Search for Rare and Forbidden Charm Meson Decays $D^0 \rightarrow V\ell^+\ell^-$ and $hh\ell\ell$

E. M. Aitala,⁹ S. Amato,¹ J. C. Anjos,¹ J. A. Appel,⁵ D. Ashery,¹⁴ S. Banerjee,⁵ I. Bediaga,¹ G. Blaylock,⁸ S. B. Bracker,¹⁵ P. R. Burchat,¹³ R. A. Burnstein,⁶ T. Carter,⁵ H. S. Carvalho,¹ N. K. Coptly,¹² L. M. Cremaldi,⁹ C. Darling,¹⁸ K. Denisenko,⁵ A. Fernandez,¹¹ G. F. Fox,¹² P. Gagnon,² C. Gobel,¹ K. Gounder,⁹ A. M. Halling,⁵ G. Herrera,⁴ G. Hurvits,¹⁴ C. James,⁵ P. A. Kasper,⁶ S. Kwan,⁵ D. C. Langs,¹² J. Leslie,² B. Lundberg,⁵ J. Magnin,¹ S. May-Tal-Beck,¹⁴ B. Meadows,³ J. R. T. de Mello Neto,¹ D. Mihalcea,⁷ R. H. Milburn,¹⁶ J. M. de Miranda,¹ A. Napier,¹⁶ A. Nguyen,⁷ A. B. d'Oliveira,^{3,11} K. O'Shaughnessy,² K. C. Peng,⁶ L. P. Perera,³ M. V. Purohit,¹² B. Quinn,⁹ S. Radeztsky,¹⁷ A. Rafatian,⁹ N. W. Reay,⁷ J. J. Reidy,⁹ A. C. dos Reis,¹ H. A. Rubin,⁶ D. A. Sanders,⁹ A. K. S. Santha,³ A. F. S. Santoro,¹ A. J. Schwartz,³ M. Sheaff,¹⁷ R. A. Sidwell,⁷ A. J. Slaughter,¹⁸ M. D. Sokoloff,³ J. Solano,¹ N. R. Stanton,⁷ R. J. Stefanski,⁵ K. Stenson,¹⁷ D. J. Summers,⁹ S. Takach,¹⁸ K. Thorne,⁵ A. K. Tripathi,⁷ S. Watanabe,¹⁷ R. Weiss-Babai,¹⁴ J. Wiener,¹⁰ N. Witchey,⁷ E. Wolin,¹⁸ S. M. Yang,⁷ D. Yi,⁹ S. Yoshida,⁷ R. Zaliznyak,¹³ and C. Zhang⁷

(Fermilab E791 Collaboration)

¹ *Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*² *University of California, Santa Cruz, California 95064*³ *University of Cincinnati, Cincinnati, Ohio 45221*⁴ *CINVESTAV, 07000 Mexico City, DF Mexico*⁵ *Fermilab, Batavia, Illinois 60510*⁶ *Illinois Institute of Technology, Chicago, Illinois 60616*⁷ *Kansas State University, Manhattan, Kansas 66506*⁸ *University of Massachusetts, Amherst, Massachusetts 01003*⁹ *University of Mississippi-Oxford, University, Mississippi 38677*¹⁰ *Princeton University, Princeton, New Jersey 08544*¹¹ *Universidad Autonoma de Puebla, Mexico*¹² *University of South Carolina, Columbia, South Carolina 29208*¹³ *Stanford University, Stanford, California 94305*¹⁴ *Tel Aviv University, Tel Aviv, Israel*¹⁵ *Box 1290, Enderby, British Columbia, V0E 1V0, Canada*¹⁶ *Tufts University, Medford, Massachusetts 02155*¹⁷ *University of Wisconsin, Madison, Wisconsin 53706*¹⁸ *Yale University, New Haven, Connecticut 06511*

(November 1, 2000)

We report the results of a search for flavor-changing neutral current, lepton-flavor, and lepton-number violating decays of the 3 and 4-body decay modes of D^0 (and its antiparticle) containing muons and electrons. Using data from Fermilab charm hadroproduction experiment E791, we examine modes with two leptons and either a ρ^0 , \bar{K}^{*0} , or ϕ vector meson or a non-resonant $\pi\pi$, $K\pi$, or KK pair of pseudoscalar mesons. No evidence for any of these decays is found. Therefore, we present branching-fraction upper limits at 90% confidence level for the 27 decay modes examined (18 new).

PACS numbers: 11.30.Fs, 12.15.Mm, 13.20.Fc, 14.80.Cp

In previous work, the E791 Collaboration reported new limits on rare and forbidden dilepton decays of the charged charm D meson [1,2]. Such measurements probe the $SU(2)\times U(1)$ Standard Model (SM) of electroweak interactions in search of new mediators and couplings. We extend the methodology to 3 and 4-body decays of the neutral D meson, whose rates are expected to be dominated by long-distance effects. A recent calculation [3] using a vector meson dominance model predicts branching fractions at the level of 10^{-6} ; observing a rate significantly above this could indicate new physics.

We have searched for 27 dilepton decay modes of the neutral charm meson, where the leptons are either muons or electrons. These dilepton decay modes are either resonant modes of the form $D^0 \rightarrow V\ell^+\ell^-$, where V is either a ρ^0 , \bar{K}^{*0} , or ϕ , or non-resonant modes of the form $D^0 \rightarrow hh\ell\ell$, where each h is either a pion or a kaon (note: charge-conjugate modes are included implicitly throughout this paper). These decays fall into three categories:

1. FCNC – flavor-changing neutral current decays (in which the leptons are both of the same generation and are oppositely charged);
2. LFV – lepton flavor-violating decays (in which the leptons belong to different generations);
3. LNV – lepton number-violating decays (in which the leptons belong to the same generation, but have the same sign charge).

Decay modes belonging to (1) occur within the Standard Model via higher-order diagrams, but the estimated branching fractions are 10^{-10} to 10^{-9} [4,5]. Such rates are below the sensitivity of current experiments. However, if additional particles such as supersymmetric squarks or charginos exist, they could contribute additional amplitudes that would make these modes observable [6]. Also long range effects (e.g., $D^0 \rightarrow \bar{K}^{*0}\rho^0, \rho^0 \rightarrow e^+e^-$) can contribute at the 10^{-6} level [3,5,7]. Decay modes belonging to (2) and (3) do not conserve lepton number and thus are forbidden within the Standard Model. However, lepton number conservation is not required by Lorentz invariance or gauge invariance, and a number of theoretical extensions to the Standard Model predict lepton-number violation [6]. Many experiments have studied rare decays of the charge $-1/3$ strange quark and searched for rare decays of the charge $-1/3$ beauty quark. However, charge $2/3$ charm quarks may couple differently than charge $-1/3$ quarks [8]. The limits we present here are often more stringent than those obtained from previous searches [9,10], or are the first reported.

The data come from measurements with the Fermilab E791 spectrometer [11]. A total of 2×10^{10} events were taken with a loose transverse energy requirement. These events were produced by a 500 GeV/ c π^- beam

interacting in a fixed target consisting of five thin, well-separated foils. Track and vertex information came from “hits” in 23 silicon microstrip planes and 45 wire chamber planes. This information and the bending provided by two dipole magnets were used for momentum analysis of charged particles. Kaon identification was carried out by two multi-cell Čerenkov counters that provided π/K separation in the momentum range 6 – 60 GeV/ c [12]. We required that the momentum-dependent light yield in the Čerenkov counters be consistent for kaon-candidate tracks, except for those in decays with $\phi \rightarrow K^+K^-$, where the narrow mass window for the ϕ decay provided sufficient kaon identification.

For this analysis we made extensive use of electron and muon identification (ID). Electron ID was based on transverse shower shape plus matching wire chamber tracks to shower positions and energies in an electromagnetic calorimeter [13]. The electron ID efficiency varied from 62% below 9 GeV/ c to 45% above 20 GeV/ c . The probability to misidentify a pion as an electron was $\sim 0.8\%$, independent of pion momentum.

Muon ID was obtained from two planes of scintillation counters. The first plane (5.5 m \times 3.0 m) of 15 counters measured the horizontal position while the second plane (3.0 m \times 2.2 m) of 16 counters measured the vertical position. There were about 15 interaction lengths of shielding upstream of the counters to filter out hadrons. Data from $D^+ \rightarrow \bar{K}^{*0}\mu^+\nu_\mu$ decays [14] were used to choose selection criteria for muon candidates. Timing information from the smaller set of muon scintillation counters was used to improve the horizontal position resolution. Counter efficiencies, measured using muons originating from the primary target, were found to be $(99 \pm 1)\%$ for the smaller counters and $(69 \pm 3)\%$ for the larger counters. The probability for misidentifying a pion as a muon decreased with momentum, from about 6% at 8 GeV/ c to $(1.3 \pm 0.1)\%$ above 20 GeV/ c .

After reconstruction, events with evidence of well-separated production (primary) and decay (secondary) vertices were selected to separate charm candidates from background. Secondary vertices were required to be separated from the primary vertex by greater than $12\sigma_L$, where σ_L is the calculated resolution of the measured longitudinal separation. In addition, the secondary vertex had to be separated from the closest material in the target foils by greater than $5\sigma'_L$, where σ'_L is the uncertainty in this separation. The vector sum of the momenta of tracks from the secondary vertex was required to pass within 40 μm of the primary vertex in the plane perpendicular to the beam. Finally, the net momentum of the charm candidate transverse to the line connecting the production and decay vertices had to be less than 300 MeV/ c . Decay track candidates were required to pass approximately 10 times closer to the secondary vertex than to the primary vertex. These selection crite-

ria and kaon identification requirements were the same for both the search mode and for its normalization signal (discussed below). The mass ranges used for the resonant masses were: $|m_{\pi^+\pi^-} - m_{\rho^0}| < 150 \text{ MeV}/c^2$, $|m_{K^-\pi^+} - m_{\bar{K}^{*0}}| < 55 \text{ MeV}/c^2$, and $|m_{K^+K^-} - m_{\phi}| < 10 \text{ MeV}/c^2$.

To determine our selection cuts we used a “blind” analysis technique. Before the selection criteria were finalized, all events having masses within a window ΔM_S around the mass of the D^0 were “masked” so that the presence or absence of any potential signal candidates would not bias our choice of selection criteria. All criteria were then chosen by studying events generated by a Monte Carlo (MC) simulation program (see below) and background events, outside the signal windows, from real data. The criteria were chosen to maximize the ratio $N_{MC}/\sqrt{N_B}$, where N_{MC} and N_B are the numbers of MC and background events, respectively, after all selection criteria were applied. The data within the signal windows were unmasked only after this optimization. We used asymmetric windows for the decay modes containing electrons to allow for the bremsstrahlung low-energy tail. The signal windows were: $1.83 < M(D^0) < 1.90 \text{ GeV}/c^2$ for $\mu\mu$ and $1.76 < M(D^0) < 1.90 \text{ GeV}/c^2$ for $e\bar{e}$ and μe modes.

We normalize the sensitivity of our search to topologically similar hadronic 3-body (resonant) or 4-body (non-resonant) decays. One exception to this is the case of $D^0 \rightarrow \rho^0 \ell^\pm \ell^\mp$ where we normalize to nonresonant $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ because there is no published branching fraction for $D^0 \rightarrow \rho^0 \pi^+ \pi^-$. Table I lists the normalization mode used for each signal mode and the fitted number of data events (N_{Norm}).

The upper limit for each branching fraction B_X is calculated using the following formula:

$$B_X = \frac{N_X}{N_{\text{Norm}}} \frac{\varepsilon_{\text{Norm}}}{\varepsilon_X} \times B_{\text{Norm}} \quad (1)$$

where N_X is the 90% confidence level (CL) upper limit on the number of decays for the rare or forbidden decay mode X , and ε_X is that mode’s detection efficiency. $\varepsilon_{\text{Norm}}$ is the normalization mode detection efficiency and B_{Norm} is the normalization mode branching fraction obtained from the Particle Data Group [9].

The ratio of detection efficiencies is

TABLE I. Normalization modes used.

Decay Mode	Norm. Mode	N_{Norm}
$D^0 \rightarrow \rho^0 \ell^\pm \ell^\mp$	$D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$	2049±53
$D^0 \rightarrow \bar{K}^{*0} \ell^\pm \ell^\mp$	$D^0 \rightarrow \bar{K}^{*0} \pi^+ \pi^-$	5451±72
$D^0 \rightarrow \phi \ell^\pm \ell^\mp$	$D^0 \rightarrow \phi \pi^+ \pi^-$	113±19
$D^0 \rightarrow \pi \pi \ell \ell$	$D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$	2049±53
$D^0 \rightarrow K \pi \ell \ell$	$D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$	11550±113
$D^0 \rightarrow K K \ell \ell$	$D^0 \rightarrow K^+ K^- \pi^+ \pi^-$	406±41

$$\frac{\varepsilon_{\text{Norm}}}{\varepsilon_X} = \frac{N_{\text{Norm}}^{\text{MC}}}{N_X^{\text{MC}}} \quad (2)$$

where $N_{\text{Norm}}^{\text{MC}}$ and N_X^{MC} are the numbers of Monte Carlo events that are reconstructed and pass the final selection criteria, for the normalization and decay modes respectively. The simulations use PYTHIA/JETSET [15] as the physics generator and model the effects of resolution, detector geometry, magnetic fields, multiple scattering, interactions in the detector material, detector efficiencies, and the analysis selection criteria. The efficiencies for the normalization modes varied from approximately 0.2% to 1% depending on the mode, and the efficiencies for the search modes varied from approximately 0.05% to 0.34%. We take muon and electron ID efficiencies from data.

Monte Carlo studies show that the experiment’s acceptances are nearly uniform across the Dalitz plots, except that the dilepton identification efficiencies typically drop to near zero at the dilepton mass threshold. While the loss in efficiency varies channel by channel, the efficiency typically reaches its full value at masses only a few hundred MeV/c^2 above the dilepton mass threshold. We use a constant weak-decay matrix element when calculating the overall detection efficiencies.

The 90% CL upper limits N_X are calculated using the method of Feldman and Cousins [16] to account for background, and then corrected for systematic errors by the method of Cousins and Highland [17]. In these methods, the numbers of signal events are determined by simple counting, not by a fit. All results are shown in Fig. 1 and listed in Table II. The upper limits are determined using the number of candidate events observed and the expected number of background events within the signal region.

Background sources that are not removed by the selection criteria discussed earlier include decays in which hadrons (from real, fully-hadronic decay vertices) are misidentified as leptons. These misidentified leptons can come from hadronic showers reaching muon counters, decays-in-flight, and random overlaps of tracks from otherwise separate decays (“accidental” sources). In the case where kaons are misidentified as leptons, candidates have effective masses that lie below the signal windows. We identify events from background sources that contain a different number of kaons than the candidate decays. These reflections are explicitly removed prior to the selection-criteria optimization, if they lie inside our D^0 mass window.

There remain two sources of background: hadronic decays where pions are misidentified as leptons (N_{MisID}) and “combinatoric” background (N_{Cmb}) arising primarily from false vertices and partially reconstructed charm decays. The background N_{MisID} arises from the normalization modes. To estimate the rate for misidentifying $\pi\pi$ as $\ell\ell$, for all but the $D^0 \rightarrow K^- \pi^+ \ell^+ \ell^-$ modes, we assume all $D^0 \rightarrow K^- \pi^+ \ell^+ \ell^-$ candidates re-

sult from misidentification of $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ decays and count the number of $D^0 \rightarrow K^- \pi^+ \ell^+ \ell^-$ decays passing the final selection criteria. We then divide by twice the number of $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ normalization events with $K^- \pi^+ \ell^+ \ell^-$ mass within ΔM_S boundaries (twice because there are two possible π^+ misidentifications). To estimate the misidentification rates for the $D^0 \rightarrow K^- \pi^+ \ell^+ \ell^-$ modes themselves, we take the smaller of these rates and the misidentification rates obtained from our previous study [2]. This results in a conservative upper limit. As it turned out the rates based on the actual number of observed events from $D^0 \rightarrow K^- \pi^+ \ell^+ \ell^-$ modes were smaller. The following misidentification rates were obtained: $r_{\mu\mu} = (3.4 \pm 2.4) \times 10^{-4}$,

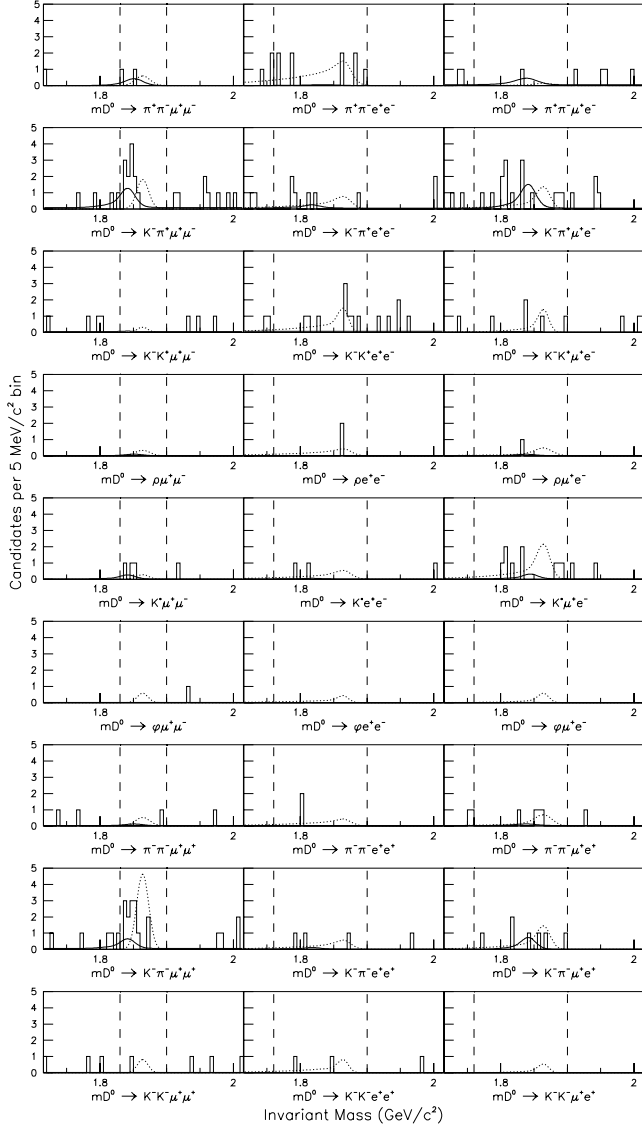


FIG. 1. Final event samples for the opposite signed dilepton (rows 1–3), resonant (rows 4–6), and same signed dilepton modes (rows 7–9) of D^0 decays. The solid curves represent estimated background; the dotted curves represent signal shape for a number of events equal to the 90% CL upper limit. The dashed vertical lines are the ΔM_S boundaries.

$r_{\mu e} = (4.2 \pm 1.4) \times 10^{-4}$, and $r_{ee} = (9.0 \pm 6.2) \times 10^{-5}$. For modes in which two possible pion combinations can contribute, e.g., $D^0 \rightarrow K^- \pi^+ \mu^\pm \mu^\mp$, we use twice the above rate and for $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$, where there are 4 possible combinations, we use 4 times this rate in calculating $D^0 \rightarrow \pi^+ \pi^- \ell^+ \ell^-$. Using these rates, we estimate the numbers of misidentified candidates, $N_{\text{MisID}}^{V\ell\ell}$ and $N_{\text{MisID}}^{hh\ell\ell}$, in the signal windows as follows:

$$N_{\text{MisID}}^{hh\ell\ell} = r_{\ell\ell} \times N_{\text{Norm}}^{hh\pi\pi} \text{ and } N_{\text{MisID}}^{V\ell\ell} = r_{\ell\ell} \times N_{\text{Norm}}^{V\pi\pi}, \quad (3)$$

where $N_{\text{Norm}}^{hh\pi\pi}$ and $N_{\text{Norm}}^{V\pi\pi}$ are the numbers of normalization hadronic decay candidates within the signal windows.

To estimate the combinatoric background N_{Cmb} within a signal window ΔM_S , we count events having masses within an adjacent background mass window ΔM_B , and scale this number ($N_{\Delta M_B}$) by the relative sizes of these windows: $N_{\text{Cmb}} = (\Delta M_S / \Delta M_B) \times N_{\Delta M_B}$. To be conservative in calculating our 90% confidence level upper limits, we take combinatoric backgrounds to be zero when no events are located above the mass windows. In Table II we present the numbers of combinatoric background, misidentification background, and observed events for all 27 modes.

TABLE II. E791 90% confidence level (CL) upper limits on the number of events and branching fraction limits ($\times 10^{-5}$). Previously published limits are listed for comparison [9,10].

Mode $D^0 \rightarrow$	(Est. N_{Cmb})	BG N_{MisID}	N_X	Sys. Err.	90% CL	E791 Limit	PDG Limit
$\pi^+ \pi^- \mu^+ \mu^-$	0.00	3.15	2	11%	2.96	3.0	
$\pi^+ \pi^- e^+ e^-$	0.00	0.73	9	12%	15.16	37.3	
$\pi^+ \pi^- \mu^\pm e^\mp$	5.25	3.46	1	15%	1.06	1.5	
$K^- \pi^+ \mu^+ \mu^-$	3.65	7.91	12	16%	7.23	16.8	
$K^- \pi^+ e^+ e^-$	3.50	2.07	6	23%	5.84	28.8	
$K^- \pi^+ \mu^\pm e^\mp$	5.25	9.75	15	16%	7.75	23.8	
$K^+ K^- \mu^+ \mu^-$	2.13	0.17	0	17%	1.22	3.3	
$K^+ K^- e^+ e^-$	6.13	0.04	9	18%	9.61	31.5	
$K^+ K^- \mu^\pm e^\mp$	3.50	0.17	5	17%	6.61	17.5	
$\rho^0 \mu^+ \mu^-$	0.00	0.75	0	10%	1.80	2.2	23.0
$\rho^0 e^+ e^-$	0.00	0.18	1	12%	4.28	12.4	10.0
$\rho^0 \mu^\pm e^\mp$	0.00	0.82	1	11%	3.60	6.6	4.9
$\bar{K}^{*0} \mu^+ \mu^-$	0.30	1.68	3	24%	5.66	2.5	118.0
$\bar{K}^{*0} e^+ e^-$	0.88	0.44	2	25%	4.78	4.8	14.0
$\bar{K}^{*0} \mu^\pm e^\mp$	1.75	2.08	9	24%	13.07	8.5	10.0
$\phi \mu^+ \mu^-$	0.30	0.04	0	33%	2.33	3.1	41.0
$\phi e^+ e^-$	0.00	0.01	0	33%	2.75	5.9	5.2
$\phi \mu^\pm e^\mp$	0.00	0.05	0	33%	2.71	4.7	3.4
$\pi^- \pi^- \mu^+ \mu^+$	0.91	0.79	1	9%	2.78	2.9	
$\pi^- \pi^- e^+ e^+$	0.00	0.18	1	11%	4.26	11.2	
$\pi^- \pi^- \mu^+ e^+$	2.63	0.86	4	10%	5.18	7.9	
$K^- \pi^- \mu^+ \mu^+$	2.74	3.96	14	9%	15.70	39.0	
$K^- \pi^- e^+ e^+$	0.88	1.04	2	16%	4.14	20.6	
$K^- \pi^- \mu^+ e^+$	0.00	4.88	7	11%	7.81	21.8	
$K^- K^- \mu^+ \mu^+$	1.22	0.00	1	17%	3.27	9.4	
$K^- K^- e^+ e^+$	0.88	0.00	2	17%	5.28	15.2	
$K^- K^- \mu^+ e^+$	0.00	0.00	0	17%	2.52	5.7	

The sources of systematic errors in this analysis include: errors from the fit to the normalization sample N_{Norm} ; statistical errors on the numbers of Monte Carlo generated events for both $N_{\text{Norm}}^{\text{MC}}$ and N_X^{MC} ; uncertainties in the calculation of misidentification background; and uncertainties in the relative efficiency for each mode, including lepton tagging efficiencies. These tagging efficiency uncertainties include: 1) muon counter efficiencies from hardware performance; and 2) the fraction of signal events (based on simulations) that would remain outside the signal window due to bremsstrahlung tails. Also, for the $D^0 \rightarrow \rho^0 \ell^+ \ell^-$ modes, an additional systematic error is included because we are using $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ as the normalization mode since there is no published branching fraction for $D^0 \rightarrow \rho^0 \pi^+ \pi^-$. The sums, taken in quadrature, of these systematic errors are listed in Table II.

In summary, we use a “blind” analysis of data from Fermilab experiment E791 to obtain upper limits on the dilepton branching fractions for 27 flavor-changing neutral current, lepton-number violating, and lepton-family violating decays of D^0 mesons. No evidence for any of these 3 and 4-body decays is found. Therefore, we present upper limits on the branching fractions at the 90% confidence level. Four limits represent significant improvements over previously published results. Eighteen of these modes have no previously reported limits.

We gratefully acknowledge the assistance of the staffs of Fermilab and of all the participating institutions. This research was supported by the Brazilian Conselho Nacional de Desenvolvimento Científico e Tecnológico, CONACyT (Mexico), the Israeli Academy of Sciences and Humanities, the U.S. Department of Energy, the U.S.-Israel Binational Science Foundation, and the U.S. National Science Foundation. Fermilab is operated by the Universities Research Association, Inc., under contract with the U.S. Department of Energy.

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