4 ± 1.0(stat.) ± 0.8(syst.) |
| φπ^±             | +0.2 ± 1.5(stat.) ± 0.6(syst.) |
| K^{00}K^±        | +0.9 ± 1.7(stat.) ± 0.7(syst.) |
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