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RARE AND FORBIDDEN DECAYS OF D MESONS

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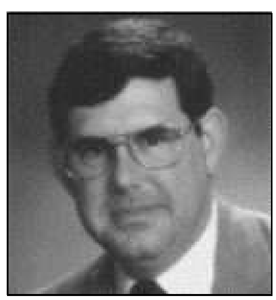

We summarize the results of two recent searches for flavor-changing neutral current, lepton-flavor violating, and lepton-number violating decays of D^+, D_s^+, and D^0 mesons (and their antiparticles) into modes containing muons and electrons. Using data from Fermilab charm hadroproduction experiment E791, we examined D^+ and D_s^+ $\pi\ell\ell$ and $K\ell\ell$ decay modes and the D^0 dilepton decay modes containing either $\ell^+\ell^-$, a ρ^0, $\overline{K}^{*0}$, 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 was found. Therefore, we presented branching-fraction upper limits at 90% confidence level for the 51 decay modes examined. Twenty-six of these modes had no previously reported limits, and eighteen of the remainder were reported with significant improvements over previously published results.

1 Introduction

The E791 Collaboration has previously reported limits on rare and forbidden dilepton decays of charged charm mesons [1,2]. Such measurements probe the SU(2)×U(1) Standard Model of electroweak interactions in search of new mediators and couplings [3,4]. Here we summarize the results of two related analyses. First [2] we examined the $\pi\ell\ell$ and $K\ell\ell$ decay modes of D^+ and D_s^+ and the $\ell^+\ell^-$ decay modes of D^0. Then we extend the methodology to 27 dilepton decay modes of the D^0 meson [5] containing either resonant $V\ell^+\ell^-$ decays, where V is a ρ^0, $\overline{K}^{*0}$, or ϕ, and non-resonant $h_1 h_2 \ell\ell$ decays, where h_i is either a π or a K. The leptons were either muons or electrons. Charge-conjugate modes are implied. The modes are lepton flavor-violating (e.g., $D^+ \to \pi^+\mu^+e^-$), or lepton number-violating (e.g., $D_s^+ \to \pi^-\mu^+\mu^+$), or flavor-changing neutral current decays (e.g., $D^0 \to \overline{K}^{*0}e^+e^-$). Box diagrams can mimic FCNC decays, but only at the 10^{-10} to 10^{-9} level [4,6]. Long range effects through resonant modes (e.g., $D^0 \to \overline{K}^{*0}\rho^0$, $\rho^0 \to e^+e^-$) can occur at the 10^{-6} level [6,7]. Numerous experiments have studied rare decays of charge -1/3 strange quarks. Charge 2/3 charm quarks are interesting because they may exhibit a different coupling [8].

The data come from measurements made with the Fermilab E791 spectrometer [9]. 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 [10] that provided π/K separation in the momentum range $6 - 60$ GeV/c. We required that the momentum-dependent light yield in the Čerenkov counters be consistent for kaon-candidate tracks, except for those in decays with $\phi \to K^+K^-$, where the narrow mass window for the ϕ decay provided sufficient kaon identification (ID).

Electron ID was based on transverse shower shape plus matching wire chamber tracks to shower positions and energies in an electromagnetic calorimeter [11]. 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 × 3.0 m) of 15 counters measured the horizontal position while the second plane (3.0 m × 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 $D^+ \to \overline{K}^{*0}\mu^+\nu_\mu$ decays [12] 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 $(99\pm1)\%$ for the smaller counters and $(69\pm3)\%$ for the larger counters. The probability of misidentifying a pion as a muon decreased with increasing momentum, from about 6% at 8 GeV/c to 1.3% above 20 GeV/c.

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 $20\,\sigma_L$ for D^+ decays and greater than $12\,\sigma_L$ for D^0 and D_s^+ decays, where σ_L is the calculated resolution of the measured longitudinal separation. Also, 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 from secondary vertex tracks was required to pass within 40 μm of the primary vertex in the plane perpendicular to the beam. 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 for D^0 candidates, less than 250 MeV/c for D_s^+ candidates, and less than 200 MeV/c for D^+ candidates. Finally, decay track candidates were required to pass approximately 10 times closer to the secondary vertex than to the primary vertex. These selection criteria and kaon identification requirements were the same for both the search mode and for its normalization signal (discussed below).

To determine our selection criteria, 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 [13] 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: $1.83 < M(D^0) < 1.90$ GeV/c^2 for $\mu\mu$ and $1.76 < M(D^0) < 1.90$ GeV/c^2 for ee and μe modes.

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

$$B_X = \frac{N_X}{N_{\text{Norm}}} \frac{\varepsilon_{\text{Norm}}}{\varepsilon_X} \times B_{\text{Norm}}; \text{ where } \frac{\varepsilon_{\text{Norm}}}{\varepsilon_X} = \frac{f^{\text{MC}}_{\text{Norm}}}{f^{\text{MC}}_X}. \quad (1)$$

N_X is the 90% confidence level (CL) upper limit on the number of decays for the rare or forbidden decay mode X and B_{Norm} is the normalization mode branching fraction obtained from the Particle Data Group [14]. $\varepsilon_{\text{Norm}}$ and ε_X are the detection efficiencies while $f^{\text{MC}}_{\text{Norm}}$ and f^{MC}_X are the fractions of Monte Carlo events that were reconstructed and passed the final selection criteria, for the normalization and decay modes, respectively.

The 90% CL upper limits N_X are calculated using the method of Feldman and Cousins [15] to account for background, and then corrected for systematic errors by the method of Cousins and Highland [16]. In these methods, the numbers of signal events are determined by simple counting, not by a fit. Upper limits are determined using the number of candidate events observed and expected number of background events within the signal region. (See Refs. [2,5] for a more detailed discussion of backgrounds.)

2 The $D^+ \to h\ell\ell$, $D_s^+ \to h\ell\ell$ and $D^0 \to \ell^+\ell^-$ Analysis

We normalized the sensitivity of our search to topologically similar Cabibbo-favored decays. For the D^+ decays we used 24010 ± 166 $D^+ \to K^-\pi^+\pi^+$; for D_s^+ decays we used 782 ± 30 $D_s^+ \to \phi\pi^+$; and for D^0 decays we used 25210 ± 179 $D^0 \to K^-\pi^+$ events. The widths of our normalization modes were 10.5 MeV/c^2 for D^+, 9.5 MeV/c^2 for D_s^+, and 12 MeV/c^2 for D^0. The results are shown in Table 1 and compared with previous results in Figure 1.

Table 1: E791 90% confidence level branching fraction upper limits for $D^+ \to h\ell\ell$, $D_s^+ \to h\ell\ell$ and $D^0 \to \ell^+\ell^-$.

Mode	E791 Limit	Mode	E791 Limit	Mode	E791 Limit
$D^+ \to \pi^+\mu^+\mu^-$	1.5×10^{-5}	$D^+ \to \pi^+e^+e^-$	5.2×10^{-5}	$D^+ \to \pi^+\mu^\pm e^\mp$	3.4×10^{-5}
$D^+ \to \pi^-\mu^+\mu^+$	1.7×10^{-5}	$D^+ \to \pi^-e^+e^+$	9.6×10^{-5}	$D^+ \to \pi^-\mu^+e^+$	5.0×10^{-5}
$D^+ \to K^+\mu^+\mu^-$	4.4×10^{-5}	$D^+ \to K^+e^+e^-$	2.0×10^{-4}	$D^+ \to K^+\mu^\pm e^\mp$	6.8×10^{-5}
$D_s^+ \to K^+\mu^+\mu^-$	1.4×10^{-4}	$D_s^+ \to K^+e^+e^-$	1.6×10^{-3}	$D_s^+ \to K^+\mu^\pm e^\mp$	6.3×10^{-4}
$D_s^+ \to K^-\mu^+\mu^+$	1.8×10^{-4}	$D_s^+ \to K^-e^+e^+$	6.3×10^{-4}	$D_s^+ \to K^-\mu^+e^+$	6.8×10^{-4}
$D_s^+ \to \pi^+\mu^+\mu^-$	1.4×10^{-4}	$D_s^+ \to \pi^+e^+e^-$	2.7×10^{-4}	$D_s^+ \to \pi^+\mu^\pm e^\mp$	6.1×10^{-4}
$D_s^+ \to \pi^-\mu^+\mu^+$	8.2×10^{-5}	$D_s^+ \to \pi^-e^+e^+$	6.9×10^{-4}	$D_s^+ \to \pi^-\mu^+e^+$	7.3×10^{-4}
$D^0 \to \mu^+\mu^-$	5.2×10^{-6}	$D^0 \to e^+e^-$	6.2×10^{-6}	$D^0 \to \mu^\pm e^\mp$	8.1×10^{-6}

3 The $D^0 \to V\ell^+\ell^-$ and $D^0 \to hh\ell\ell$ Analysis

There were a few minor differences between this analysis and our previous analysis as discussed above. First, we examined resonant modes, where the mass ranges used were: $\left| m_{\pi^+\pi^-} - m_{\rho^0} \right| < 150$ MeV/c^2,

$\left|m_{K^-\pi^+} - m_{\overline{K}^{*0}}\right| < 55$ MeV$/c^2$, and $|m_{K^+K^-} - m_\phi| < 10$ MeV$/c^2$. We normalized the sensitivity of each search to similar hadronic 3-body (resonant) or 4-body (non-resonant) decays. One exception is the case of $D^0 \to \rho^0\ell^\pm\ell^\mp$ where we normalize to nonresonant $D^0 \to \pi^+\pi^-\pi^+\pi^-$ because no published branching fraction exists for $D^0 \to \rho^0\pi^+\pi^-$. Table 2 lists the normalization mode used for each signal mode and the fitted numbers of normalization data events ($N_{\rm Norm}$).

Table 2: Normalization modes used for $D^0 \to V\ell^+\ell^-$ and $D^0 \to hh\ell\ell$.

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

The final results are shown in Table 3 and compared with previous results in Figure 2.

Table 3: E791 90% confidence level branching fraction upper limits for $D^0 \to V\ell^+\ell^-$ and $D^0 \to hh\ell\ell$.

Mode	E791 Limit	Mode	E791 Limit	Mode	E791 Limit
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	3.0×10^{-5}	$D^0 \to \pi^+\pi^-e^+e^-$	3.7×10^{-4}	$D^0 \to \pi^+\pi^-\mu^\pm e^\mp$	1.5×10^{-5}
$D^0 \to K^-\pi^+\mu^+\mu^-$	3.6×10^{-4}	$D^0 \to K^-\pi^+e^+e^-$	3.9×10^{-4}	$D^0 \to K^-\pi^+\mu^\pm e^\mp$	5.5×10^{-4}
$D^0 \to K^+K^-\mu^+\mu^-$	3.3×10^{-5}	$D^0 \to K^+K^-e^+e^-$	3.2×10^{-4}	$D^0 \to K^+K^-\mu^\pm e^\mp$	1.8×10^{-4}
$D^0 \to \rho^0\mu^+\mu^-$	2.2×10^{-5}	$D^0 \to \rho^0e^+e^-$	1.2×10^{-4}	$D^0 \to \rho^0\mu^\pm e^\mp$	6.6×10^{-5}
$D^0 \to \overline{K}^{*0}\mu^+\mu^-$	2.4×10^{-5}	$D^0 \to \overline{K}^{*0}e^+e^-$	4.7×10^{-5}	$D^0 \to \overline{K}^{*0}\mu^\pm e^\mp$	8.3×10^{-5}
$D^0 \to \phi\mu^+\mu^-$	3.1×10^{-5}	$D^0 \to \phi e^+e^-$	5.9×10^{-5}	$D^0 \to \phi\mu^\pm e^\mp$	4.7×10^{-5}
$D^0 \to \pi^-\pi^-\mu^+\mu^+$	2.9×10^{-5}	$D^0 \to \pi^-\pi^-e^+e^+$	1.1×10^{-4}	$D^0 \to \pi^-\pi^-\mu^+e^+$	7.9×10^{-5}
$D^0 \to K^-\pi^-\mu^+\mu^+$	3.9×10^{-4}	$D^0 \to K^-\pi^-e^+e^+$	2.1×10^{-4}	$D^0 \to K^-\pi^-\mu^+e^+$	2.2×10^{-4}
$D^0 \to K^-K^-\mu^+\mu^+$	9.4×10^{-5}	$D^0 \to K^-K^-e^+e^+$	1.5×10^{-4}	$D^0 \to K^-K^-\mu^+e^+$	5.7×10^{-5}

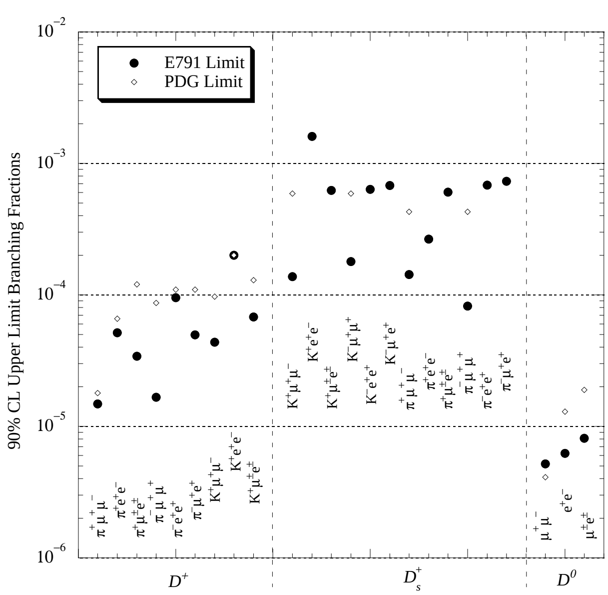

Figure 1: Comparison of the 90% CL upper-limit branching fractions from E791 data (dark circles) with existing limits (open diamonds) from the 1998 PDG[14].

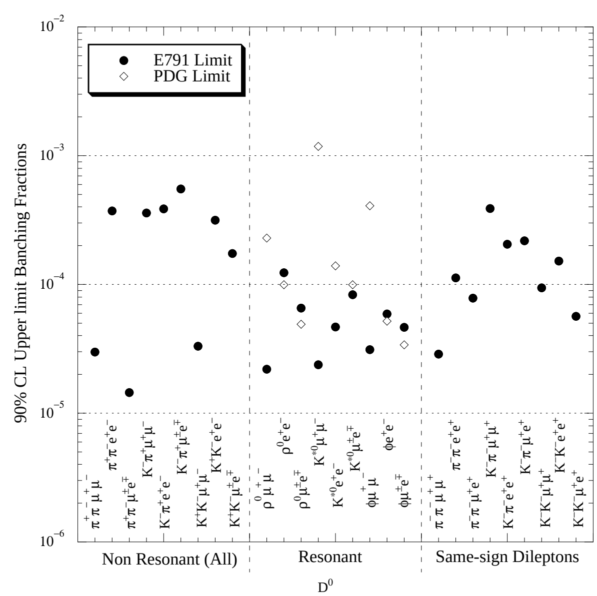

Figure 2: Comparison of the 90% CL upper-limit branching fractions from E791 data (dark circles) with existing limits (open diamonds) from the 2000 PDG[14].

4 Conclusion

We used a "blind" analysis of data from Fermilab experiment E791 to obtain upper limits on the dilepton branching fractions for 51 flavor-changing neutral current, lepton-number violating, and lepton-family violating decays of D^+, D_s^+, and D^0 mesons. No evidence for any of these 2, 3 and 4-body decays was found. Therefore, we presented upper limits on the branching fractions at the 90% confidence level. Eighteen limits represented significant improvements over previously published results. Twenty-six of the remaining modes had no previously reported limits.

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References

1. E. M. Aitala *et al.*, *Phys. Rev. Lett.* **76**, 364 (1996).
2. E. M. Aitala *et al.*, *Phys. Lett.* B **462**, 401 (1999).
3. See for example: S. Pakvasa, hep-ph/9705397;
   S. Pakvasa, *Chin. J. Phys. (Taipei)* **32**, 1163 (1994);
   D. A. Sanders, *Mod. Phys. Lett.* A **15**, 1399 (2000).
4. A. J. Schwartz, *Mod. Phys. Lett.* A **8**, 967 (1993).
5. E. M. Aitala *et al.*, *Phys. Rev. Lett.* **86**, 3969 (2001).
6. S. Fajfer, S. Prelovšek, and P. Singer, *Phys. Rev.* D **58**, 094038 (1998);
   S. Prelovšek, "Weak Decays of Heavy Mesons," hep-ph/0010106.
7. P. Singer, *Acta Phys. Polon.* B **30**, 3861 (1999);
   P. Singer and D.-X. Zhang, *Phys. Rev.* D **55**, 1127 (1997).
8. G. López Castro, R. Martínez, and J. H. Muñoz, *Phys. Rev.* D **58**, 033003 (1998).
9. J. A. Appel, Ann. Rev. Nucl. Part. Sci. **42** (1992) 367;
   D. J. Summers *et al.*, Proceedings of the $XXVII^{th}$ *Rencontre de Moriond*, Electroweak Interactions and Unified Theories, Les Arcs, France (15-22 March, 1992) 417, hep-ex/0009015;
   E. M. Aitala *et al.*, *Phys. Lett.* B **371**, 157 (1996);
   S. Amato *et al.*, *Nucl. Instrum. Methods* A **324**, 535 (1993);
   S. Bracker *et al.*, *IEEE Trans. Nucl. Sci.* **43**, 2457 (1996);
   E. M. Aitala *et al.*, *Eur. Phys. J. direct* C **4**, 1 (1999).
10. D. Bartlett *et al.*, *Nucl. Instrum. Methods* A **260**, 55 (1987).
11. V. K. Bharadwaj *et al.*, *Nucl. Instrum. Methods* **155**, 411 (1978);
    V. K. Bharadwaj *et al.*, *Nucl. Instrum. Methods* A **228**, 283 (1985);
    D. Summers, *Nucl. Instrum. Methods* A **228**, 290 (1985).
12. E. M. Aitala *et al.*, *Phys. Lett.* B **440**, 435 (1998).
13. H.-U. Bengtsson and T. Sjöstrand, *Comp. Phys. Comm.* **82**, 74 (1994);
    T. Sjöstrand, PYTHIA 5.7 and JETSET 7.4 Physics and Manual, CERN-TH.7112/93, hep-ph/9508391, 1995.
14. Particle Data Group, C. Caso *et al.*, *Eur. Phys. J.* C **3**, 1 (1998);
    Particle Data Group, D. E. Groom *et al.*, *Eur. Phys. J.* C **15**, 1 (2000).
15. G. J. Feldman and R. D. Cousins, *Phys. Rev.* D **57**, 3873 (1998).
16. R. D. Cousins and V. L. Highland, *Nucl. Instrum. Methods* A **320**, 331 (1992).