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Search for Non-Spectator 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 G.Wolf

The MARK III Collaboration

California Institute of Technology, Pasadena, CA 91125
University of California at Santa Cruz, Santa Cruz, CA 95064
University of Illinois at Urbana-Champaign, Urbana, IL 61801
Stanford Linear Accelerator Center, Stanford, CA 94305
University of Washington, Seattle, WA 98195

Abstract

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 non-spectator amplitudes in D^0 decays, a significant fraction of the decays occur through both higher and lower mass K^+K^- systems. Limits are set on the decays $D^0 \to \bar{K}^0 K^0$ and $(\bar{K}^{*0}K^0 + \bar{K}^0 K^{*0})$, also thought to proceed by non-spectator processes. The decay $D^0 \to (K^{*-}K^+ + K^- K^{*+})$ is also measured.

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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 $D^0 \rightarrow \bar{K}^0\phi$, $\bar{K}^0K^0$ and $\bar{K}^{*0}K^0$ ($\bar{K}^0K^{*0}$). 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 $D^0 \rightarrow \bar{K}^0\phi$ has been previously reported.[7] Further evidence is presented for this non-spectator decay through a measurement of $B(D^0 \rightarrow \bar{K}^0\phi)$ in the $K^0_sK^+K^-$ final state, and a detailed study of its backgrounds. Limits are established for the decays $D^0 \rightarrow \bar{K}^0K^0$ and $(\bar{K}^{*0}K^0 + \bar{K}^0K^{*0})$.

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^0_s decay into $\pi^+\pi^-$, in which at least one π is required to miss the beam interaction point by $R_{miss} \geq$ 2mm in the transverse plane. The pair's direction at the decay point of the K^0_s 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^0_s mass. Charged kaons are identified by cuts on time-of-flight[4] and dE/dx loss.[9] The momentum of the $K^0_sK^+K^-$ is required to lie within $\pm$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 Figure 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 $K_s^0K^+K^-$ 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 Figure 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 $1.019 \pm .015$ 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 $K_s^0K^+K^-$ combinations consistent with the D^0 mass, but lying in the momentum sidebands. Of these, 5 K^+K^- pairs lie within the ϕ region, yielding a limit of ≤ 1.7 events at 90% 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 $D^0 \rightarrow \phi\pi^+\pi^-$ 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 selecting 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 ≤ 0.3 events. The decay $D^0 \rightarrow K^-K^+\pi^+\pi^-$ 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, ≤ 0.80 events of these remain, with ≤ 0.14 events in the ϕ region itself. Two more potential backgrounds are nonresonant $D^0 \rightarrow \bar{K}^0K^+K^-$ 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 events respectively, in the ϕ region. Events from $D^0 \rightarrow \bar{K}^0S^{*0}$, $S^{*0} \rightarrow K^+K^-$ would produce a cusp below the ϕ. The S^{*0} decays predominantly to $\pi^+\pi^-$[10] but is not seen in $D^0 \rightarrow \bar{K}^0\pi^+\pi^-$.[11] Hence, no significant contribution from this source is expected. Another possible source of background is the decay $D^0 \rightarrow \bar{K}^0\delta^0$, which peaks at low K^+K^- masses but extends to higher K^+K^- masses.[12]

Figure 3 shows the Dalitz plots for the 28 data events, and 400 Monte Carlo events each, in the $D^0 \rightarrow \bar{K}^0\delta^0$ 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

$K_s^0 K^+ K^-$ mass distributions and the fits for $|\cos\theta^*| \geq 0.0$, 0.2, 0.4, and 0.6 are shown in Figs. 1(a)-(d) and Figs. 2(a)-(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 $\geq$0.6, respectively. The Monte Carlo predicts 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 $K_s^0 K^+ K^-$ signal *not* arising from $\bar{K}^0\phi$ and to reduce correlations, no cut on $\cos\theta^*$ is applied in the fit. Using these fits, the D^0 production cross section,[13] and the detection efficiencies, the following branching fractions are obtained:

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

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

The first error is statistical, and the second systematic, arising primarily from uncertainties in detection efficiency (17-20%), the fitting technique (12-31%) and the normalization (8.3%). The branching ratio for the $\bar{K}^0 K^+ K^-_{non-\bar{K}^0\phi}$ 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 $\bar{K}^0 K^+ K^-$.

The decay $D^0 \to \bar{K}^0 K^0$ is analyzed in the $K_s^0 K_s^0$ final state, with tighter vertex cuts ($R_{miss} \geq$ 5mm) 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 $K_s^0 K_s^0$

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) or $\leq 0.60\%$ for $B(D^0 \rightarrow \bar{K}^0 K^0)$ at 90% C.L..

The decays $D^0 \rightarrow \bar{K}^{*0} K^0$ and $\bar{K}^0 K^{*0}$ both appear in the final states $\bar{K}^0 K^+ \pi^-$ and $K^0 K^- \pi^+$ and as such are not separable. Tight vertex cuts ($R_{miss} \geq 5$mm) on candidate K_s^0 decays reduce contamination from the Cabibbo-allowed decay $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$. To separate contributions from $K^{*-} K^+ + K^{*+} K^-$ and nonresonant $K^0 K^- \pi^+ + \bar{K}^0 K^+ \pi^-$, the resonant decay is enhanced by cuts on the K^* mass (0.842 to 0.942 GeV/c^2) and decay angle ($|\cos\theta^*| \geq 0.3$). The nonresonant part is isolated by requiring $K\pi$ masses to lie outside the K^* mass range. The results are shown in Figure 4 . The numbers of events are extracted from each distribution by a fit extended to 1.960 GeV/c^2, to avoid the region of kinematic reflections from the misidentified Cabibbo-allowed decay $D^0 \rightarrow K^{*-} \pi^+$. The feed-down from $K^- \pi^+ \pi^- \pi^+$ is estimated from K_s^0 sidebands and is subtracted from each channel.[14] A Monte Carlo generated efficiency and misidentification matrix is employed to unfold the remaining overlap between channels and to correct for losses. This yields:

$$B(D^0 \rightarrow K^0 K^- \pi^+ + \bar{K}^0 K^+ \pi^-)_{non-res} \leq 1.6\% \text{ at 90\% C.L.}$$

$$B(D^0 \rightarrow \bar{K}^{*0} K^0 + K^{*0} \bar{K}^0) \leq 0.73\% \text{ at 90\% C.L.}$$

$$B(D^0 \rightarrow K^{*-} K^+ + K^- K^{*+}) = 1.1 \pm 0.5 \pm 0.2\ \%$$

In summary, evidence for the decay $D^0 \rightarrow \bar{K}^0 \phi$, which occurs only through flavor-annihilation, 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 wavefunction 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 wavefunction, 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 $\bar{K}^0 K^0$ must occur through flavor-annihilation, it is Cabibbo-suppressed and vanishes in the limit of exact SU(3) symmetry. The decay to $\bar{K}^{*0} K^0 + \bar{K}^0 K^{*0}$, while Cabibbo suppressed, is not suppressed in SU(3).[17] Upper limits on these decays relative to other Cabibbo-allowed decays[18] are consistent with this picture of D^0 decay, but are not sufficiently strong to draw any further conclusions on the existence of non-spectator amplitudes.

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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 using 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.

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18. The preliminary limits obtained from references 9 and 14 are:

$$\Gamma(D^0 \to K^0\bar{K}^0)/\Gamma(D^0 \to K^-\pi^+) \leq 0.11 \ \text{at 90\% C.L.}$$

$$\Gamma(D^0 \to K^{*0}\bar{K}^0 + \bar{K}^{*0}K^0)/\Gamma(D^0 \to K^{*-}K^+ + K^-\rho^+) \leq 0.034 \ \text{at 90\% C.L.}$$

FIGURE CAPTIONS

1. (a)$K_s^0 K^+ K^-$ mass and fit. Here and 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.

   (b)$K_s^0 K^+ K^-$ mass and fit for $|\cos\theta^*| \geq 0.2$.

   (c)$K_s^0 K^+ K^-$ mass and fit for $|\cos\theta^*| \geq 0.4$.

   (d)$K_s^0 K^+ K^-$ mass and fit for $|\cos\theta^*| \geq 0.6$.

2. (a)$K^+ K^-$ mass in $K_s^0 K^+ K^-$; solid curve is the combined fit, dashed the $\bar{K}^0 \delta^0$, and dotdash the random background,

   (b)Fit for $|\cos\theta^*| \geq 0.2$,

   (c)Fit for $|\cos\theta^*| \geq 0.4$,

   (d)Fit for $|\cos\theta^*| \geq 0.6$.

3. Dalitz plot for (a)Data,

   (b)Monte Carlo for $D^0 \to \bar{K}^0 \delta^0$,

   (c)Monte Carlo for $D^0 \to \bar{K}^0 \phi$.

4. Data with cuts for (a)$(K^0 K^- \pi^+ + \bar{K}^0 K^+ \pi^-)_{non-resonant}$,

   (b)$\bar{K}^{*0} K^0 + \bar{K}^0 K^{*0}$,

   (c)$K^{*-} K^+ + K^{*+} K^-$.

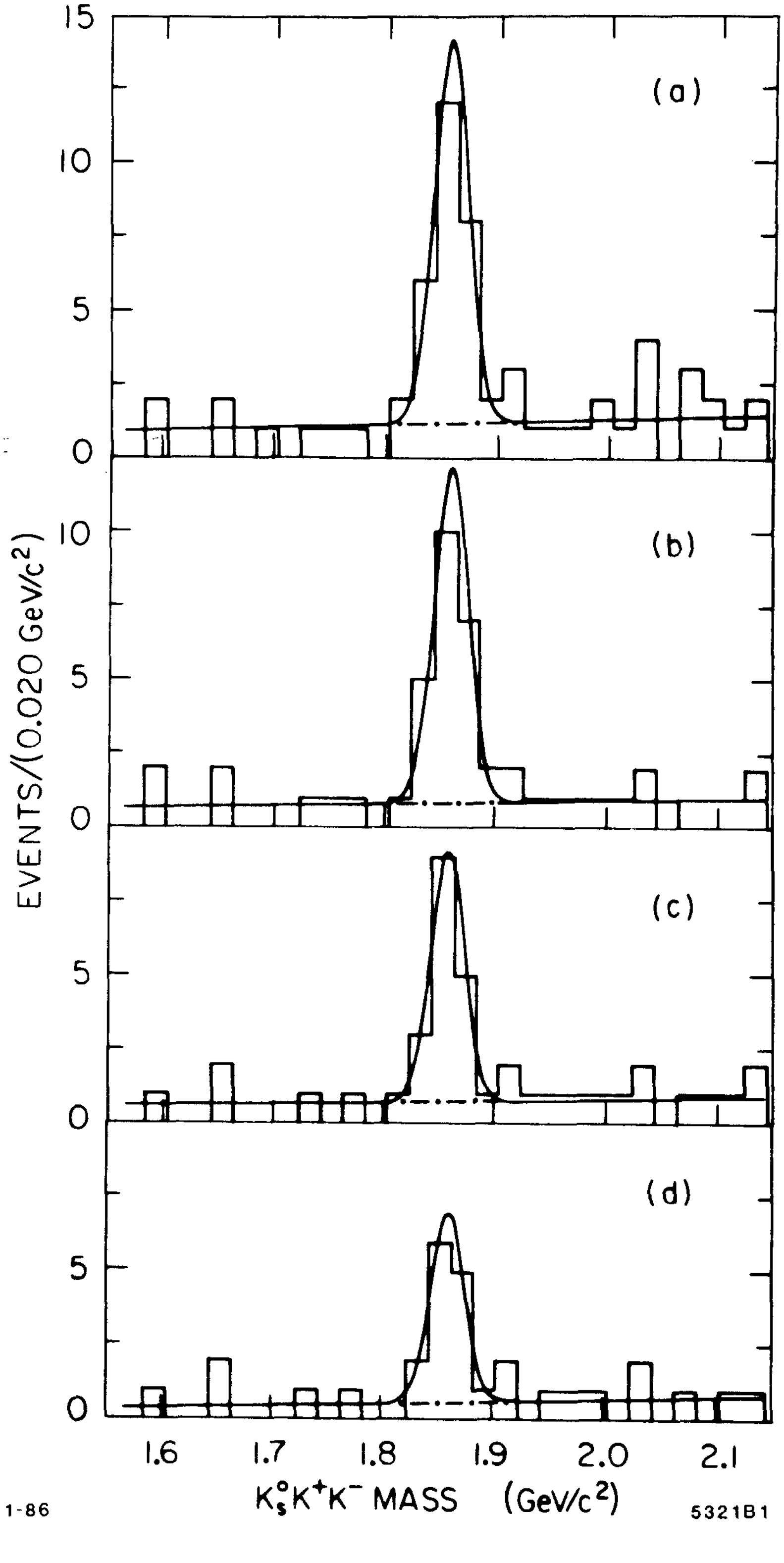
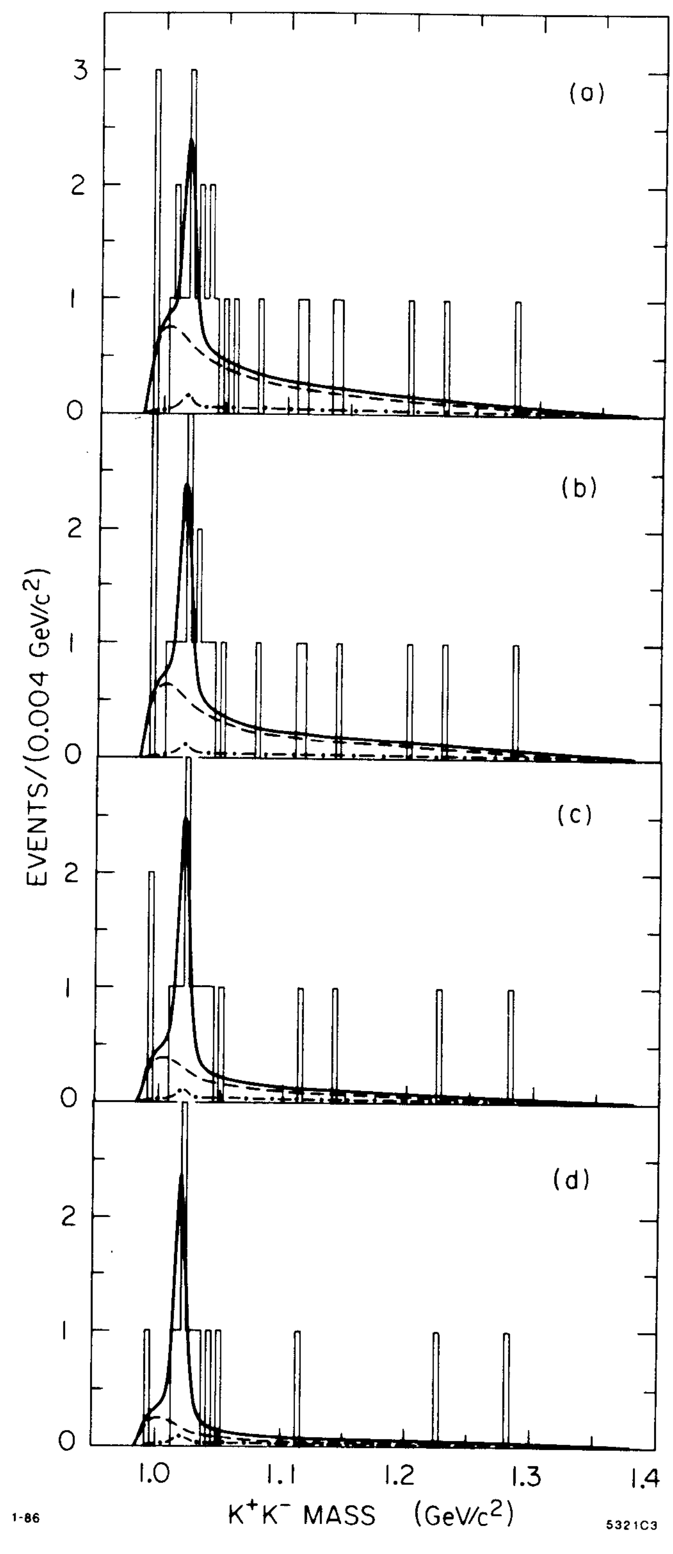

15
10
5
0
(a)
(b)
(c)
(d)
EVENTS/(0.020 GeV/c^2)
1.6
1.7
1.8
1.9
2.0
2.1
$K_s^0K^+K^-$ MASS (GeV/c^2)
1-86
5321B1

Fig. 1


(a)
(b)
(c)
(d)
EVENTS/(0.004 GeV/c2)
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1
2
3
1.0
1.1
1.2
1.3
1.4
K+K- MASS (GeV/c2)
1-86
5321C3

Fig. 2

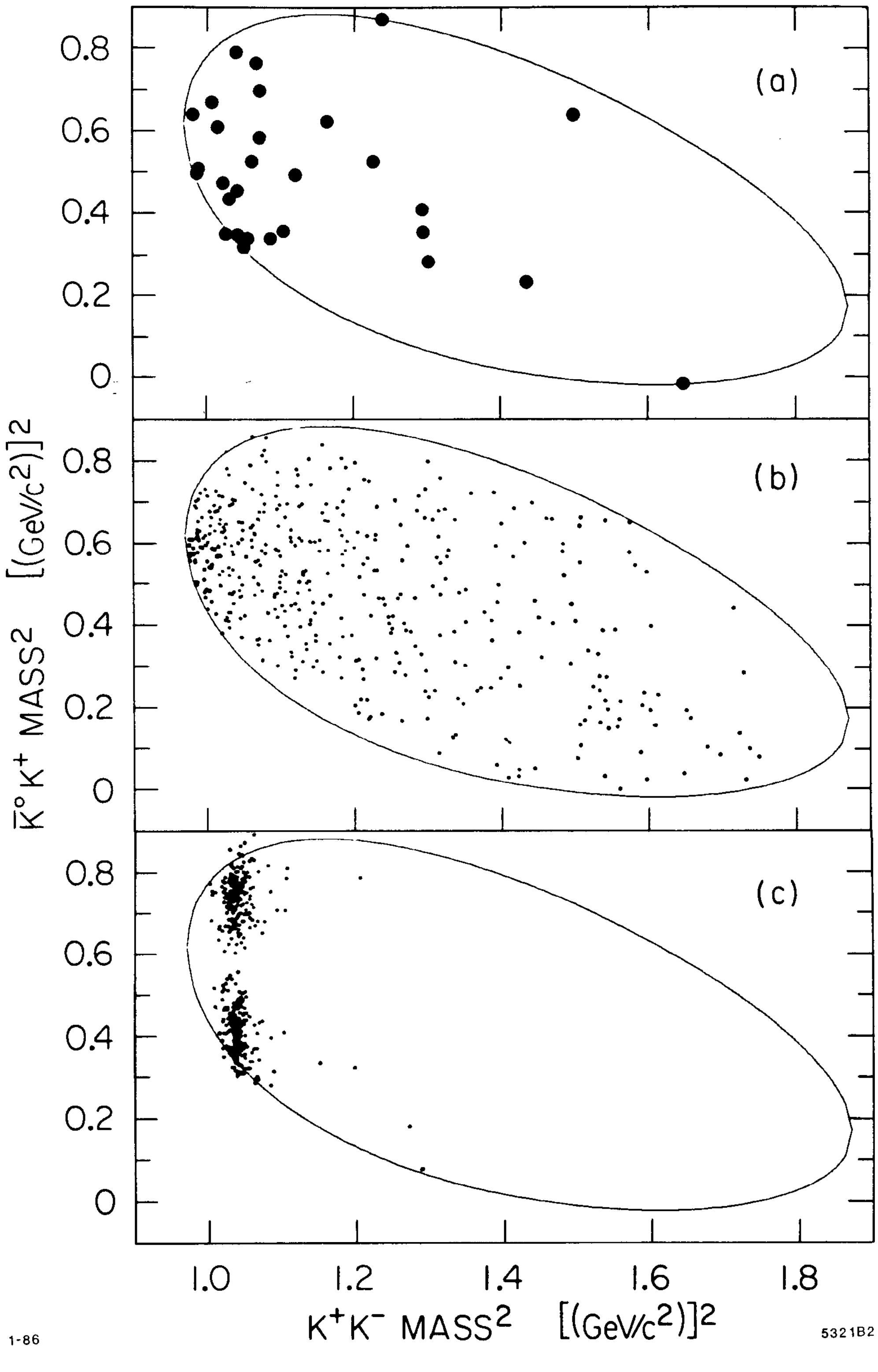
(a)
(b)
(c)
0.8
0.6
0.4
0.2
0
$\bar{K}^0 K^+$ MASS^2 [(GeV/c^2)]^2
1.0
1.2
1.4
1.6
1.8
K^+K^- MASS^2 [(GeV/c^2)]^2
1-86
5321B2

Fig. 3

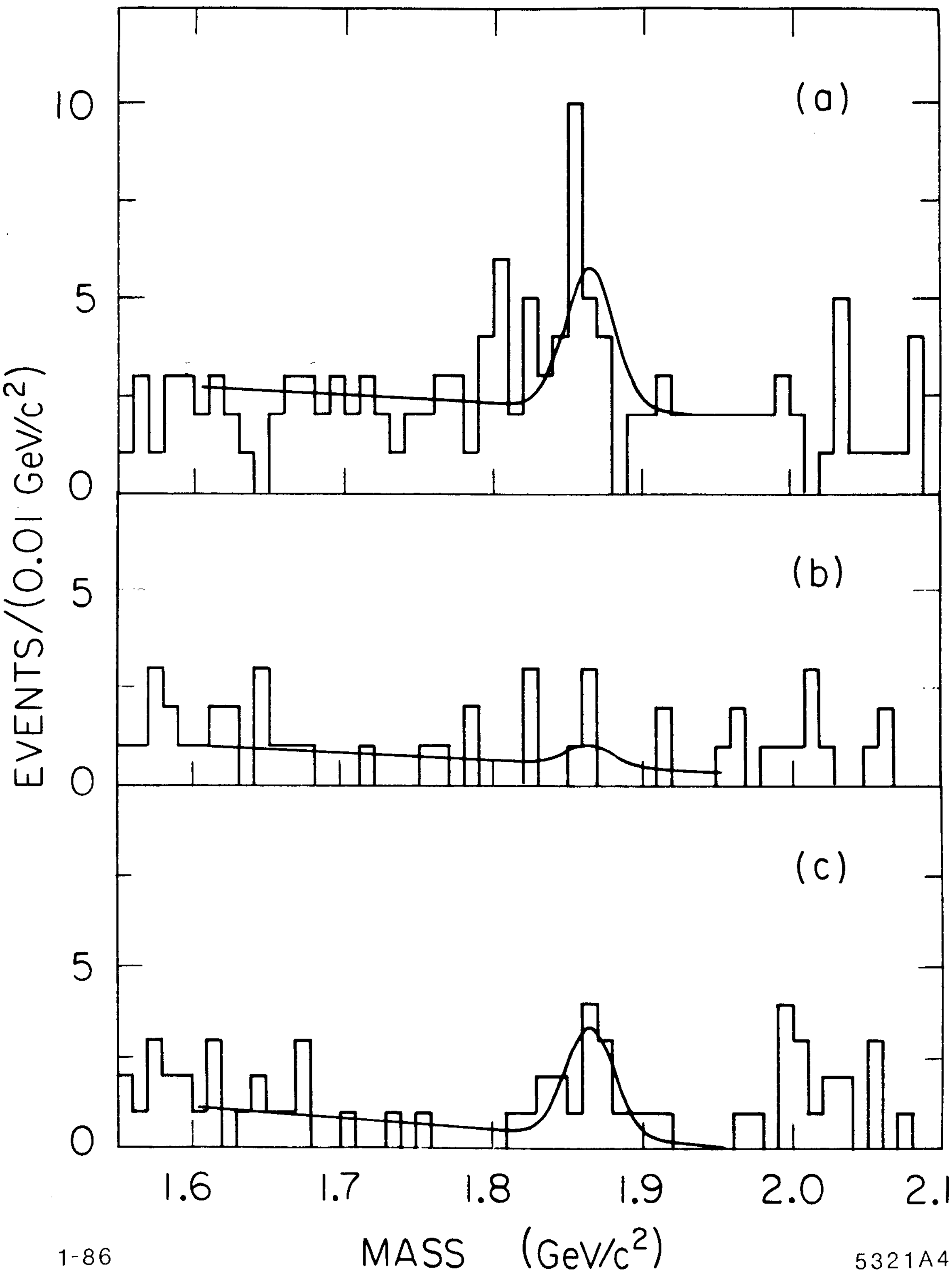
(a)
(b)
(c)
10
5
0
5
0
5
0
EVENTS/(0.01 GeV/c^2)
1.6
1.7
1.8
1.9
2.0
2.1
MASS (GeV/c^2)
1-86
5321A4

Fig. 4