Search for *CP* Violation in the decays $D^+ \to K_S\pi^+$ and $D^+ \to K_SK^+$

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A high-statistics sample of photoproduced charm from the FOCUS experiment has been used to search for direct *CP* violation in the decay rates for $D^+ \to K_S\pi^+$ and $D^+ \to K_SK^+$. We have measured the following asymmetry parameters relative to $D^+ \to K^-\pi^+\pi^+$: $A_{CP}(K_S\pi^+) = (-1.6 \pm 1.5 \pm 0.9)\%$, $A_{CP}(K_SK^+) = (+6.9 \pm 6.0 \pm 1.5)\%$, and $A_{CP}(K_SK^+) = (+7.1 \pm 6.1 \pm 1.2)\%$ relative to $D^+ \to K_S\pi^+$. We have also measured the relative branching ratios and found $\Gamma(D^+ \to \bar{K}^0\pi^+)/\Gamma(D^+ \to K^-\pi^+\pi^+) = (30.60 \pm 0.46 \pm 0.32)\%$, $\Gamma(D^+ \to \bar{K}^0K^+)/\Gamma(D^+ \to K^-\pi^+\pi^+) = (6.04 \pm 0.35 \pm 0.30)\%$, and $\Gamma(D^+ \to \bar{K}^0K^+)/\Gamma(D^+ \to \bar{K}^0\pi^+) = (19.96 \pm 1.19 \pm 0.96)\%$.

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CP is violated when the decay rate of a particle differs from that of its *CP* conjugate [1]. In the Kobayashi-Maskawa ansatz this arises due to the nonvanishing phase in the Cabibbo-Kobayashi-Maskawa matrix when the decay amplitude has contributions from at least two quark diagrams with differing weak phases. In addition final state interactions (FSI) must provide a strong phase shift. In the standard model, direct *CP* violation in the charm meson system is predicted to occur at the level of 10^{-3} or below [2]. The mechanism usually considered is the interference of the tree and penguin amplitudes in singly Cabibbo suppressed (SCS) decays. In the decay $D^+ \to K_S\pi^+$ (the charge conjugate state is implied unless stated otherwise), the Cabibbo favored (CF) and doubly Cabibbo suppressed (DCS) amplitudes contribute coherently with, perhaps, a different weak phase. In addition the isospin content of the DCS amplitude differs from that of the CF case so we can expect a nontrivial strong phase shift. Several authors have commented on the effect of K^0 mixing on the *CP* asymmetry for this decay mode and the possibility of using it to search for new physics [3,4].

Differences in the weak two-body nonleptonic decay amplitudes of charmed mesons are almost certainly due to FSI. These effects tend to be large in the charmed system making it an ideal laboratory for their study [5]. The isospin amplitudes and phase shifts in $D \to KK$, $D \to K\pi$ and $D \to \pi\pi$ decays can be extracted from measurements of the branching fractions [6]. For example, the magnitude of the $I = 3/2$ amplitude can be obtained directly from the $D^+ \to \bar{K}^0\pi^+$ partial width [7].

Previous studies of $D^+ \to K_S\pi^+$ and $D^+ \to K_SK^+$ have concentrated on measuring relative branching ratios [8,9]. This paper reports the first measurement of the *CP* asymmetry for these decays.

The data were collected during the 1996–1997 fixed target run at Fermilab. Bremsstrahlung of electrons and positrons with an end point energy of approximately 300 GeV produces a photon beam. These beam photons interact in a segmented beryllium-oxide target and produce charmed particles. The average photon energy for events which satisfy our trigger is $\simeq$180 GeV. FOCUS uses an upgraded version of the E687 spectrometer which is described in detail elsewhere [10].

The $D^+ \to K^-\pi^+\pi^+$ decay is reconstructed using a candidate driven vertexing algorithm. A decay vertex is formed using the reconstructed tracks, after which the momentum vector of the parent D meson is intersected with other tracks in the event to form a production vertex. The confidence level of the secondary vertex is required to be greater than 1%. The likelihood for each charged particle to be an electron, pion, kaon or proton based on the light yield from each threshold Čerenkov counter is computed [11]. We demand that the kaon hypothesis W_K, i.e., $-2\ln(\text{kaon\_likelihood})$, be favored over the pion hypothesis W_π by $\Delta W = W_\pi - W_K \geq 1$. We also make a pion consistency cut by finding the alternative minimum hypothesis $W_{\min}$ and requiring $W_{\min} - W_\pi > -2$ for both pions. We eliminate contamination due to $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ by asking that neither $K\pi$ invariant mass combination lies within 25 MeV$/c^2$ of the nominal D^0 mass.

The techniques used for K_S reconstruction are described elsewhere [12]. The reconstructed K_S signal comes from the decay chain $\bar{K}^0 \to K_S \to \pi^+\pi^-$. Because 90% of K_S decays occur after the K_S has passed through the silicon strip detector we are unable to employ the same vertexing algorithm used to reconstruct the $D^+ \to K^-\pi^+\pi^+$ decay. Instead we use the momentum information from the K_S decay and the silicon track of the charged daughter to form a candidate D vector. This vector is intersected with candidate production vertices which are formed from two other silicon tracks. As a final check we force the D vector to originate at our production vertex and calculate the confidence level that forms a vertex with the charged daughter. This confidence level must be greater than 2%. We require that the momentum of the charged daughter be greater than 10 GeV$/c$, that the confidence level for it to be a muon be less than 1%, and that it traverse the entire length of the spectrometer. For the decay $D^+ \to K_S\pi^+$ we demand that $W_{\min} - W_\pi > -6$ and $W_\pi - W_K < 0$; for $D^+ \to K_SK^+$ we ask that the kaon hypothesis be favored over both the proton and pion hypotheses by requiring $W_p - W_K > 0$ and $W_\pi - W_K > 3$. We remove electron contamination by ensuring that the charged D daughter links to only one silicon microstrip track. Electron pairs usually have a very small opening angle in the silicon, and chamber tracks tend to link to both tracks. Checks for electron contamination of the K_S sample using the electromagnetic calorimeters showed no significant effect. We use only K_S candidates which have a normalized mass [13] within three standard deviations of the nominal value. Additionally, to reduce backgrounds in the $D^+ \to K_SK^+$ mode, we do not use the category of K_S decays which occur downstream of the silicon where both K_S daughters lie outside the acceptance of the downstream magnet. We make the same cut on the $D^+ \to K_S\pi^+$ normalization signal. When the K_S decays in the silicon detector we demand that all three tracks be inconsistent with originating at the same vertex. This eliminates backgrounds from decays such as $D^+ \to \pi^-\pi^+\pi^+$.

For all modes we require that the production vertex have a confidence level greater than 1%, that the maximum confidence level for a candidate-D daughter track to form a vertex with tracks from the primary vertex be less than 20%, that the significance of separation of the production and decay vertices be greater than 7.5, and that both vertices lie upstream of the first trigger counter. The momentum of the D must be greater than 40 GeV$/c$. In Figs. 1, 2, and 3 we show the invariant mass distributions for the decays $K_S\pi^+$, K_SK^+, and $K^-\pi^+\pi^+$, respectively.

We construct the *CP* asymmetry, A_{CP} as the difference in the yields (corrected for efficiency and acceptance) of the decay in question divided by the sum. We must also account for differences in production between the D^+ and D^-. To do this we normalize the corrected yields to those of a Cabibbo favored decay which is assumed to be *CP* conserving. We measure

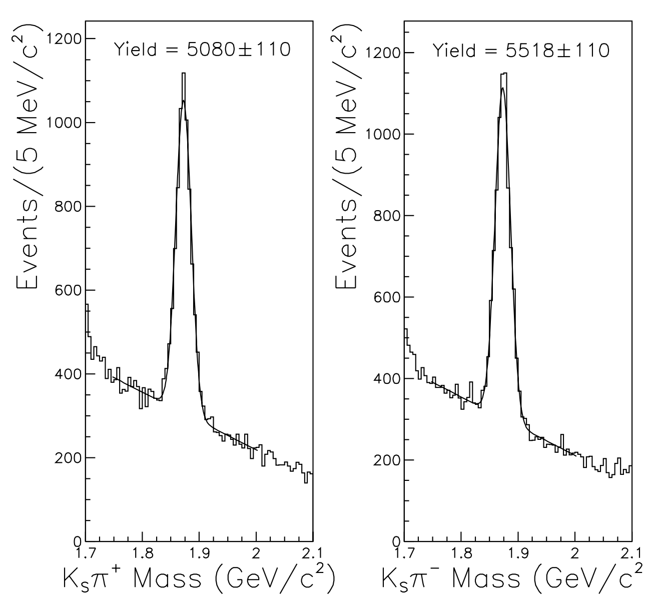

FIG. 1. $D^+ \to K_S\pi^+$ and $D^- \to K_S\pi^-$ invariant mass plots.

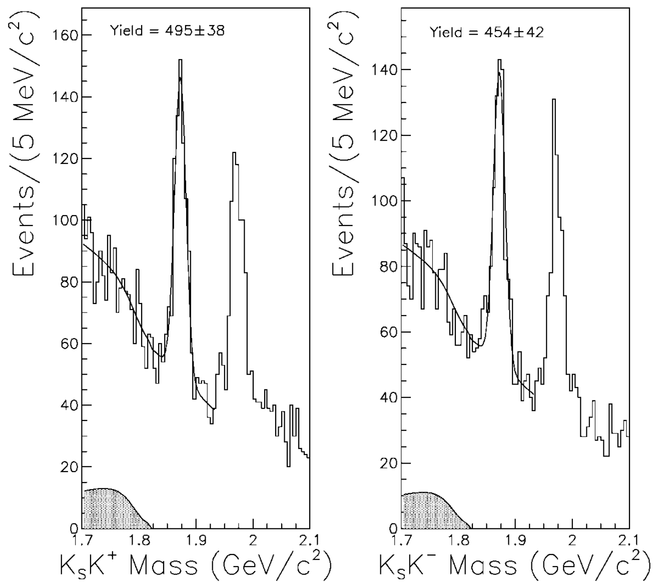

FIG. 2. $D^+ \rightarrow K_S K^+$ and $D^- \rightarrow K_S K^-$ invariant mass plots. The shaded area is the smoothed background shape from $D_s^+ \rightarrow K^{*+}\bar{K}^0$ and $D_s^+ \rightarrow \bar{K}^{*0}K^+$.

$$A_{CP} = \frac{\eta(D^+) - \eta(D^-)}{\eta(D^+) + \eta(D^-)},$$

where $\eta(D^+)$ is the ratio of the corrected yields for each decay, which is equivalent to the relative branching ratio. To account for non-Gaussian tails in the $D^+ \rightarrow K^-\pi^+\pi^+$ signals we find it necessary to fit these distributions by using two Gaussians and a third-degree polynomial. The $K_S\pi^+$ distribution is fit using a Gaussian and a linear polynomial. The nonlinear background shape below 1.75 GeV/c^2 in the $K_S\pi^+$ plot is primarily due to $D^+ \rightarrow K_S l^+ \nu_l$ and is not included in the fit. We fit the $K_S K^+$ signal using a combination of a Gaussian, linear polynomial, and a background shape derived from the Monte Carlo method. This shape is a smoothed fit to $D_s^+ \rightarrow K^{*+}\bar{K}^0$ and $D_s^+ \rightarrow \bar{K}^{*0}K^+$ decays which, due to a missing π^0, are responsible for the background shape below the D^+ peak. Because of the difficulty in fitting the region between the D^+ and D_s^+ peak in the $K_S K^+$ distribution we fit only up to 1.935 GeV/c^2. To minimize systematic errors we change the K_S selection cuts on the $D^+ \rightarrow K_S\pi^+$ normalization signal to match those used for the $D^+ \rightarrow K_S K^+$ mode. The fit yields and relative reconstruction efficiencies are shown in Table I. We can now calculate the relative branching ratios and *CP* asymmetries. The results are shown in Tables II and III.

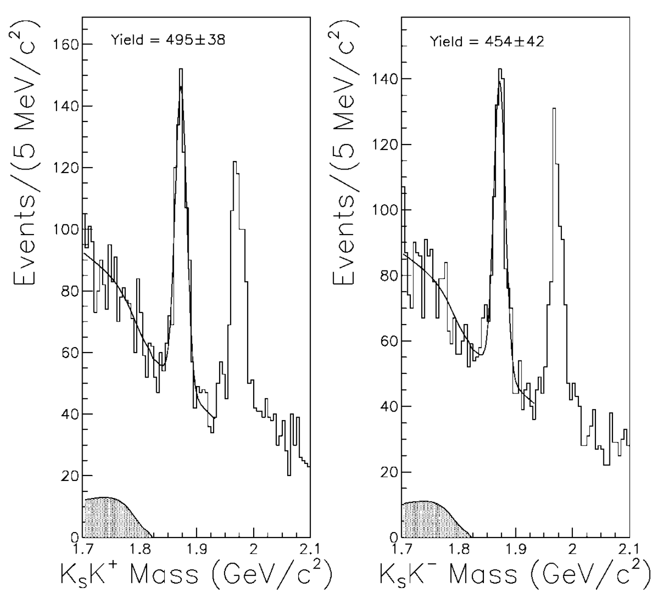

FIG. 3. Invariant mass plot for $D^+ \rightarrow K^-\pi^+\pi^+$ and $D^- \rightarrow K^+\pi^-\pi^-$. The shaded area is the third-degree polynomial background in the fit region.

We studied systematic effects due to uncertainties in our Monte Carlo production model, reconstruction algorithm, and variations in our selection cuts. For the $D^+ \rightarrow K_S\pi^+$ measurements we split the sample into eight statistically independent subsamples based on D^+ momentum, loose and tight normalized K_S mass cuts, and the time period in which the data were collected. Independent analyses, such as *CP* asymmetry measurements for CF modes, have revealed no evidence of a charge dependent bias in our spectrometer. The momentum dependence of the result arises mainly due to uncertainties in the parameters used to generate our Monte Carlo. The $D^+ \rightarrow K_S\pi^+$ topology and reconstruction algorithm is substantially different from that of the $D^+ \rightarrow K^-\pi^+\pi^+$ and the two modes differ in how well the Monte Carlo matches the data. For example, there is a slight difference in how well the generated and accepted momentum distributions agree in each case. We use a technique modeled after the *S-factor* method used by the Particle Data Group [14] to evaluate the systematic error. A scaled variance is calculated using the eight independent subsamples. The split-sample systematic is defined as the difference between the scaled variance and the statistical variance when the former exceeds the latter. Because of the smaller statistics in the $D^+ \rightarrow K_S K^+$ decay mode we can form only four independent subsamples. These are based on the run period in which the data were collected and on the normalized K_S mass.

TABLE I. Yields and relative efficiencies for $D^+ \rightarrow K_S\pi^+$, $D^+ \rightarrow K_S K^+$, and $D^+ \rightarrow K^-\pi^+\pi^+$. Efficiency numbers are quoted relative to the average of the $D^+ \rightarrow K^-\pi^+\pi^+$ and $D^+ \rightarrow K^-\pi^-\pi^-$ efficiencies. We generated a very large Monte Carlo sample to render the statistical error on the efficiencies negligible.

Decay Mode	$D^+ \rightarrow K_S\pi^+$ Yield	cuts Eff.	$D^+ \rightarrow K_S K^+$ Yield	cuts Eff.
$D^+ \rightarrow K_S\pi^+$	5080 ± 110	0.58	4487 ± 96	0.51
$D^+ \rightarrow K_S\pi^-$	5518 ± 110	0.56	4770 ± 96	0.50
$D^+ \rightarrow K_S K^+$	...	...	495 ± 38	0.26
$D^+ \rightarrow K_S K^-$	...	...	454 ± 42	0.25
$D^+ \rightarrow K^-\pi^+\pi^+$	84750 ± 512	1.01	84750 ± 512	1.01
$D^+ \rightarrow K^+\pi^-\pi^-$	91520 ± 508	0.99	91520 ± 508	0.99

TABLE II. Relative branching ratio results. The first error is statistical and the second is systematic. We account for the decay chain $\bar{K}^0 \to K_S \to \pi^+\pi^-$ by multiplying our K_S numbers by a factor of 2.91, assuming that $\Gamma(D^+ \to \bar{K}^0\pi^+) = 2 \times \Gamma(D^+ \to K_S\pi^+)$; we then quote these results in terms of $\bar{K}^0$.

Measurement	Result	PDG average [14]
$\frac{\Gamma(D^+\to\bar{K}^0\pi^+)}{\Gamma(D^+\to K^-\pi^+\pi^+)}$	(30.60 ± 0.46 ± 0.32)%	(32.0 ± 4.0)%
$\frac{\Gamma(D^+\to\bar{K}^0\pi^+)}{\Gamma(D^+\to K^-\pi^+\pi^+)}$	(6.04 ± 0.35 ± 0.30)%	(7.7 ± 2.2)%[a]
$\frac{\Gamma(D^+\to\bar{K}^0\pi^+)}{\Gamma(D^+\to K^0\pi^+)}$	(19.96 ± 1.19 ± 0.96)%	(26.3 ± 3.5)%

[a]This is the measurement of Ref. [6] with statistical and systematic errors added in quadrature.

We evaluate systematic uncertainties due to the fitting procedure by calculating our results for various fit conditions, such as rebinning the histograms, changing the background shapes, and in the case of $D^+ \to K_SK^+$ also fitting the D_s peak. Since these different results are all *a priori* likely, we use the resulting sample variance as a systematic. The total systematic is calculated by adding the fit-variant systematic and the split-sample systematic in quadrature. For the $D^+ \to K_S\pi^+$ measurements the systematic has contributions from both the split-sample and fit-variant analyses. For the $\Gamma(D^+ \to \bar{K}^0\pi^+)/\Gamma(D^+ \to K^-\pi^+\pi^+)$ measurement the contribution from the split sample is 0.301% and from the fit variant 0.098%. For the $A_CP(K_S\pi^+)$ measurement the split-sample contribution is 0.92% and that of the fit variant is 0.13%. We find no systematic contribution to the $D^+ \to K_SK^+$ measurements from the split-sample technique, and therefore the fit-variant contributions are identical to the total systematic error and are as shown in Tables II and III. Because of the lower statistics we did not split the $D^+ \to K_SK^+$ sample by momentum. Instead we treated the weighted average of two samples split by momentum as a fit variant.

We have searched for evidence of direct *CP* violation in the decays $D^+ \to K_S\pi^+$ and $D^+ \to K_SK^+$ and measured their branching ratios relative to each other and to $D^+ \to K^-\pi^+\pi^+$. Our relative branching ratios are a considerable improvement over previous measurements. The *CP* asymmetries have not been previously measured for these modes and are consistent with zero.

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TABLE III. *CP* asymmetry measurements. The first error is statistical and the second is systematic.

Measurement	Result
$A_{CP}(K_S\pi^+)$ w.r.t. $D^+ \to K^-\pi^+\pi^+$	(−1.6 ± 1.5 ± 0.9)%
$A_{CP}(K_SK^+)$ w.r.t. $D^+ \to K^-\pi^+\pi^+$	(+6.9 ± 6.0 ± 1.5)%
$A_{CP}(K_SK^+)$ w.r.t. $D^+ \to K_S\pi^+$	(+7.1 ± 6.1 ± 1.2)%

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