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Measurement of the decays $D^0 \to \pi^- \pi^+$ and $D^0 \to K^- K^+$

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Using data from Fermilab photoproduction experiment E691, we measure the ratio of branching fractions between the Cabibbo-suppressed modes $B(D^0 \to K^- K^+)/B(D^0 \to \pi^- \pi^+)$ to be $1.95 \pm 0.34 \pm 0.22$. We also report branching fractions for the modes $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ relative to the Cabibbo-allowed decay $D^0 \to K^- \pi^+$. Furthermore, we place an upper limit of 0.45 at the 90% C.L. on the *CP*-violating asymmetry in $D^0 \to K^- K^+$ vs $\bar{D}^0 \to K^- K^+$ decays.

I. INTRODUCTION

A key element in understanding the pattern of heavy-quark decays into hadronic final states is the role of the strong interaction. The quarks resulting from the weak decay must combine with the other valence or sea quarks to form the decay products. The hadronic structure of decays with exactly two particles in the final state is unambiguous, in contrast with multibody decays in which resonant final-state particles may be present. We have measured the branching ratios of the Cabibbo-suppressed modes $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ relative to the Cabibbo-allowed channel $D^0 \to K^- \pi^+$. These decays proceed via external spectator diagrams [1]. All decays implicitly include the charge conjugate unless otherwise stated.

If there were an unbroken SU(3) flavor symmetry in the amplitudes of the two decays, then the ratio of branching fractions

$$R(KK/\pi\pi) = \frac{B(D^0 \to K^- K^+)}{B(D^0 \to \pi^- \pi^+)}$$

would be determined solely by the difference in phase space, and should equal 0.86. Models [1] for hadronic charm decays which take into account SU(3) breaking due to strong interactions predict R to be about 1.4. In this Rapid Communication, we present results on the branching fractions for the decay modes discussed above based on data from the photoproduction experiment E691 at Fermilab. In addition, we have analyzed the decay modes $D^0 \to K^- K^+$ and $\bar{D}^0 \to K^- K^+$ for the presence of a *CP*-violating asymmetry.

The E691 spectrometer and the event-reconstruction procedure are described in Ref. [2]. In this analysis, events were selected by requiring at least one downstream vertex. This reduced the number of events from 10^8 to 1.2×10^7. Events were then selected which had at least one secondary vertex with two oppositely charged tracks, more than a certain number of standard deviations (SDZ), downstream of the primary interaction vertex. The tracks from the secondary vertex were required to pass closer to that vertex than to the primary. The χ^2/N_{DF} of the secondary vertex was required to be less than 1.7. The line of flight of the resultant D^0 candidate was determined from the summed three-momentum of the two tracks and the position of the two-track vertex. Only those candidates were selected whose line of flight passed within 80 μm of the primary vertex. Probabilities for particle identification were assigned to each charged track based on the light seen in Čerenkov counter phototubes [3]. To extract the signals for $D^0 \to \pi^- \pi^+$ and $D^0 \to K^- K^+$, decay candidates were selected in which both tracks had pion probabilities > 0.84 or kaon probabilities > 0.4, respectively. No Čerenkov cut was required to extract a signal for $D^0 \to K^- \pi^+$. All tracks were required to have a χ^2/N_{DF} less than 5.0 and to pass through both spectrometer magnets.

II. ANALYSIS FOR RELATIVE BRANCHING FRACTIONS

To determine the relative branching fractions, we used the D^0 candidates described above, requiring a vertex separation of SDZ > 9.0. The resulting mass plots for $D^0 \to \pi^- \pi^+$ and $D^0 \to K^- K^+$ are shown in Figs. 1 and 2, respectively.

In the $\pi^- \pi^+$ mass plot, in addition to the signal, there is a broad peak at 1.77 GeV/c^2 due to $D^0 \to K^- \pi^+$ decays where the kaon is misidentified as a pion. A

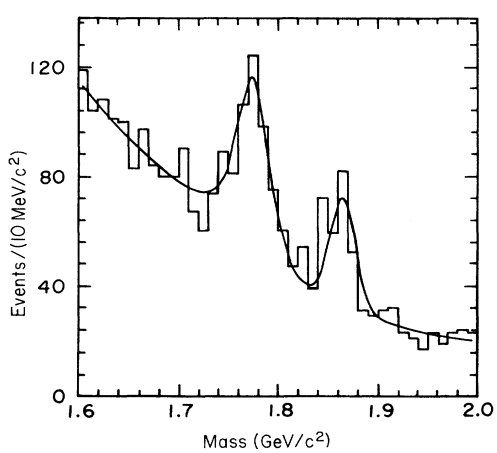

FIG. 1. Signal and fit for $D^0 \to \pi^- \pi^+$.

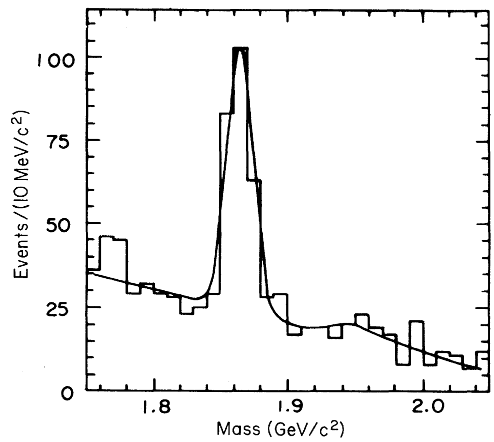

FIG. 2. Signal and fit for $D^0 \to K^- K^+$.

parametrization of this "false peak" is found from the large number of $D^0 \to K^- \pi^+$ events and from the E691 Monte Carlo (MC) simulation. A term of the form $Am^2 + Bm + C$ is used for the additional background. The signal term is a Gaussian with mean fixed at the established value of 1.865 GeV/c^2 and σ fixed at 0.012 GeV/c^2, as determined from the MC simulation. We studied the background due to the decays $D^0 \to K^- \pi^+ \pi^0$ and $D^0 \to K^- \pi^+ \pi^0 \pi^0$ using the MC simulation. In both cases, the contribution is about 1% of the entires in the $\pi^- \pi^+$ mass plot, and therefore no explicit term for these modes was included. A least-squares fit, of the form described above, gives a signal of 120 ± 18 $\pi\pi$ events.

In fitting the $K^- K^+$ mass plot, we included a term for a "false peak" at 1.95 GeV/c^2 due to misidentified $D^0 \to K^- \pi^+$ decays. The number of signal events was determined by a least-squares fit of the type described above, but with $\sigma = 0.0091$ GeV/c^2 for the Gaussian signal. The width for $D^0 \to K^- K^+$ is slightly smaller than that for $D^0 \to \pi^- \pi^+$ because the Q values of these decays differ. The fit for $D^0 \to K^- K^+$ gives 193 ± 18 signal events. The analysis for the decay $D^0 \to K^- \pi^+$ is straightforward because the only significant background is combinatoric. The $K\pi$ mass plot (not shown here) was fit using the technique described above and yielded 4322 ± 97 signal events.

The calculation of the relative branching fractions between these three decay modes requires knowledge of the relative detection efficiency ϵ for each mode. These were determined as the product of two contributions: $\epsilon = \epsilon_G \epsilon_C$, where ϵ_G is the combination of the geometric, track reconstruction, and vertexing efficiencies of the apparatus and ϵ_C is the Čerenkov efficiency. The efficiency ϵ_G is estimated from the MC simulation to be 0.104 ± 0.002 for $K^- K^+$, 0.097 ± 0.002 for $K^- \pi^+$, and 0.093 ± 0.002 for $\pi^- \pi^+$. The efficiencies for these three decay modes differ because their Q values differ. Since no Čerenkov cut was applied to the $K^- \pi^+$ signal, we used this mode to measure ϵ_C. The Čerenkov efficiency for individual pions and kaons, as a function of particle momentum, was determined experimentally from the signals for the decay chain $D^{*+} \to \pi^+ D^0$, $D^0 \to K^- \pi^+$. Based on the single-particle efficiencies, the Čerenkov efficiencies for the

TABLE I. Comparison of relative branching fractions.

	$K^-K^+/K^-\pi^+$	$\pi^-\pi^+/K^-\pi^+$	$K^-K^+/\pi^-\pi^+$
E691	$0.107 \pm 0.010 \pm 0.009$	$0.055 \pm 0.008 \pm 0.005$	$1.95 \pm 0.34 \pm 0.22$
CLEO	$0.117 \pm 0.010 \pm 0.007$	$0.050 \pm 0.007 \pm 0.005$	$2.35 \pm 0.37 \pm 0.28$
ARGUS	$0.10 \pm 0.02 \pm 0.01$	$0.040 \pm 0.007 \pm 0.006$	2.5 ± 0.7
Mark III	0.122 ± 0.018	0.033 ± 0.010	3.7 ± 1.4
Mark II	0.113 ± 0.030	0.033 ± 0.015	3.4 ± 1.8

events passing the geometric and other cuts are $\epsilon_C(\pi^-\pi^+)=0.526 \pm 0.021$ and $\epsilon_C(K^-K^+)=0.389 \pm 0.015$. Since no Čerenkov cut was applied to the $D^0 \to K^-\pi^+$ signal, $\epsilon_C(K^-\pi^+)$ is unity by definition.

Combining the results for efficiency and the number of signal events, the relative branching fractions are given in Table I. The first error quoted is statistical. The second quoted is the combined systematic error due to ϵ_C, ϵ_G and from the different parametrizations of the background. Our results for all three decay modes are consistent with those of other experiments [4], also shown in Table I. Our value of $R(KK/\pi\pi)$ is consistent with the theoretical predictions from Ref. [1].

III. ANALYSIS OF CP VIOLATION IN D^0-$\bar{D}^0$ SYSTEM

CP violation in charm decays has not been previously explored experimentally. This violation can be observed through the interference of at least two amplitudes for decay to the same final state. This could lead to a difference in the decay rates of the particle and antiparticle and is characterized by the asymmetry

$$A = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}},$$

where Γ and $\bar{\Gamma}$ are the partial decay widths of the particle and antiparticle into the same final state. For neutral D mesons, this interference may occur via two processes. In the first, the final state is a CP eigenstate, reachable from either direct D^0 decay or through D^0-$\bar{D}^0$ mixing, and the asymmetry depends on the decay time. The second does not involve mixing, but requires interference between two diagrams describing the same decay, and is not time dependent.

For the decays $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$, Bigi [5] has estimated that CP asymmetries are at most a few times 10^{-3} within the standard model. Of the two decay modes to CP eigenstates that we have measured, the signal sizes are comparable, but the K^-K^+ mode has much less background. As a result, only the K^-K^+ data provides sufficient statistical power for a CP-violation analysis. In this case, the decay rates are given by

$$\mathrm{Rate}(D^0 \to K^-K^+) = |T_{KK}|^2 e^{-\Gamma_{D}t}[1 - a\sin(\Delta m t)],$$

$$\mathrm{Rate}(\bar{D}^0 \to K^-K^+) = \bar{T}_{KK}|^2 e^{-\Gamma_{D}t}[1 + a\sin(\Delta m t)],$$

where Δm is the mass difference between the mass eigenstates, a is the CP-violating decay parameter due to mixing, T_{KK} and $\bar{T}_{KK}$ are the decay amplitudes for the particle and antiparticle, respectively. Bigi has pointed out that even though Δm has been measured to be small ($\Delta m < 1.5 \times 10^{-4}$ eV/c^2 from E691 [6]), a decay asymmetry (outside the standard model) could be as large as 0.09 if $|a|$ is near its limit of 1 or even larger than 0.09 if there is direct CP violation in the decay amplitudes, i.e., $|T_{KK}|^2 \neq |\bar{T}_{KK}|^2$.

For this analysis, in addition to the cuts described in the Introduction, we required SDZ ≥ 5.0. To tag the initial state as charm or anticharm, we used the decay chain $D^{*+} \to \pi^+ D^0$+c.c. The pion from D^* decay was required to pass through both spectrometer magnets. The mass distributions for $D^0 \to K^-K^+$ and $\bar{D}^0 \to K^-K^+$ are shown in Figs. 3 and 4, respectively.

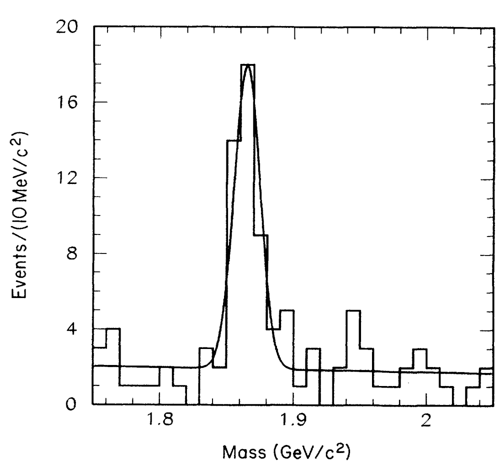

FIG. 3. Signal and fit for $D^0 \to K^-K^+$ from D^{*+}.

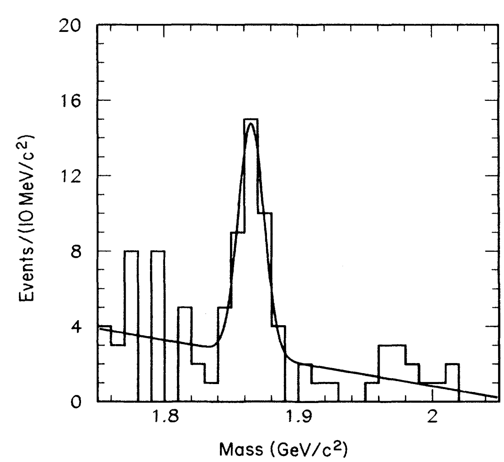

FIG. 4. Signal and fit for $\bar{D}^0 \to K^-K^+$ from D^{*-}.

If the Δm limit is fixed at the E691 value, the deviation from exponential decay is never more than 0.05%, even with the maximum allowed value of $|a|=1$. With the statistics of our data sample, we have no sensitivity to this deviation; hence, we fit to the time-integrated mass distributions, using the maximum-likelihood method. The signal was parametrized by a Gaussian of fixed mass and width and the background by a polynomial. We measure $N_{KK}=39\pm8$ $D^0\rightarrow K^-K^+$ events and $\bar{N}_{KK}=30\pm7$ $\bar{D}^0\rightarrow K^-K^+$ events.

To determine the relative decay rates, we normalize the observed signals to the ratio of D^{*-} vs D^{*+} cross sections measured in this experiment, 1.15 ± 0.07 [7]. Using the signals quoted above, we obtain $A=0.20\pm0.15$, or $A\leq0.45$ at the 90% confidence level. This limit is on the time-independent asymmetry for the case of direct *CP* violation. In the case of mixing, the limit is on the combination ax where $x=\Delta m/\Gamma$. Since the limit on x from E691 is 0.09, we are not able to restrict the allowed region for a from this measurement. Although not stringent, the result reported here is the first limit on *CP* violation in charm decays.

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