Study of the decays $D \to \bar{K}^0\pi^+$ and $D \to \bar{K}^0K^+$

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. Elliott,[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,[e] U. Nauenberg,[d] P. Ong,[h] J. Pinfold,[b] G. Punkar,[a] M. V. Purohit,[i] A. F. S. Santoro,[c] J. S. Sidhu,[b,**] 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. Stundzia,[k] and M. S. Witherell[a]

[a]*University of California, Santa Barbara, California 93106*
[b]*Carleton University, Ottawa, Ontario, Canada K1S5B6*
[c]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
[d]*University of Cincinnati, Cincinnati, OH 45221*
[e]*University of Colorado, Boulder, Colorado 80309*
[f]*Fermilab National Accelerator Laboratory, Batavia, Illinois 60510*
[g]*University of Mississippi, Oxford, MS 38677*
[h]*National Research Council, Ottawa, Ontario, Canada K1A0R6*
[i]*Princeton University, Princeton, NJ 08544*
[j]*Universidade de São Paulo, São Paulo, Brazil*
[k]*University of Toronto, Toronto, Canada M5S1A7*
[l]*Yale University, New Haven, Connecticut 06511*

(Received 10 October 1989)

We report measurements of the decays $D^+ \to \bar{K}^0\pi^+$, $D^+ \to \bar{K}^0K^+$, and $D_s^+ \to \bar{K}^0K^+$ from Fermilab photoproduction experiment E691. The relative branching fractions obtained are $B(D^+ \to \bar{K}^0\pi^+)/B(D^+ \to K^-\pi^+\pi^+) = 0.274 \pm 0.030 \pm 0.031$, $B(D^+ \to \bar{K}^0K^+)/B(D^+ \to \bar{K}^0\pi^+) = 0.271 \pm 0.065 \pm 0.039$, and $B(D_s^+ \to \bar{K}^0K^+)/B(D_s^+ \to \phi\pi^+) = 1.15 \pm 0.31 \pm 0.19$.

Two-body pseudoscalar-pseudoscalar decays of charmed mesons have been treated in detail in theory.[1–5] We report observations of the decays $D^+ \to \bar{K}^0\pi^+$, $D^+ \to \bar{K}^0K^+$, and $D_s^+ \to \bar{K}^0K^+$, where the charge-conjugate states are implicitly included. These decays are observed in Fermilab experiment E691 using a high-precision vertex detector, and, together with the decay $\Lambda_c^+ \to \Lambda\pi^+$ seen in the same experiment,[6] represent the first cases where silicon-microstrip vertex techniques have been successfully applied to single-charged-track charm-decay vertices.

The data on two-body decays are in qualitative agreement with a pattern in which Cabibbo-allowed D^+ decays are suppressed by interference effects, since there are two $\bar{d}$ quarks in the decay and therefore two amplitudes which produce the same final state. Perturbative QCD, at the quark level, predicts that the interference is destructive, and possibly large enough to explain the large D^+-D^0 lifetime difference. In the absence of interference effects the ratio of branching ratios of $D^+ \to \bar{K}^0K^+$ to $D^+ \to \bar{K}^0\pi^+$ would be expected to be roughly given by $\tan^2\theta_C$, where θ_C is the Cabibbo angle. The interference picture predicts a substantially larger ratio, because there is no interference in $D^+ \to \bar{K}^0K^+$. The $D_s^+ \to \bar{K}^0K^+$ decay is important in that it is the only pseudoscalar-pseudoscalar D_s^+ decay which has been convincingly observed to date.

The charmed-meson signals discussed in this paper were extracted from 10^8 data events accumulated for the experiment. The two magnet spectrometer had good acceptance and provided precision vertexing using high-resolution silicon-microstrip detectors (SMD's). It had good particle identification using gas threshold Cherenkov counters, electromagnetic and hadronic calorimeters, and muon detectors, and good momentum resolution using a system of 35 drift-chamber planes. The detector is discussed in detail elsewhere.[6,7] The data were produced by directing a bremsstrahlung photon beam with energies of 70–260 GeV onto a 5-cm beryllium target, and events with total transverse energy greater than 2.2 GeV were selected. The transverse energy requirement rejected 70% of the background hadronic interactions while accepting 80% of the charm events.

The $\bar{K}^0$ sample was observed in the $K_S^0 \to \pi^+\pi^-$ decay channel. The candidate pion tracks in the K_S^0 decay were restricted to the set of tracks found only in the drift chambers since the $\pi^+\pi^-$ combinations containing SMD tracks contributed only $\sim 20\%$ of the reconstructed K_S^0's and generated most of the neutral-particle background. The K_S^0 sample used in the analyses (see Fig. 1) was selected by requiring that the decay position of the neutral vertex be greater than 5 cm downstream of the target, by requiring that the distance of closest approach of the decay products be less than 0.5 cm, and by applying a Cherenkov probability cut on the pions which eliminated candidates that had been positively identified as a kaon or a proton. A similar cut was applied to the bachelor pion in the $\bar{K}^0\pi^+$ decay candidates. The Cherenkov cut applied to the bachelor K^+ in the $\bar{K}^0K^+$ combinations excluded track candidates with large pion probabilities.

The angle between the bachelor track and the charm momentum vector in the center of mass of the charmed-

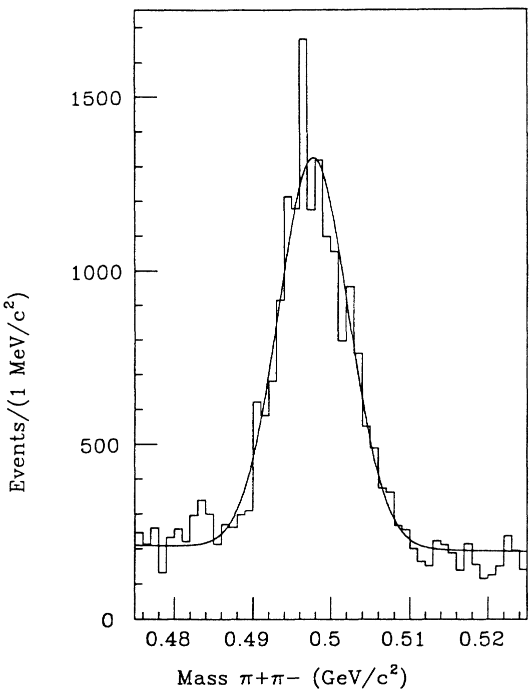

FIG. 1. Invariant $\pi^+\pi^-$ mass spectrum. The signal was fit to a Gaussian plus a linear background giving 12700±160 events, for ~0.5% of our data sample. Only $\pi^+\pi^-$ combinations between 0.486 and 0.510 were used in the analyses.

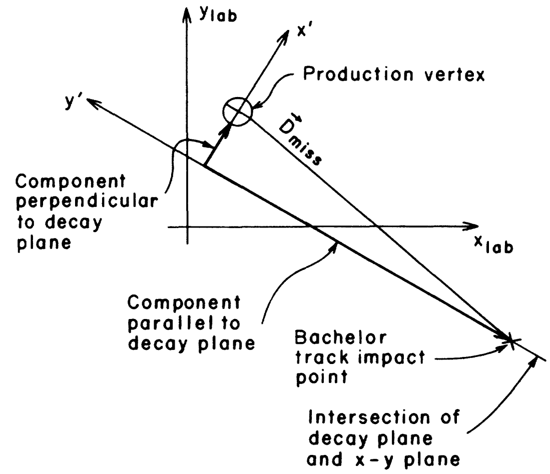

FIG. 2. The vector distance between the production vertex and the impact point of the bachelor track is shown ($\mathbf{D}_{\rm miss}$). The x-y laboratory plane is perpendicular to the beam direction, contains the production vertex, and is intersected by the charm decay plane as shown. The vector $\mathbf{D}_{\rm miss}$ is decomposed into two parts: one parallel and one perpendicular to this line of intersection.

particle candidate ($\theta_{\rm c.m.}$) was then restricted such that $-7. < \cos(\theta_{\rm c.m.}) < 0.7$, for all decay modes. This cut is effective because the charmed mesons decay isotropically in their center of mass while the background peaks in the forward and background directions. In the $D^+ \to \bar{K}^0\pi^+$ channel, this cut eliminated ~40% of the background while reducing the acceptance by less than 10%.

The isolation of clean signals in these charm decays is made possible by the use of the high-precision vertex detector. In this experiment transverse vertex position resolutions for vertices involving two or more charged tracks were typically 20–30 μm, much smaller than typical decay-track impact parameters of about $c\tau$, where τ is the charmed-particle lifetime. The charm decays studied here contained only a single charged track, and as a consequence the vertex isolation procedure is more complicated. In all cases, to avoid biases, the cuts were defined by comparing Monte Carlo–simulated charm events with background events from the experiment. The cuts were chosen to give the maximum ratio of signal from the Monte Carlo events to the square root of the background.

The set of SMD tracks, excluding the bachelor track, was used to form the production vertex. All vertices generated from this set of tracks with $\chi^2/N_{\rm DF} < 3$ were deemed candidates for production vertices. The non-SMD tracks, and in particular, the K_S^0-decay products, were not used in this track set because the position errors assigned to these tracks were much worse than those assigned to SMD tracks. Shown in Fig. 2 is an x-y plane, perpendicular to the photon beam direction, which contains a candidate production vertex. Also shown in this figure is the vector ($\mathbf{D}_{\rm miss}$) from the candidate production vertex to the impact point of the bachelor track in this plane, as well as the line of intersection of this plane with the charm decay plane. The charm decay plane was defined using the momentum of the K_S^0 and the momentum and position of the bachelor track. $\mathbf{D}_{\rm miss}$ was decomposed into two components, one contained in the decay plane, the other perpendicular to it. The candidate pro-

TABLE I. Ratios of D-meson branching ratios.

	E691	Others
$\dfrac{B(D^+\to\bar{K}^0\pi^+)}{B(D^+\to K^-\pi^+\pi^+)}$	0.274±0.030±0.031	0.348±0.033±0.037 (Ref. 9)
$\dfrac{B(D^+\to\bar{K}^0K^+)}{B(D^+\to\bar{K}^0\pi^+)}$	0.271±0.065±0.039	0.317±0.086±0.048 (Ref. 9)
$\dfrac{B(D_s^+\to\bar{K}^0K^+)}{B(D_s^+\to\phi\pi^+)}$	1.15±0.31±0.19	0.93±0.25±0.10 (Ref. 8) 0.92±0.32±0.20 (Ref. 9) 0.99±0.17±0.10 (Ref. 10)

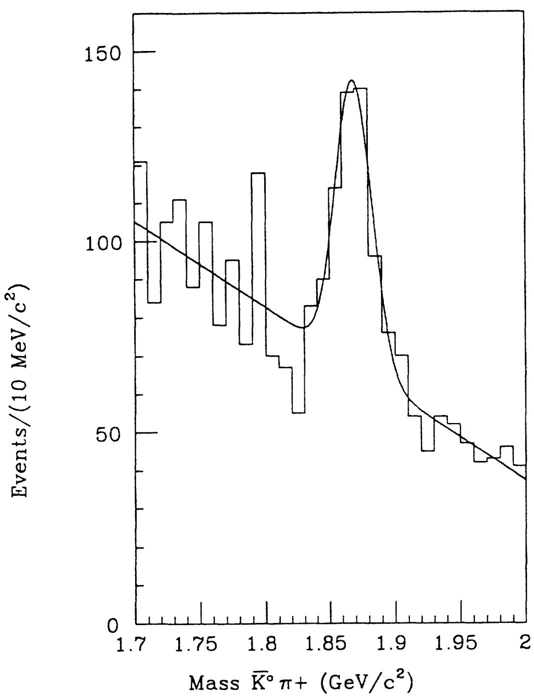

FIG. 3. Invariant $\bar{K}^0\pi^+$ mass spectrum.

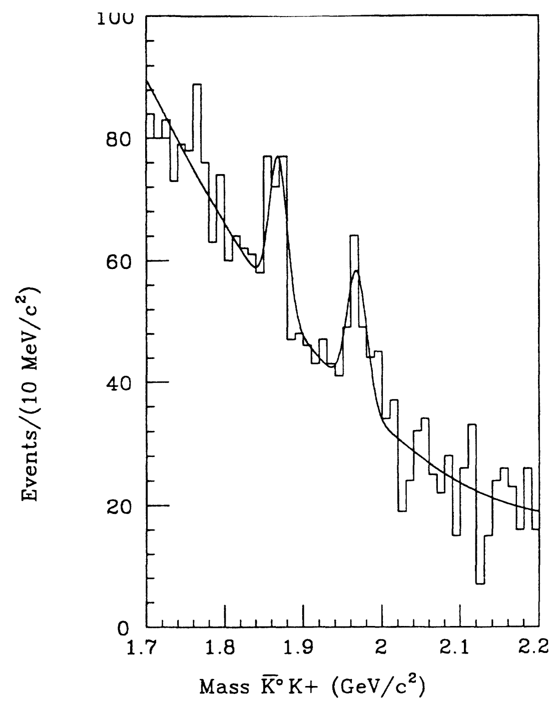

FIG. 4. Invariant $\bar{K}^0K^+$ mass spectrum.

duction vertex associated with the smallest perpendicular component was then chosen as the production vertex for the event since, in the ideal case, the production vertex is contained in the charm decay plane.

Good events have a small transverse component of ($\mathbf{D}_{\text{miss}}$), and a large component in the decay plane since the bachelor decay track does not come from the production vertex. The transverse component was required to be less than 80 μm for the $\bar{K}^0\pi^+$ combinations and less than 100 μm for the $\bar{K}^0K^+$ combinations. The component contained in the charm decay plane had to be greater than 120 μm for the $\bar{K}^0\pi^+$ and greater than 80 μm for the $\bar{K}^0K^+$ combinations since, for charm decays, the bachelor track originates downstream of the production vertex. The cuts were tighter for $\bar{K}^0\pi^+$ due to the larger combinatorial factor.

We were able, at this point, to calculate a well-defined secondary vertex position. Attaching the charm momentum vector to the production vertex, we computed the distance of closest approach between this new vector and the bachelor track. This gave us the decay distance as well. We then required that the decay distance be at least 8σ downstream of the production vertex for the $\bar{K}^0\pi^+$ combinations and at least 6σ downstream for the $\bar{K}^0K^+$ combinations, where σ is the combination in quadrature of the errors on the production and secondary vertices. The secondary vertex error was parametrized as the inverse of the opening angle of the charmed-decay products times a constant (chosen by Monte Carlo studies).

The $\bar{K}^0\pi^+$ invariant-mass distribution is shown in Fig. 3. The signal is fit to a Gaussian plus a linear background, with the width fixed to 13.6 MeV/c^2, as predicted by the Monte Carlo simulation. This fit gives 264±25 events with a mass of 1.869±0.002 GeV/c^2. The reconstruction efficiency for this decay mode is 5.3%, as determined by Monte Carlo simulation and by an evaluation of the neutral-kaon detection efficiency using data. With this signal, we obtain a relative branching ratio of $B(D^+\to\bar{K}^0\pi^+)/B(D^+\to K^-\pi^+\pi^+)=0.274\pm0.030$ ±0.031 which agrees with the Mark III measurement given in Table I. Taking the Mark III value for $B(D^+\to K^-\pi^+\pi^+)=0.091\pm0.013\pm0.004$ (Ref. 9), we obtain $B(D^+\to\bar{K}^0\pi^+)=0.025\pm0.004\pm0.003$, where the statistical and systematic errors have been separately combined in quadrature. The absolute branching fractions are compared with the theoretical predictions in Table II.

The $\bar{K}^0K^+$ invariant-mass distribution is shown in Fig. 4. The spectrum is fit to the sum of two Gaussians plus a quadratic background term. The mass and width

TABLE II. Absolute branching fractions: experiment and theory.

	E691	Theory	
$B(D^+\to\bar{K}^0\pi^+)$	0.025±0.004±0.003	0.036 (Ref. 1),	0.025 (Ref. 2)
$B(D^+\to\bar{K}^0K^+)$	0.0068±0.0020±0.0013	0.012 (Ref. 1),	0.005 (Ref. 2)

of the first Gaussian were set to 1.869 GeV/c^2 and 11.3 MeV/c^2, while the mass and width of the second Gaussian were set to 1.968 GeV/c^2 and 12.7 MeV/c^2. The widths were taken from the Monte Carlo simulation as before. The fit with this function gives 69±15 events at 1.869 GeV/c^2 and 68±16 events at 1.968 GeV/c^2. Because of the difference in the D^+ and D_s^+ lifetimes, the reconstruction efficiencies for these two decays were 5.1% and 2.4%, respectively. The branching ratio obtained for the D^+ decay was $B(D^+\to\bar{K}^0K^+)/B(D^+\to\bar{K}^0\pi^+)=0.271\pm0.065\pm0.039$ (Table I). Taking the value for $B(D^+\to\bar{K}^0\pi^+)$ derived above, we obtain $B(D^+\to\bar{K}^0K^+)=0.0068\pm0.0020\pm0.0013$.

The D_s^+ decay yields the branching ratio $B(D_s^+\to\bar{K}^0K^+)/B(D_s^+\to\phi\pi^+) = 1.15\pm0.31\pm0.19$. This measurement agrees with the results given in Table I. The systematic error assigned to the measurements of the $D^+\to\bar{K}^0\pi^+$ and $D_s^+\to\bar{K}^0K^+$ decay modes is dominated by the uncertainty in the detection efficiency for the neutral-strange particles. This efficiency was determined from a careful study of the data and has an error of 9%. This uncertainty cancels out of the systematic error in the measurement of $B(D^+\to\bar{K}^0K^+)/B(D^+\to\bar{K}^0\pi^+)$.

In summary, we have measured signals of 11.5σ in the decay mode $D^+\to\bar{K}^0\pi^+$, of 4.2σ in the decay mode $D^+\to\bar{K}^0K^+$, and of 4.4σ in the decay mode $D_s^+\to\bar{K}^0K^+$. The value observed for the relative branching fraction $B(D^+\to\bar{K}^0K^+)/B(D^+\to\bar{K}^0\pi^+)(=0.271\pm0.065\pm0.039)$ supports the hypothesis that interference is an important effect in D^+ decays. Given that the decay $D^+\to\bar{K}^0K^+$ is Cabibbo suppressed, we expect this ratio to be of order $\tan^2(\theta_C)(\sim0.05)$ in the absence of interference (or other) effects.

We gratefully acknowledge the assistance of the staffs of Fermilab and of all the participating institutions. This research was supported by the U.S. Department of Energy, by the Natural Sciences and Engineering Research Council of Canada through the Institute of Particle Physics, by the National Research Council of Canada, and by the Brazilian Conselho Nacional de Desenvolvimento Científico e Tecnológico.

*Present address: Cornell University Ithaca, NY 14853.
†Present address: Electromagnetic Applications, Inc., Denver, CO 80226.
‡Present address: Nichols Research, Inc., Colorado Springs, CO 80919.
§Present address: CERN, Division EP, CH-1211 Genève, Suisse.
**Deceased.
††Present address: Tufts University, Medford, MA 02155.

[1]M. Bauer, B. Stech, and M. Wirbel, Z. Phys. C **34**, 103 (1987).
[2]B. Y. Blok and M. A. Shifman, Yad. Fiz. **45**, 841 (1987) [Sov. J. Nucl. Phys. **45**, 522 (1987)].
[3]L. L. Chau and H. Y. Cheng, Phys. Rev. D **36**, 137 (1987).
[4]A. N. Kamal and R. C. Verma, Phys. Rev. D **35**, 3515 (1987); **36**, 3527(E) (1987).
[5]R. J. Morrison and M. S. Witherell, Annu. Rev. Nucl. Part. Sci. **39**, 183 (1989).
[6]M. Gibney, Ph.D. thesis, University of Colorado, Boulder, 1989; J. C. Anjos *et al.*, Phys. Rev. D **41**, 801 (1990).
[7]For details, see J. C. Anjos *et al.*, Phys. Rev. Lett. **58**, 311 (1987); J. Raab, Ph.D. thesis, University of California, Santa Barbara, 1987; T. Browder, Ph.D. thesis, University of California, Santa Barbara, 1988.
[8]ARGUS Collaboration, M. V. Danilov, in *Proceedings of the XXIV International Conference on High Energy Physics,* Munich, West Germany, 1988, edited by R. Kotthaus and J. H. Kühn (Springer, Berlin, 1989).
[9]R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **56**, 2140 (1986); R. M. Baltrusaitis *et al.*, *ibid.* **55**, 150 (1985); J. Adler *et al.*, *ibid.* **60**, 89 (1988); **63**, 2858 (E) (1988); J. Adler *et al.*, *ibid.* **63**, 1211 (1989).
[10]W. Y. Chen *et al.*, Phys. Lett. B **226**, 192 (1989).