Search for $CP$ violation in the decay $D^{+} \to K^{0}\pi^{+}$


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We report on a search for CP violation in the decay $D^+ \rightarrow K^0_S \pi^+$ using a data set corresponding to an integrated luminosity of 469 fb$^{-1}$ collected with the BABAR detector at the PEP-II asymmetric energy $e^+e^-$ storage rings. The CP-violating decay rate asymmetry $A_{CP}$ is determined to be $(-0.44 \pm 0.13({\text{stat}}) \pm 0.10({\text{syst}}))\%$, consistent with zero at 2.7$\sigma$ and with the standard model prediction of $(-0.332 \pm 0.006)\%$. This is currently the most precise measurement of this parameter.

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In the standard model (SM), CP violation (CPV) arises from the complex phase of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. Measurements of the CPV asymmetries in the K and B meson systems are consistent with expectations based on the SM and, together with theoretical inputs, lead to the determination of the parameters of the CKM matrix. CPV has not yet been observed in the charm sector, where the theoretical predictions based on the SM for CPV asymmetries are at the level of $10^{-3}$ or below [2].

In this paper we present a search for CPV in the decay $D^\pm \to K_S^0 \pi^\pm$ by measuring the CPV parameter $A_{CP}$ defined as

$$A_{CP} = \frac{\Gamma(D^+ \to K_S^0 \pi^+) - \Gamma(D^- \to K_S^0 \pi^-)}{\Gamma(D^+ \to K_S^0 \pi^+) + \Gamma(D^- \to K_S^0 \pi^-)},$$

(1)

where $\Gamma$ is the partial decay width for this decay. This decay mode has been chosen because of its clean experimental signature. Although direct CP violation due to interference between Cabibbo-allowed and doubly Cabibbo-suppressed amplitudes is predicted to be negligible within the SM [3], $K^0 - \bar{K}^0$ mixing induces a time-integrated CP-violating asymmetry of $(-0.332 \pm 0.006\%)$ [4]. Contributions from non-SM processes may reduce the value of the measured $A_{CP}$ or enhance it up to the level of 1% [3,5]. Therefore, a significant deviation of the $A_{CP}$ measurement from pure $K^0 - \bar{K}^0$ mixing effects would be evidence for the presence of new physics beyond the SM. Because of the smallness of the expected value, this measurement requires a large data sample and precise control of the systematic uncertainties. Previous measurements of $A_{CP}$ have been reported by the CLEO-c ($(0.6 \pm 1.0$ (stat) $\pm 0.3$ (syst))% [6]) and Belle collaborations ($(0.71 \pm 0.19$ (stat) $\pm 0.20$ (syst))% [7]).

The data used in this analysis were recorded at or near the Y(4S) resonance by the BABAR detector at the PEP-II storage rings. The BABAR detector is described in detail elsewhere [8]. The data sample corresponds to an integrated luminosity of 469 fb$^{-1}$. To avoid any bias from adapting the analysis procedure to the data, we perform a “blind” analysis where all aspects of the analysis, including the statistical and systematic uncertainties, are validated with data and Monte Carlo (MC) simulation based on GEANT4 [9] before looking at the value of $A_{CP}$. The MC samples include $e^+ e^- \to q\bar{q}$ ($q = u, d, s, c$) events, simulated with JETSET [10] and $BB$ decays simulated with the EvtGen generator [11]. The coordinate system defined in [8] is assumed throughout the paper.

We select $D^\pm \to K_S^0 \pi^\pm$ decays by combining a $K_S^0$ candidate reconstructed in the decay mode $K_S^0 \to \pi^+ \pi^-$ with a charged pion candidate. A $K_S^0$ candidate is reconstructed from two oppositely charged tracks with an invariant mass within $\pm 10$ MeV/$c^2$ of the nominal $K_S^0$ mass [4], which is equivalent to slightly more than $\pm 2.5 \sigma$ in the measured $K_S^0$ mass resolution. The $\chi^2$ probability of the $\pi^+ \pi^-$ vertex fit must be greater than 0.1%. To reduce combinatorial background, we require the measured flight length of the $K_S^0$ candidate to be greater than 3 times its uncertainty. A reconstructed charged track that has $p_T \geq 400$ MeV/$c$ is selected as a pion candidate, where $p_T$ is the magnitude of the momentum in the plane perpendicular to the z axis. At BABAR, charged hadron identification is achieved through measurements of ionization energy loss in the tracking system and the Cherenkov angle obtained from a detector of internally reflected Cherenkov light. A CsI(Tl) electromagnetic calorimeter provides photon detection, electron identification, and neutral pion reconstruction [8]. In our measurement, the pion candidate is required not to be identified as a kaon, a proton, or an electron. These selection criteria for the pion candidate are very effective in reducing the charge asymmetry from track reconstruction and identification, as inferred from studying the large control sample described later. A kinematic vertex fit to the whole decay tree is then performed with no additional constraints [12]. We retain only $D^\pm$ candidates having a $\chi^2$ probability for this fit greater than 0.1% and an invariant mass $m(K_S^0 \pi^\pm)$ within $\pm 65$ MeV/$c^2$ of the nominal $D^+$ mass [4], which is equivalent to more than $\pm 8 \sigma$ in the measured $D^\pm$ mass resolution. Motivated by Monte Carlo simulation studies, we further require the magnitude of the $D^\pm$ candidate momentum in the $e^+ e^-$ center-of-mass (CM) system, $p_T(D^\pm)$, to be between 2 and 5 GeV/$c$. This criterion reduces the combinatorial background to an acceptable level, but also keeps some $D^\pm$ mesons from B mesons decays (they are $\sim 8\%$ of the selected sample) [13]. Additional background rejection is obtained by requiring that the impact parameter of the $D^\pm$ candidate with respect to the beam-spot [8], projected onto the plane perpendicular to the z axis, be less than 0.3 cm and the $D^\pm$ lifetime $\tau_{xy}(D^\pm)$ be between $\pm 12.5$ and 31.3 ps. The lifetime is measured using $L_{xy}(D^\pm)$, defined as the distance of the $D^\pm$ decay vertex from the beam-spot projected onto the plane perpendicular to the z axis.

To further improve the search sensitivity, a Boosted Decision Tree (BDT) algorithm [14] is constructed from seven discriminating variables for each $D^\pm$ candidate: $\tau_{xy}(D^\pm)$, $L_{xy}(D^\pm)$, the CM momentum magnitude $p_T(D^\pm)$, the momentum magnitudes and transverse components with respect to the beam axis for both the $K_S^0$ and pion candidates. Because all the input variables contains no charge information, no charge bias is expected to be introduced by the algorithm and this assumption has been verified using a large sample of MC simulated events. The final selection criteria are based on the BDT output and optimized using truth-matched signal and background candidates from the MC sample. For the optimization, we maximize the $S/\sqrt{S + B}$ ratio, where $S$ and $B$ are the numbers of signal and background candidates whose invariant mass is within $\pm 31$ MeV/$c^2$ of the nominal $D^\pm$ mass.
of two other contributions in addition to $A_{CP}$. There is a physics component due to the forward-backward (FB) asymmetry ($A_{FB}$) in $e^+e^- \rightarrow c\bar{c}$, arising from $\gamma^*Z^0$ interference and high order QED processes in $e^+e^- \rightarrow c\bar{c}$. This asymmetry will create a difference in the number of reconstructed $D^+$ and $D^-$ decays due to the FB detection asymmetries arising from the boost of the CM system relative to the laboratory frame. There is also a detector-induced component due to the difference in the reconstruction efficiencies of $D^+ \rightarrow K^0_S\pi^+$ and $D^- \rightarrow K^0_S\pi^-$ generated by differences in the track reconstruction and identification efficiencies for $\pi^+$ and $\pi^-$. While $A_{FB}$ is measured together with $A_{CP}$ using the selected data set, we correct the data set itself for the reconstruction and identification effects using control data sets.

In this analysis we have developed a data-driven method to determine the charge asymmetry in track reconstruction as a function of the magnitude of the track momentum and its polar angle. Since $B$ mesons are produced in the process $e^+e^- \rightarrow Y(4S) \rightarrow BB$ nearly at rest in the CM frame and decay isotropically in the $B$ rest frame, these events provide a very large control sample essentially free of any physics-induced charge asymmetry. However, data recorded at the $Y(4S)$ resonance also include continuum production $e^+e^- \rightarrow q\bar{q}(q = u, d, s, c)$, where there is a non-negligible FB asymmetry due to the interference between the single virtual photon process and other production processes, as described above. The continuum contribution is estimated using the off-resonance data re-scaled to the same luminosity as the on-resonance data sample. Subtracting the number of reconstructed tracks in the rescaled off-resonance sample from the number of tracks in the on-resonance one, we obtain the number of tracks corresponding to the $B$ meson decays only. Therefore, the relative detection and identification efficiencies of the positively and negatively charged particles for given selection criteria can be determined using the numbers of positively and negatively reconstructed tracks directly from data.

Using samples of 8.5 fb$^{-1}$ on-resonance and 9.5 fb$^{-1}$ off-resonance data, applying the same charged pion track selection criteria used in the reconstruction of $D^\pm \rightarrow K^0_S\pi^\pm$ decays, and subtracting the off-resonance sample from the on-resonance sample, we obtain a sample of more than $20 \times 10^6$ tracks. We use this sample to produce a map for the ratio of detection efficiencies for $\pi^+$ and $\pi^-$ as a function of the track-momentum magnitude and $\cos\theta$, where $\theta$ is the polar angle of the track in the laboratory frame. The map and associated statistical errors are shown in Fig. 2. Since the charm meson production is azimuthally uniform, the $\phi$ dependence of this ratio is found to be very small and uncorrelated with momentum magnitude and polar angle. Therefore, the ratio of detection efficiencies is averaged over the $\phi$ coordinate. The statistical uncertainties can be reduced by increasing the control sample.
The selected sample is divided into ten subsamples corresponding to ten \( \cos\theta_D^* \) bins of equal width and a simultaneous binned ML fit is performed on the invariant mass distributions of \( D^+ \) and \( D^- \) candidates for each subsample to extract the signal yield asymmetries. The PDF shape that describes the distribution in each subsample is the same as that used in the fit to the full sample, but the following parameters are allowed to float separately in each subsample: the yields and the asymmetries for signal and combinatorial events, the mean of the second and third Gaussians for the signal PDF, and the first order coefficient for the polynomial of the combinatorial background. The relative fractions corresponding to the second Gaussian are allowed to float only for three high-statistics subsamples, while they have been fixed to zero for other ones in order to have a converged fit. The means of the three Gaussians for the signal PDF, the width of the first Gaussian, and the second-order coefficient for the polynomial of the combinatorial background are allowed to float, but they have the same values for all the subsamples. Therefore, the final fit involves a total of 78 free parameters. Using the asymmetry measurements in five positive and in five negative \( \cos\theta_D^* \) bins, we obtain five \( A_{FB} \) and five \( A_{CP} \) values. As \( A_{CP} \) does not depend upon \( \cos\theta_D^* \), we compute a central value of this parameter using a \( \chi^2 \) minimization to a constant: \( A_{CP} = (-0.39 \pm 0.13)\% \), where the error is statistical only. The \( A_{CP} \) and \( A_{FB} \) values are shown in Fig. 3, together with the central value and \( \pm 1\sigma \) confidence interval for \( A_{CP} \).

We perform two tests to validate the analysis procedure. The first involves generating ensembles of toy MC experiments and extracting \( A_{CP} \) for each experiment. We determine that the fitted value of the \( A_{CP} \) parameter is unbiased, and that the fit returns an accurate estimate of the statistical uncertainty. The second test involves fitting a large number of MC events from the full BABAR detector simulation. We measure \( A_{CP} \) from this MC sample to be within \( \pm 1\sigma \) from the generated value of zero.

The primary sources of systematic uncertainty are the contamination in the composition of particles for the data control sample used to determine the charge asymmetry in track reconstruction efficiencies and statistical uncertainties in the detection efficiency ratios used to weight the \( D^- \) yields. The charged pion sample selected to determine the ratio of detection efficiencies for \( \pi^- \) and \( \pi^+ \) contains a contamination of kaons, electrons, muons, and protons at the percent level due to particle misidentification and inefficiencies. This contamination introduces a small bias in the \( A_{CP} \) measurement due to the slightly different particle identification efficiencies between positively and negatively charged nonpion particles. The particle identification efficiencies, measured in the data for positively and negatively charged tracks using the method described in the previous paragraphs, are found to be in a good agreement with the MC simulation. We therefore study this bias using
the systematic contribution from the difference in the composition of the control sample compared to the signal sample (±0.05%), as described earlier, the total contribution from the correction technique is ±0.08%, which is the dominant source of systematic error. We also consider a possible systematic uncertainty due to the regeneration of $K^0$ and $\bar{K}^0$ mesons in the material of the detector. $K^0$ and $\bar{K}^0$ mesons produced in the decay process can interact with the material around the interaction point before they decay. Following a method similar to that described in [15], we compute the probability for $K^0$ and $\bar{K}^0$ to interact inside the BABAR tracking system. We numerically integrate the interaction probability distribution, which depends on the measured nuclear cross-section for $K^\pm$ (assuming isospin symmetry), the amount of material in the BABAR beam-pipe and tracking detectors, the $K^0/\bar{K}^0$ time evolutions, and the $K^0_s$ kinematic distribution and reconstruction efficiency as determined from simulation studies. From the difference between the interaction probabilities for $K^0$ and $\bar{K}^0$, we estimate a systematic uncertainty of ±0.06%. Minor systematic uncertainties from the simultaneous ML fit are also considered: the choice of the signal and background PDF, the limited MC data set to estimate the normalization of $D_s^\pm \to K^0_sK^\pm_s$, and the choice of binning in $\cos \theta^*_D$, for a total contribution of ±0.01%. The combined systematic uncertainty in the $CP$ asymmetry measurement including all the contributions is calculated as the quadrature sum and is found to be ±0.10%.

In conclusion, we measure the direct $CP$ asymmetry, $A_{CP}$, in the $D^\pm \to K^0_s\pi^\pm$ decay using approximately 800,000 $D^\pm$ signal candidates. We obtain

$$A_{CP} = (-0.44 \pm 0.13 \pm 0.10)\%,$$

where the first error is statistical and the second is systematic. The result is consistent with the prediction of $(-0.332 \pm 0.006)\%$ for this mode based on the SM.

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[13] The contribution from CP violation in B decays from the standard model processes is estimated to be negligible.
