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Experimental probes of final-state interactions in D^0-meson decays

J. C. Anjos,[c] J. A. Appel,[f] A. Bean,[a] S. B. Bracker,[k] T. E. Browder,[a,*] L. M. Cremaldi,[g] J. E. Duboscq,[a] J. R. Elliot,[e,†] C. O. Escobar,[j] M. C. Gibney,[e,‡] G. F. Hartner,[k] P. E. Karchin,[l] B. R. Kumar,[k] M. J. Losty,[h] G. J. Luste,[k] P. M. Mantsch,[f] J. F. Martin,[k] S. McHugh,[a] S. R. Menary,[k,§] R. J. Morrison,[a] T. Nash,[f] P. Ong,[k] J. Pinfold,[b] G. Punkar,[a,**] M. V. Purohit,[i] W. R. Ross,[l] A. F. S. Santoro,[c] A. L. Shoup,[d,††] K. Sliwa,[f,‡‡] M. D. Sokoloff,[d] M. H. G. Souza,[c] W. J. Spalding,[f] M. E. Streetman,[f] A. B. Stundžia,[k] and M. S. Witherell[a]

[a]*University of California, Santa Barbara, California 93106*
[b]*Carleton University, Ottawa, Ontario, Canada K1S 5B6*
[c]*Centro Brasilero de Pesquisas Fisicas, Rio de Janeiro CEP 22290, Brazil*
[d]*University of Cincinnati, Cincinnati, Ohio 45221*
[e]*University of Colorado, Boulder, Colorado 80309*
[f]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[g]*University of Mississippi, University, Mississippi 38677*
[h]*National Research Council, Ottawa, Ontario, Canada K1S 5B6*
[i]*Princeton University, Princeton, New Jersey 08544*
[j]*Universidade de São Paulo, São Paulo BR-01498, Brazil*
[k]*University of Toronto, Toronto, Ontario, Canada M5S 1A7*
[l]*Yale University, New Haven, Connecticut 06511*

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Using data from the Fermilab photoproduction experiment E691, we have measured the branching ratio for the decay $D^0 \rightarrow \bar{K}^0\pi^0$ to be $(5.0 \pm 0.8 \pm 0.9)\%$. We see no evidence for the decay $D^0 \rightarrow \bar{K}^0K^0$ and set a 90% confidence level upper limit of 0.12%. The large $\bar{K}^0\pi^0$ branching ratio (relative to $K^-\pi^+$) indicates either a lack of color suppression or significant elastic final-state interactions. The upper limit on the $\bar{K}^0K^0$ mode indicates that final-state interactions mix final states such as K^+K^- or $\pi^+\pi^-$ into the $\bar{K}^0K^0$ less than 27% of the time at the 90% confidence level.

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INTRODUCTION

Final-state interactions in charmed particle weak decays may seriously complicate the traditional interpretation of experimental results [1–4]. These interactions can be classified into two types: elastic, which preserve final-state quark content, and inelastic, which can change final-state quark content (transforming $u\bar{u}s\bar{s}$

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[*] Now at Cornell University, Ithaca, NY 14853.
[†] Now at Electromagnetic Applications, Denver, CO 80226.
[‡] Now at Nichols Research, Inc., Colorado Springs, CO 80226.
[§] Now at CERN, Division EP, CH-1211, Genève, Switzerland.
[**] Now at SLAC, Stanford, CA 94309.
[††] Now at University of California, Irvine, CA 92716.
[‡‡] Now at Tufts University, Medford, MA 02155.

to $d\bar{d}s\bar{s}$, for instance). The major mechanisms of D^0 decays are illustrated in Fig. 1: spectator decays [Figs. 1(a) and 1(b)] and *W*-exchange decays [Figs. 1(c) and 1(d)]. The weak annihilation mechanism does not contribute to D^0 decays due to the absence of flavor-changing neutral currents. We present a measurement of the decay $D^0 \to \bar{K}^0\pi^0$ and an upper limit for the decay $D^0 \to \bar{K}^0K^0$ whose rates are sensitive to final-state interactions.

The effect of elastic final-state interactions on D^0 decays can be explored by comparing the $D^0 \to \bar{K}^0\pi^0$ and $D^0 \to K^-\pi^+$ decay rates. Both decays proceed through Cabibbo-allowed spectator diagrams: $K^-\pi^+$ through an outer *W* [Fig. 1(a)] and $\bar{K}^0\pi^0$ through an inner *W* [Fig. 1(b)]. The weak parts of the two decays are identical and the available phase space is almost identical. Any difference between the branching ratios of these two modes would be evidence of quark recombination differences. Simple color suppression arguments [3,4] predict the ratio of $\bar{K}^0\pi^0$ to $K^-\pi^+$ to be about 0.1. Lipkin [1], Donoghue [3], and Bauer, Stech, and Wirbel [4] have argued that elastic finate-state interactions can change the relative rates of these two decay modes by inducing a phase shift between their isospin-$\frac{1}{2}$ and isospin-$\frac{3}{2}$ amplitudes. Another possibility, sometimes called bleaching [5], is that soft gluons could be exchanged between final-state quarks to change their color, reducing any color suppression.

The Cabibbo-suppressed decay $D^0 \to \bar{K}^0K^0$ is sensitive to inelastic final-state interactions. This decay cannot proceed through a spectator amplitude alone; there is no $\bar{u}$ quark in the final-state hadrons. Two *W*-exchange diagrams [Figs. 1(c) and 1(d)] could contribute, but in the absence of SU(2)-flavor symmetry breaking, their amplitudes cancel each other through the Glashow-Iliopoulos-Maiani (GIM) [2] mechanism. The $\bar{K}^0K^0$ final state can be produced with inelastic final-state interactions as illustrated in Fig. 2. The big *S* represents a hadronic interaction which changes the $d\bar{d}$ pair into a $u\bar{u}$ pair. If the $D^0 \to \bar{K}^0K^0$ decay proceeds at a rate similar to other Cabibbo-suppressed decays, inelastic final-state interactions may be significant. If the rate is well below other Cabibbo-suppressed rates, it could be explained by SU(2)-flavor symmetry breaking. Such symmetry breaking can occur through differences in the probability of an $s\bar{s}$ or $d\bar{d}$ popping up from the vacuum. It may also occur through a difference in the helicity suppression of coupling a *W* vector boson to an *s* quark relative to that for coupling to a *d* quark in the *W*-exchange diagrams shown in Figs. 1(c) and 1(d).

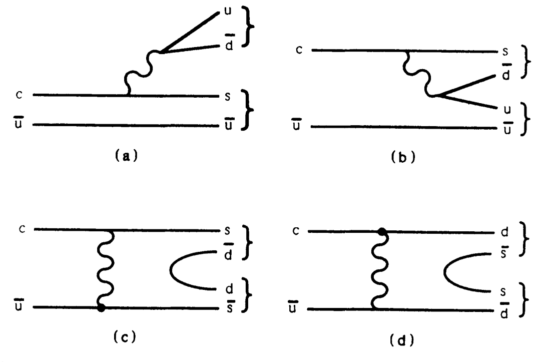

FIG. 1. Feynman diagrams for weak charmed meson decays. The dots mark the Cabibbo-suppressed vertices. (a) Outer-*W* spectator; (b) inner-*W* spectator; (c) and (d) are two of the possible *W*-exchange diagrams. The curly brackets indicate how quarks combine.

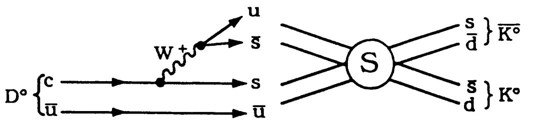

FIG. 2. Mechanism to produce the decay $D^2 \to \bar{K}^0K^0$ from a spectator decay, using inelastic final-state interactions. The big *S* represents a hadronic interaction which changes the $u\bar{u}$ pair into a $d\bar{d}$ pair.

EXPERIMENTAL SETUP

Fermilab experiment E691 was a photoproduction experiment designed to study the production and decay properties of charmed particles. Photons with energy between 80 and 240 GeV interacted in a 5-cm beryllium target. Reconstructed D^0's produced from these interactions generally had momenta between 30 and 120 GeV/*c* with an average momentum of 60 GeV/*c*.

Events were detected in the Tagged Photon Spectrometer (TPS), an open-geometry, two-magnet spectrometer. Silicon microstrip detectors (SMD's) and drift chambers tracked charged particles. Two threshold Čerenkov counters, divided into a total of 60 cells, provided particle identification. A segmented liquid ionization calorimeter (SLIC) was used to measure electromagnetic showers produced by electrons and photons. The SLIC resolved shower centroids to about 3 mm and had a fractional energy resolution of about $21\%/\sqrt{E\,(\mathrm{GeV})}$. Mass resolutions were typically 8 and 12 MeV/c^2 for K_S^0's and π^0's, respectively. More complete descriptions of the detector, of our particle identification and vertexing algorithms, and of related results are found in Refs. [6–9].

$D^0 \to \bar{K}^0\pi^0$

The $D^0 \to \bar{K}^0\pi^0$ sample was obtained from the decay chain $D^{*+} \to D^0\pi^+$, $D^0 \to \bar{K}^0\pi^0$, $\bar{K}^0 \to K_S^0 \to \pi^+\pi^-$, $\pi^0 \to \gamma\gamma$ (charge conjugate states are implicitly included). We required each $\pi^+\pi^-$ pair to form a good downstream vertex and to have an invariant mass within 17 MeV/c^2 (2σ) of the K_S^0 mass [10]. The two photons each had energy > 2.0 GeV, satisfied geometric cuts to reduce backgrounds from beam photons, and satisfied additional cuts to accept only well-identified photons [10]. The $\gamma\gamma$ invariant mass was required to lie within 24 MeV/c^2 (2σ) of the π^0 mass.

All possible charged pions were individually combined with each D^0 candidate. The mass difference ΔM

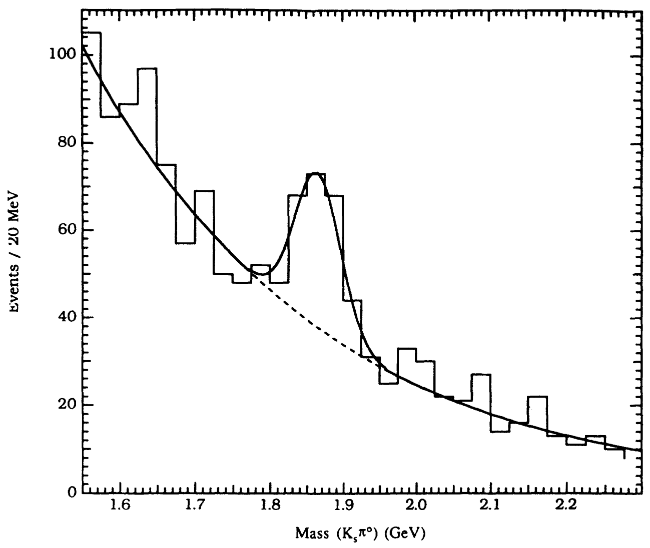

FIG. 3. $K_S^0\pi^0$ invariant mass histogram. The dashed line shows the fitted background contribution under the signal.

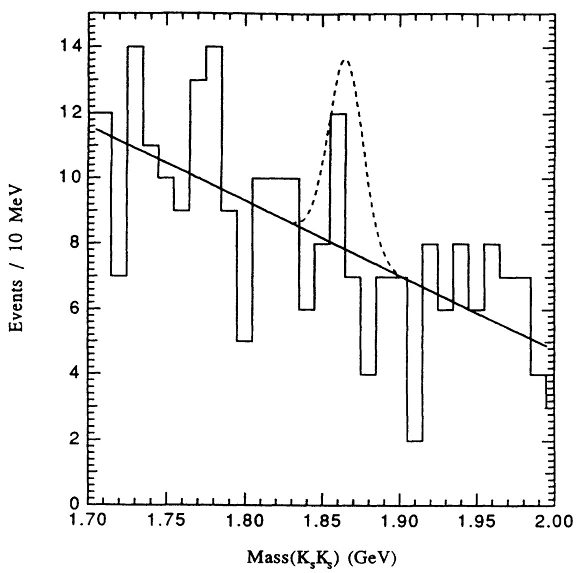

FIG. 4. $K_S^0K_S^0$ invariant mass histogram. The dashed line shows the signal level corresponding to our 90% C.L. upper limit.

$=M(K_S^0\pi^0\pi^+)-M(K_S^0\pi^0)$ was required to lie between 0.144 and 0.147 GeV/c^2, consistent with the hypothesis $D^{*+}\rightarrow D^0\pi^+$. This mass difference requirement reduced combinatorial backgrounds by a factor of 50, while losing only 25% of the D^*'s. We also required $|\cos\theta_{\text{c.m.}}|<0.7$ where $\theta_{\text{c.m.}}$ is the angle of the π^0 momentum relative to the D^0 boost direction in the D^0 rest frame. Our background tended to peak at $\cos\theta_{\text{c.m.}}$ near $+1$ and we had no acceptance near -1. Except for acceptance, the signal should be flat in $\cos\theta_{\text{c.m.}}$ since the $\bar{K}^0$ and π^0 are in a relative s wave.

The $K_S^0\pi^0$ invariant mass histogram, displayed in Fig. 3, was fit to the sum of a Gaussian signal plus an exponential background. The Gaussian width was fixed to that calculated from our Monte Carlo simulation and the central value fixed at the D^0 mass. We find a signal of 119 ± 15 $D^0\rightarrow K_S^0\pi^0$ events. To compute the ratio of $D^0\rightarrow\bar{K}^0\pi^0$ to $D^0\rightarrow K^-\pi^+$, we corrected the signal for the $\bar{K}^0\rightarrow K_S^0\rightarrow\pi^+\pi^-$ branching ratios and for our reconstruction efficiency of $(1.9\pm0.3)\%$. We divided by our acceptance and efficiency corrected $D^{*+}\rightarrow D^0\pi^+$, $D^0\rightarrow K^-\pi^+$ signal [9], giving

$$\frac{B(D^0\rightarrow\bar{K}^0\pi^0)}{B(D^0\rightarrow K^-\pi^+)}=1.36\pm0.23\pm0.22$$

($\pm$statistical$\pm$systematic, discussed below). Using the Particle Data Group [11] value of $3.71\pm0.25\%$ for $B(D^0\rightarrow K^-\pi^+)$, we obtain $B(D^0\rightarrow\bar{K}^0\pi^0)=5.0\pm0.8$ $\pm0.9\%$.

$D^0\rightarrow\bar{K}^0K^0$

The decay mode $D^0\rightarrow\bar{K}^0K^0$ was analyzed through the decay chain $D^{*+}\rightarrow D^0\pi^+$, $D^0\rightarrow\bar{K}^0K^0$, $\bar{K}^0K^0\rightarrow K_S^0K_S^0$, $K_S^0\rightarrow\pi^+\pi^-$. The analysis was similar to that for $D^0\rightarrow\bar{K}^0\pi^0$. Both K_S^0 candidates were required to form good downstream vertices and have invariant mass within 17 MeV/c^2 (2σ) of the K_S^0 mass. The D^*-D^0 mass difference, ΔM, was required to lie within the range 0.144–0.147 GeV/c^2. The $K_S^0K_S^0$ invariant mass histogram, shown in Fig. 4, was fit to the sum of a Gaussian signal plus a linear background. The width was fixed to that determined from our Monte Carlo simulation. The central value was fixed to the D^0 mass. There is no evidence of a signal in the histogram, and we found 0.0 ± 4.5 $D^0\rightarrow\bar{K}^0K^0$ events. We corrected this result for the $(6.3\pm0.8)\%$ reconstruction efficiency for this decay chain and for the $\bar{K}^0K^0\rightarrow K_S^0K_S^0$ and $K_S^0\rightarrow\pi^+\pi^-$ branching ratios. The $\bar{K}^0K^0\rightarrow K_S^0K_S^0$ branching ratio is $\frac{1}{2}$ (not $\frac{1}{4}$) because the $\bar{K}^0K^0$ must be in an even parity state, and expanding this state in terms of the weak eigenstates K_S^0 and K_L^0 leaves only the combinations $K_S^0K_S^0$ and $K_L^0K_L^0$ [10]. Normalizing to $D^0\rightarrow K^-\pi^+$, we obtain the 90% C.L. upper limit

$$\frac{B(D^0\rightarrow\bar{K}^0K^0)}{B(D^0\rightarrow K^-\pi^+)}<0.032\,.$$

Using the Particle Data Group [11] value $(3.71\pm0.25)\%$ for $B(D^0\rightarrow K^-\pi^+)$, we obtain an 90% C.L. upper limit of 0.12% for $B(D^0\rightarrow\bar{K}^0K^0)$.

SYSTEMATIC ERRORS

There are several sources of systematic uncertainty in these results. For both decay modes the uncertainty in reconstruction efficiencies found using the Monte Carlo simulation program in conjunction with correction factors determined *a posteriori* dominate the uncertainties. For most cases, the fractional error due to uncertainty in the Monte Carlo simulation of charged tracks is less than 5%. The accuracy of the $K_S^0\rightarrow\pi^+\pi^-$ reconstruction efficiency is less well known as the π tracks traverse only the drift

TABLE I. Absolute D^0 branching ratios (in percent) and ratios of branching ratios, or the corresponding 90% confidence level upper limits, from other experiments, with the E691 results for comparison. The column labeled Theory I gives predictions including final-state interactions; the column labeled Theory II gives predictions excluding final-state interactions.

Result	ARGUS [13]	CLEO [14]	Mark III [16,17]	E400 [15]	E691	Theory I [2,4]	Theory II [2,4]
$B(D^0 \to \bar{K}^0\pi^0)$		$2.3 \pm 0.4 \pm 0.05$	$1.9 \pm 0.4 \pm 0.4$		$5.0 \pm 0.8 \pm 0.9$	2.4	0.24
$\frac{B(D^0 \to \bar{K}^0\pi^0)}{B(D^0 \to K^-\pi^+)}$		$0.55 \pm 0.06 \pm 0.07$	$0.45 \pm 0.10 \pm 0.10$		$1.36 + 0.23 \pm 0.22$	0.43	0.1
$B(D^0 \to \bar{K}^0K^0)$	<0.11	$0.13^{+0.07+0.02}_{-0.05-0.02}$	<0.46	0.10 ± 0.08	<0.12	0.30	0
$\frac{B(D^0 \to \bar{K}^0K^0)}{B(D^0 \to K^+K^-)}$	<0.24			0.20 ± 0.15	<0.27	0.50	0

chambers and not the SMD's. However, the per track per plane efficiencies of the drift chambers in the Monte Carlo program and in the data, after the tracks are found, agree at the 1-2% level. We have determined that the systematic error in the K_S^0 reconstruction efficiency is 9% [10].

The accuracy of the $\pi^0 \to \gamma\gamma$ reconstruction efficiency (used in the $D^0 \to \bar{K}^0\pi^0$ decay mode) was studied using the four decay modes of K^*'s. From isospin, the π^0 reconstruction efficiency can be determined relative to the well understood π^+ efficiency using the relation [12]

$$\frac{\epsilon_{\pi^0}}{\epsilon_{\pi^+}} = 2\left[\frac{N(K^{*0} \to K_S^0\pi^0)}{N(K^{*0} \to K^-\pi^+)}\,\frac{N(K^{*+} \to K^+\pi^0)}{N(K^{*+} \to K_S^0\pi^+)}\right]^{1/2} .$$

Combining results of such a study with our Monte Carlo simulation, we have determined a π^0 reconstruction efficiency correction factor for which the systematic error is 12%. We calculated the systematic errors reported for the ratios of branching ratios as the sums in quadrature of the uncertainties described above. For the absolute branching ratios we also added (in quadrature) the fractional errors in the denominator branching ratios taken from the Particle Data Group.

SUMMARY

Our measurement and earlier measurements for the ratio $B(D^0 \to \bar{K}^0\pi^0)/B(D^0 \to K^-\pi^+)$, Table I, are much higher than the prediction from a simple color suppression model. While the branching ratio we measure is more than twice as large as the others, all three have comparable fractional errors, both statistical and systematic. All are marginally consistent with a value around 3%, and all are consistent with the predictions made by Donoghue [3] and by Bauer, Stech, and Wirbel [4] when elastic final-state interactions are included, but lower than the largest of Lipkin [1]. Since the weak components and available phase spaces of the two decays are the same, any difference in the two branching ratios must lie in the quark recombination process. Two possible explanations are that any color suppression is reduced by elastic final-state interactions or that color suppression is reduced by bleaching.

A comparison of the measurements for $D^0 \to \bar{K}^0K^0$ which are sensitive to inelastic final-state interactions shows that we and the ARGUS [13] Collaboration have obtained 90% C.L. upper bounds which are about a factor of 3 below the prediction of Pham [2]. The CLEO [14] and E400 [15] Collaborations have observations at about the same level as our upper limit. All the measurements are consistent with a low level of inelastic final-state interactions or with SU(2)-flavor symmetry breaking.

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