Search for Nonspectator Decays of the D^0

R. M. Baltrusaitis, J. J. Becker, G. T. Blaylock, J. S. Brown, K. O. Bunnell, T. H. Burnett, R. E. Cassell, D. Coffman, V. Cook, D. H. Coward, S. Dado, D. E. Dorfan, G. P. Dubois, A. L. Duncan, K. F. Einsweiler, B. I. Eisenstein, R. Fabrizio, G. Gladding, F. Grancagnolo, R. P. Hamilton, J. Hauser, C. A. Heusch, D. G. Hitlin, L. Köpke, W. S. Lockman, U. Mallik, P. M. Mockett, R. F. Mozley, A. Nappi, A. Odian, R. Partridge, J. Perrier, S. A. Plaetzer, J. D. Richman, J. Roehrig, J. J. Russell, H. F. W. Sadrozinski, M. Scarlatella, T. L. Schalk, R. H. Schindler, A. Seiden, C. Simopoulos, J. C. Sleeman, A. L. Spadafora, I. E. Stockdale, J. J. Thaler, B. Tripsas, W. Toki, F. Villa, A. Wattenberg, A. J. Weinstein, N. Wermes, H. J. Willutzki, D. Wisinski, W. J. Wisniewski, and G. Wolf

(The MARK III Collaboration)

California Institute of Technology, Pasadena, California 91125
University of California at Santa Cruz, Santa Cruz, California 95064
University of Illinois at Urbana-Champaign, Urbana, Illinois 61801
Stanford Linear Accelerator Center, Stanford, California 94305
University of Washington, Seattle, Washington 98195
(Received 13 February 1986)

The weak hadronic decay $D^0 \to \bar{K}^0 K^+ K^-$ is observed in a data sample of 9.3 pb^{-1} collected with the Mark III detector at the $\psi(3770)$ resonance. An analysis of the K^+K^- subsystem suggests that while the decay proceeds in part through the $\bar{K}^0\phi$ channel, providing evidence for the presence of nonspectator amplitudes in D^0 decays, a significant fraction of the decays occurs through both higher- and lower-mass K^+K^- systems. A limit is set on the decay $D^0 \to \bar{K}^0 K^0$, also thought to proceed by nonspectator processes.

PACS numbers: 13.25.+m

The inequality of D^0 and D^+ charmed-meson lifetimes has been demonstrated both through direct lifetime measurements[1] and by comparison of the semileptonic branching fractions.[2] This difference may arise from a suppression of the D^+ width, an enhancement of the D^0 width, or a combination of the two. Evidence for interference among final-state amplitudes leading to a suppression of the D^+ width[3] has previously been presented.[4] We address herein the question of the enhancement of the D^0 width through a study of the decays $D^0 \to \bar{K}^0\phi$ and $\bar{K}^0 K^0$. In these final states, the absence of the $\bar{u}$ quark of the parent D^0 provides a signature for flavor annihilation,[5,6] a mechanism which can enhance the Cabibbo-allowed D^0 and the Cabibbo-suppressed D^+ partial widths. Evidence for $D^0 \to \bar{K}^0\phi$ has been previously reported.[7] Further evidence is presented for this nonspectator decay through a measurement of $B(D^0 \to \bar{K}^0\phi)$ in the $K_S^0 K^+ K^-$ final state, and a detailed study of its backgrounds. A limit is also established for the decay $D^0 \to \bar{K}^0 K^0$.

The Mark III detector has been described in detail elsewhere.[8] The analysis of the $\bar{K}^0\phi$ channel proceeds as follows: The K^0 is isolated through its K_S^0 decay into $\pi^+\pi^-$, in which at least one π is required to miss the beam-interaction point by $R_{\text{miss}} \geq 2$ mm in the transverse plane. The pair's direction at the decay point must align with the vector joining the $\pi^+\pi^-$ vertex and the primary vertex, within errors. The $\pi^+\pi^-$ invariant mass is then required to lie within 0.020 GeV/c^2 of the K_S^0 mass. Charged kaons are identified by cuts on time of flight[4] and dE/dx loss.[9] The momentum of the $K_S^0 K^+ K^-$ is required to lie within ± 0.050 GeV/c of that expected for D^0's produced at the $\psi(3770)$. Combinations whose momenta lie outside the expected range (in sidebands from 0.060 to 0.110 GeV/c) are used to estimate the shape of the background. The resulting mass distribution and fit are shown in Fig. 1(a). A fit yields 25.2 ± 5.4 events in the D^0 signal when the mass resolution is fixed to 0.015 GeV/c^2 (determined from Monte Carlo calculations). Reflections from other D^0 decays in which π-K misidentification has occurred appear at higher masses (~ 1.974 GeV/c^2) and thus are not a source of background.

To study the K^+K^- system, 28 $K_S^0 K^+ K^-$ events whose masses are within ± 0.040 GeV/c^2 of the D^0 mass are selected; 4.8 of these events originate from backgrounds. The resulting K^+K^- mass distribution is shown in Fig. 2(a). Monte Carlo calculations indicate that the ϕ mass resolution is 0.0042 GeV/c^2; the K^+K^- efficiency varies slowly above 0.995 GeV/c^2. The ϕ region is defined as 1.019 ± 0.015 GeV/c^2; there are 4 events below, 11 events within, and 13 events above this region. The K^+K^- mass distribution of the 4.8 random background events is determined from a sample of 25 $K_S^0 K^+ K^-$ combinations consistent with the D^0 mass, but lying in the momen-

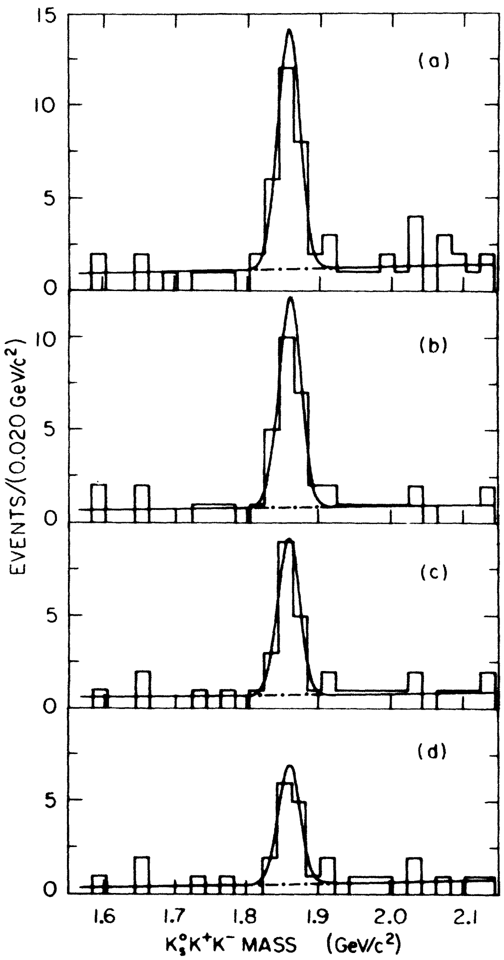

FIG. 1. (a) $K_S^0K^+K^-$ mass and fit. Throughout this paper we adopt the convention that reference to a particle state also implies reference to its charge conjugate. The background shape is derived from off-momentum events. $K_S^0K^+K^-$ mass and fit (b) for $|\cos\theta^*| \geqslant 0.2$, (c) for $|\cos\theta^*| \geqslant 0.4$, (d) for $|\cos\theta^*| \geqslant 0.6$.

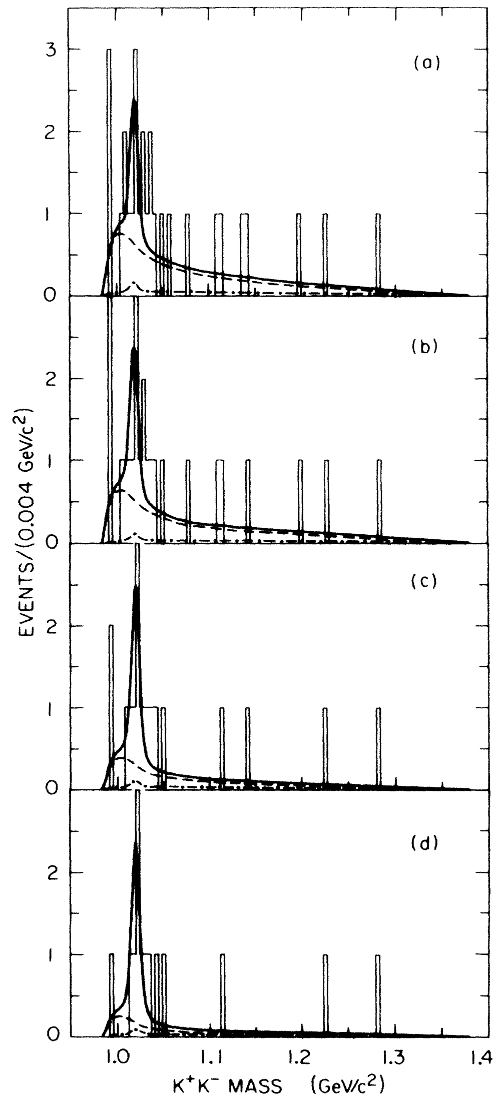

FIG. 2. (a) K^+K^- mass in $K_S^0K^+K^-$; solid curve is the combined fit; dashed curve, the $\bar{K}^0\delta^0$; and dot-dashed curve, the random background. (b) Fit for $|\cos\theta^*| \geqslant 0.2$. (c) Fit for $|\cos\theta^*| \geqslant 0.4$. (d) Fit for $|\cos\theta^*| \geqslant 0.6$.

tum sidebands. Of these 5 K^+K^- pairs lie within the ϕ region, yielding a limit of $\leqslant 1.7$ events at 90% confidence level (C.L.) from random backgrounds, when scaled to a total of 4.8 events. The shape of the distribution of these 25 events is well represented by inclusive K^+K^- pairs. This shape is used to model the random background.

Additional backgrounds arise from specific final states. Events from the Cabibbo-suppressed decay $D^0 \to \phi\pi^+\pi^-$ can have a $\pi^+\pi^-$ at the K_S^0 mass. A signal in $\phi\pi^+\pi^-$ of 10.5 ± 5.5 events is observed by selection of combinations of $\pi^+\pi^-$ excluding the K_S^0 mass. Vertex requirements on the K_S^0 reduce the contamination of these decays into $\bar{K}^0\phi$ to $\leqslant 0.3$ event. The decay $D^0 \to K^-K^+\pi^+\pi^-$ may contribute at any K^+K^- mass. No signal is observed, yielding an upper limit of 28 events in the sample. After K_S^0 vertex cuts, $\leqslant 0.80$ event of these remain, with $\leqslant 0.14$ event in the ϕ region itself. Two more potential backgrounds are nonresonant $D^0 \to \bar{K}^0K^+K^-$ and $K^-\delta^+$. Monte Carlo calculations, when normalized to signal events with K^+K^- masses above 1.050 GeV/c^2, predict less than 0.70 and 0.20 event, respectively, in the ϕ region. Events from $D^0 \to \bar{K}^0S^{*0}$, $S^{*0} \to K^+K^-$ would produce a cusp below the ϕ. The S^{*0} decays predominantly to $\pi^+\pi^-$ [10] but is not seen in $D^0 \to \bar{K}^0\pi^+\pi^-$.[11] Hence, no significant contribution from this source is expected. Another possible source of background is the decay $D^0 \to \bar{K}^0\delta^0$, which peaks at low K^+K^- masses but extends to higher K^+K^- masses.[12]

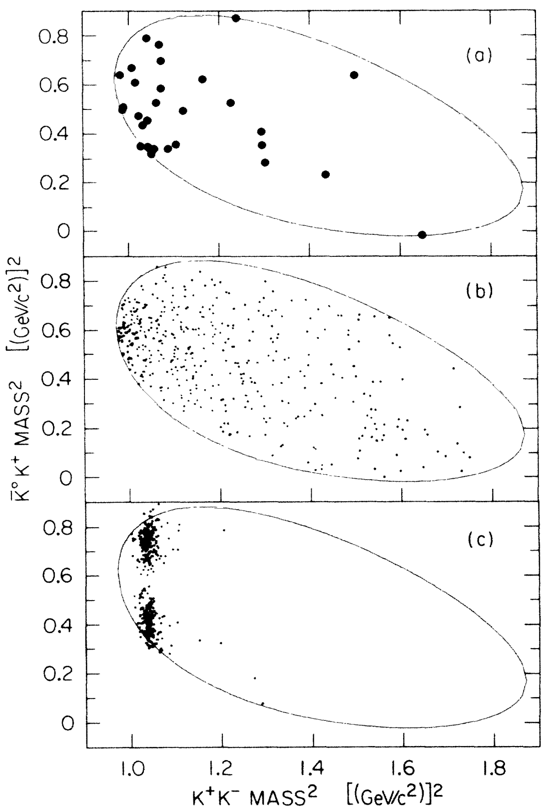

FIG. 3. Dalitz plot for (a) data, (b) Monte Carlo $D^0 \to \bar{K}^0\delta^0$ events, and (c) Monte Carlo $D^0 \to \bar{K}^0\phi$ events.

Figure 3 shows the Dalitz plots for the 28 data events, and 400 Monte Carlo events each, in the $D^0 \to \bar{K}^0\delta^0$ and $\bar{K}^0\phi$ channels. These Monte Carlo events, which include detector acceptance, are directly comparable to the data. The $\bar{K}^0\phi$ channel has a distinctive decay-angle distribution characteristic of all pseudoscalar-vector decays of the D^0.

A likelihood fit is performed to the K^+K^- projection of the Dalitz plot. An incoherent sum of $\bar{K}^0\phi$ and $\bar{K}^0\delta^0$ contributions and a term derived from the inclusive spectrum, reflecting the shape of the random background distribution, is assumed. The fit constrains the number of background events to that measured under the $K_S^0K^+K^-$ peak. To enhance the $\bar{K}^0\phi$ contribution over possible $\bar{K}^0\delta^0$ and background, four fits are performed with successively tighter cuts on the decay-angle distribution ($\cos\theta^*$) of the K^+ relative to the K_S^0 direction. The $K_S^0K^+K^-$ mass distributions and the fits for $|\cos\theta^*| \geq 0.0$, 0.2, 0.4, and 0.6 are shown in Figs. 1(a)–1(d) and Figs. 2(a)–2(d). The initial sample of 28 events is reduced to 24, 18, and 14 by these cuts. The $\bar{K}^0\phi$ contribution changes from $4.9^{+3.9}_{-3.1}$ to $6.6^{+3.5}_{-2.8}$ events, while the $\bar{K}^0\delta^0$ component falls from $19.9^{+6.0}_{-5.3}$ to $5.2^{+3.9}_{-3.2}$ events for $|\cos\theta^*| \geq 0.0$ and ≥ 0.6, respectively. The Monte Carlo calculations predict a loss of 14 $\bar{K}^0\delta^0$ events and only 1.6 $\bar{K}^0\phi$ events for this cut. The significance of the $\bar{K}^0\phi$ component increases from 1.7 to 3.1 standard deviations through this large reduction in background.

To establish the $\bar{K}^0\phi$ branching ratio, $|\cos\theta^*| \geq 0.4$ is employed, providing substantial background rejection with a predicted loss of less than 10% of the signal. There are $6.5^{+3.8}_{-3.0}$ $\bar{K}^0\phi$ events in this fit. To maximize the $K_S^0K^+K^-$ signal *not* arising from $\bar{K}^0\phi$ and to reduce correlations, no cut on $\cos\theta^*$ is applied in the fit. With use of these fits, the D^0 production cross section,[13] and the detection efficiencies, the following branching fractions are obtained:

$$B(D^0 \to \bar{K}^0\phi) = (1.1^{+0.7}_{-0.5}{}^{+0.4}_{-0.2})\%,$$

$$B(D^0 \to \bar{K}^0K^+K^-_{\text{non-}\bar{K}^0\phi}) = (1.1^{+0.4}_{-0.3}{}^{+0.3}_{-0.2})\%.$$

The first error is statistical, and the second systematic, arising from uncertainties in detection efficiency (17%–20%), fitting (12%–31%), and normalization (8.3%). The $\bar{K}^0K^+K^-_{\text{non-}\bar{K}^0\phi}$ channel includes an additional error (7.5%) allowing for uncertainty in the origin of the events: $\bar{K}^0\delta^0$, $K^-\delta^+$, and nonresonant $\bar{K}^0K^+K^-$.

The decay $D^0 \to \bar{K}^0K^0$ is analyzed in the $K_S^0K_S^0$ final state, with tighter vertex cuts ($R_{\text{miss}} \geq 5$ mm) applied to remove contamination from the large $D^0 \to \bar{K}^0\pi^+\pi^-$ channel.[14] Background is reduced by the constraint of the $K_S^0K_S^0$ energy to that of the beam. One event consistent with the D^0 mass is observed in addition to a small background, yielding an upper limit corresponding to 4.4 events (including systematic errors) of $\leq 0.60\%$ for $B(D^0 \to \bar{K}^0K^0)$ at 90% C.L.

In summary, evidence for the decay $D^0 \to \bar{K}^0\phi$, which occurs only through nonspectator processes, has been presented. The branching ratios obtained, while consistent with previous results,[15] differ in detail in the treatment of backgrounds. While the surprisingly large branching fraction is consistent with the expectations of suppression from limited phase space and the removal of an $s\bar{s}$ quark pair from the vacuum,[5] it suggests that there is little or no additional suppression from either helicity factors or wave function overlap, which would be expected if the W-exchange amplitude governed the decay.[5,16] The lack of such suppression could be due to the presence of spin-1 color-octet gluons in the D-meson wave function, raising the possibility of an unexpectedly large value for f_D.[5] Alternatively, this decay may result entirely from rescattering effects, having little or no contribution from W exchange.[6] While the decay to $\bar{K}^0K^0$ must occur through nonspectator processes, it is Cabibbo suppressed and vanishes in the limit of exact SU(3) symmetry.[17] The upper limit relative to $D^0 \to K^-\pi^+$ [18] is consistent with this picture of D^0 decay.

We gratefully acknowledge the efforts of the staff of the SLAC electron-positron storage ring SPEAR. We also wish to thank I. I. Y. Bigi and J. F. Donoghue for valuable discussions and comments. This work was supported in part by the U.S. National Science Foundation and the U.S. Department of Energy under Contracts No. DE-AC03-76SF00515, No. DE-AC02-76ER01195, No. DE-AC03-81ER40050, and No. DE-AM03-76SF00034.

---

[1]See the recent reviews by V. Lüth, in *Proceedings of the Fifth International Conference on Physics in Collision, Autun, 1985,* edited by B. Aubert and L. Montanet (Editions Frontières, Gif-sur-Yvette, France, 1985); E. Thorndike, in Proceedings of the Twelfth International Symposium on Lepton and Photon Interactions at High Energies, Kyoto, 19–24 August 1985 (to be published).

[2]W. Bacino *et al.*, Phys. Rev. Lett. **45**, 329 (1980); R. H. Schindler *et al.*, Phys. Rev. D **24**, 78 (1981); R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **54**, 1976 (1985).

[3]B. Guberina *et al.*, Phys. Lett. **89B**, 111 (1979); I. I. Y. Bigi, Phys. Lett. **90B**, 177 (1980).

[4]R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **55**, 150 (1985).

[5]S. P. Rosen, Phys. Rev. Lett. **44**, 4 (1980); M. Bander, D. Silverman, and A. Soni, Phys. Rev. Lett. **44**, 7 (1980); H. Fritzsch and P. Minkowski, Phys. Lett. **90B**, 455 (1980); I. I. Y. Bigi and M. Fukugita, Phys. Lett. **91B**, 121 (1980); A. N. Kamal, University of Alberta Report No. Thy-3-85, 1985 (to be published). Decays violating the Okubo-Zweig-Iizuka rule can also contribute at a rate $\sim 10^{-3}$ smaller; cf. I. I. Y. Bigi and M. Fukugita.

[6]J. F. Donoghue, Phys. Rev. D **33**, 1516 (1986). The author points out that the contribution from rescattering effects required by unitarity may not be negligible. Henceforth, the more general term *nonspectator* will refer to flavor annihilation and all other classes of amplitudes not contained within the simple light-quark spectator model.

[7]H. Albrecht *et al.*, Phys. Lett. **158B**, 525 (1985); P. Avery *et al.*, in Proceedings of the Twelfth International Symposium on Lepton and Photon Interactions at High Energies, Kyoto, 19–24 August 1985 (to be published).

[8]D. Bernstein *et al.*, Nucl. Instrum. Methods **226**, 310 (1984).

[9]R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **56**, 2140 (1986) (this issue).

[10]See, for example, G. Gidal *et al.*, Phys. Lett. **107B**, 153 (1981).

[11]R. H. Schindler, *et al.*, Stanford Linear Accelerator Center Report No. SLAC-PUB-3799, 1985 (to be published).

[12]The form is suggested by S. M. Flatté, Phys. Lett. **63B**, 224 (1976).

[13]The value $\sigma_{D^0} = 4.48^{+0.33}_{-0.29}{}^{+0.37}_{-0.37}\,\mathrm{nb}^{-1}$ of Ref. 9 is employed.

[14]A. J. Hauser, Ph.D. thesis, California Institute of Technology, 1985 (unpublished).

[15]A $B(D^0 \to \bar{K}^0\phi) = (1.5 \pm 0.5 \pm 0.2)\%$, from Albrecht *et al.*, Ref. 7, is obtained by use of $B(\bar{K}^0\pi^+\pi^-) = (8.3 \pm 0.9 \pm 0.8)\%$ derived from Refs. 9 and 11. From Avery *et al.*, Ref. 7, the range 0.8% to 1.9% is obtained.

[16]See, R. Rückl, Habilitationsschrift, Universität München, 1983 (unpublished), and references therein.

[17]L. L.-Chau, Phys. Rep. **95**, 1 (1983).

[18]The limit obtained from Ref. 9 is $\Gamma(D^0 \to K^0\bar{K}^0)/\Gamma(D^0 \to K^-\pi^+) \leq 0.11$ at 90% C.L.