CLNS 96/1389
CLEO 96-1
January 9, 1996

Limits on Flavor Changing Neutral Currents in D^0 Meson Decays

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(January 9, 1996)

Abstract

Using the CLEO II detector at CESR, we have searched for flavor changing neutral currents and lepton family number violations in D^0 meson decays. The upper limits on the branching fractions for $D^0 \to \ell^+\ell^-$ and $D^0 \to X^0\ell^+\ell^-$ are in the range 10^{-5} to 10^{-4}, where X^0 can be a π^0, K_s^0, η, ρ^0, ω, $\bar{K}^{*0}$, or ϕ meson, and the $\ell^+\ell^-$ pair can be e^+e^-, $\mu^+\mu^-$, or $e^\pm\mu^\mp$. Although these limits are above the theoretical predictions, most are new or an order of magnitude lower than previous limits.

PACS numbers: 12.60.-i, 13.20.Fc, 14.40.Lb

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In the Standard Model (SM), flavor changing neutral currents (FCNC) are expected to be very rare in charm decays and lepton family number violations (LFNV) are strictly forbidden. The FCNC decays, $D^0 \to \ell^+\ell^-$ and $D \to X\ell^+\ell^-$, can occur at the one loop level in the SM from penguin and box diagrams as shown in Figure 1, but are highly suppressed by the GIM mechanism [1] and by the small quark masses in the loop. The theoretical estimates for the FCNC branching fractions [2] are of order 10^{-9} for $D \to X\ell^+\ell^-$ and 10^{-19} for $D^0 \to \ell^+\ell^-$, due to the additional helicity suppression.

In addition to these short distance loop diagrams there are contributions from long distance effects that can be several orders of magnitude larger [2]. There are two categories: 1) photon pole amplitudes and 2) vector meson dominance (VMD). Both involve nonperturbative QCD factors that are difficult to calculate.

The photon pole model (Figure 2a) is essentially a W-exchange decay with a virtual photon radiating from one of the quark lines. The amplitude behaves differently depending on whether the final state meson is a vector (V) or pseudoscalar (P). The dilepton mass distribution for $D \to V\ell^+\ell^-$ modes peak at zero (small q^2) since the photon prefers to be nearly real. Contrarily, the pole amplitude for $D \to P\ell^+\ell^-$ decays vanishes for small dilepton mass because $D \to P\gamma$ is forbidden by angular momentum conservation.

The VMD model (Figure 2b) proceeds through the decay $D \to XV^0 \to X\ell^+\ell^-$, where V^0 is an intermediate ρ^0, ω, or ϕ vector meson. The V^0 mixes with a virtual photon which then couples to $\ell^+\ell^-$. The dilepton mass spectrum will have poles at the ρ^0, ω, and ϕ masses due to real V^0 mesons decaying into $\ell^+\ell^-$. There will also be another pole at zero dilepton mass from the photon propagator if X is a vector meson.

Observation of FCNC decays at rates that exceed the long distance contributions opens a window into physics beyond the Standard Model; LFNV decays may suggest leptoquarks or heavy neutral leptons with nonnegligible couplings to e and μ. Measuring the long distance contributions is also intrinsically important since our understanding at the charm sector can then be used to estimate the long distance effects for $b \to s\gamma$, which can be as large as 20% of the total decay rate [4]. Extracting $|V_{td}/V_{ts}|$ from the ratio $\mathcal{B}(B \to \rho\gamma)/\mathcal{B}(B \to K^*\gamma)$ is possible only if the short and long distance contributions can be separated.

The data were collected with the CLEO II detector at the Cornell e^+e^- storage ring CESR, which operates on and just below the $\Upsilon(4S)$ resonance. The CLEO II detector [5] is a large solenoidal detector with 67 tracking layers and a CsI electromagnetic calorimeter that provides efficient π^0 reconstruction. We have used an integrated luminosity of 3.85 fb^{-1}, which corresponds to ~ 5 million $e^+e^- \to c\bar{c}$ events.

We have searched for the FCNC and LFNV decays $D^0 \to \ell^+\ell^-$ and $D^0 \to X\ell^+\ell^-$, where X can be a π^0, K_s^0, η, ρ^0, ω, $\bar{K}^{*0}$, or ϕ meson [6]. The $\ell^+\ell^-$ pair can be either e^+e^- or $\mu^+\mu^-$ for the FCNC decays, and $e^\pm\mu^\mp$ for the LFNV decays.

Charged tracks, except for pions from K_s^0 decays, are required to be consistent with coming from the primary interaction point. Charged pion and kaon candidates are required to have dE/dx and, when available, time-of-flight information consistent with that of true pions and kaons.

Electrons are identified by requiring that the energy deposition in the CsI calorimeter be consistent with the track momentum and the specific ionization loss (dE/dx) be consistent with that of true electrons. The electron candidate must have a momentum greater than 0.4 GeV/c and satisfy $|\cos\theta| < 0.81$, where θ is the polar angle with respect to the beam axis.

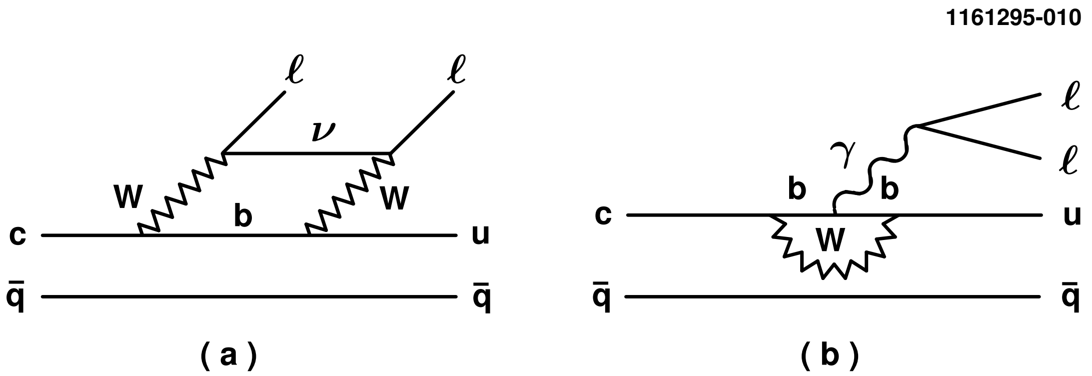

FIG. 1. Short distance contributions to FCNC decays in D mesons due to (a) box and (b) penguin diagrams.

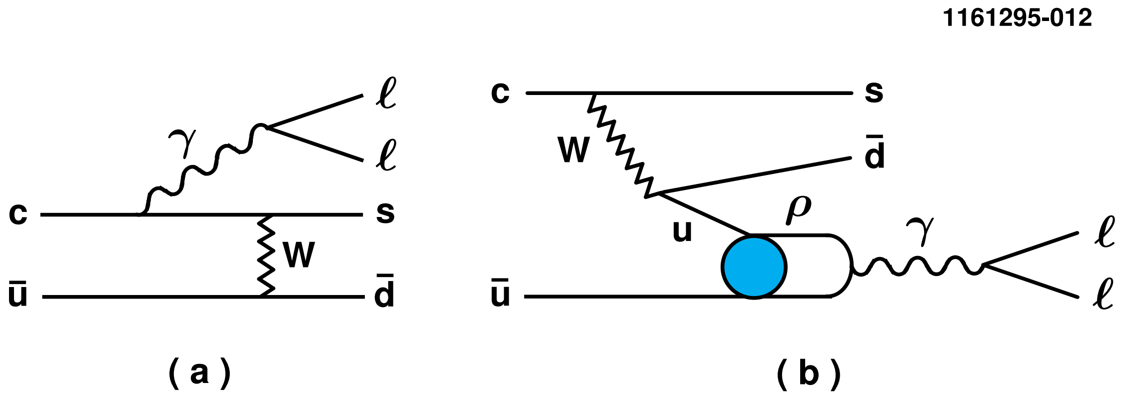

FIG. 2. Long distance contributions to FCNC decays in D mesons due to (a) photon pole amplitude and (b) vector meson dominance.

Electrons from photon conversions and π^0 Dalitz decays are rejected.

Muon candidates are selected by requiring the charged track to penetrate at least three nuclear interaction lengths of steel, which implicitly places a minimum momentum cut of 0.9 GeV/c. To further reduce the fake rate from pions we also require that the track lie in the region $|\cos\theta| < 0.7$ and that the CsI shower energy for the muon be less than 0.5 GeV.

The K_s^0 candidates are selected through the decay mode $K_s^0 \to \pi^+\pi^-$ by requiring a decay vertex displaced from the primary interaction point. The invariant mass of the K_s^0 candidates must be within 10 MeV/c^2 of its nominal value. The vector meson candidates are reconstructed through the decays $\rho^0 \to \pi^+\pi^-$, $\omega \to \pi^+\pi^-\pi^0$, $\bar{K}^{*0} \to K^-\pi^+$, and $\phi \to K^+K^-$. We require the candidates to have an invariant mass within 150, 20, 50, and 8 MeV/c^2 of their nominal mass, respectively.

We reconstruct the $\pi^0 \to \gamma\gamma$ decay mode from pairs of well-defined showers in the CsI calorimeter. The showers must not be matched to charged tracks and must have a lateral shower shape consistent with that of true photons. At least one photon must lie in the barrel region defined by $|\cos\theta| < 0.7$. The π^0 from the decay chain $D^0 \to \omega\ell^+\ell^-$, $\omega \to \pi^+\pi^-\pi^0$ ($D^0 \to \pi^0\ell^+\ell^-$) must have a momentum greater than 0.1 (0.6) GeV/c, and individual photon energies must be at least 0.03 (0.10) GeV, respectively. We select π^0 candidates that have an invariant mass within 2.5 standard deviations (σ) of the nominal mass. The photon 4-momenta are kinematically fit to the nominal π^0 mass to improve the momentum estimate.

The decay $\eta \to \gamma\gamma$ is reconstructed in a similar procedure. In addition, η candidates are rejected if either photon is consistent with coming from a π^0. The η momentum must be greater than 0.5 GeV/c and each photon must have an energy of at least 0.15 GeV. We select η candidates that have an invariant mass within 30 MeV/c^2 of the nominal mass.

In order to reduce the combinatoric background, we require the D^0 candidates to come from $D^{*+} \to D^0\pi^+$ decays. Although $\sim 75\%$ of the D^0 sample is lost by imposing the D^{*+} tag, backgrounds are reduced by a factor of 20–40. We require the mass difference $M(D^{*+}) - M(D^0)$ to be within 2.0 MeV/c^2 (2σ) of its expected value. (The D^* tag is not required for the $D^0 \to \phi\ell^+\ell^-$ modes since their backgrounds are negligible). Since charmed mesons from $e^+e^- \to c\bar{c}$ events are produced with a hard momentum spectrum, we further reduce the combinatoric background by requiring $x_p > 0.5$, where $x_p \equiv P_{D^{*+}}/\sqrt{E_{beam}^2 - M_{D^{*+}}^2}$ is the scaled momentum of the D^{*+}. Finally, the daughter particles of the D^0 candidate are required to lie within 90 degrees of the D^0 momentum vector, which further reduces backgrounds in the $D^0 \to \rho^0\ell^+\ell^-$ and $\omega\ell^+\ell^-$ modes.

The invariant mass spectra for the FCNC and LFNV decays $D^0 \to \ell^+\ell^-$ and $D^0 \to X\ell^+\ell^-$ are shown in Figures 3 and 4. We do not observe signals in any of the decay modes. The background levels are consistent with expectations from $B\bar{B}$ and continuum Monte Carlo simulations. We set upper limits on each mode by assuming all the events within 3σ of the D^0 mass ($\sim$ 30 MeV/c^2) to be signal events. Assuming that the LFNV decay rates $D^0 \to Xe^+\mu^-$ and $D^0 \to Xe^-\mu^+$ are identical, we combine these two mass spectra together to obtain a more stringent limit on $D^0 \to Xe^\pm\mu^\mp$. The number of events in each signal region is shown in Table I.

The upper limit on branching fractions for the FCNC and LFNV decay modes is given by $\mathcal{B} = \lambda_n/\epsilon N_{D^0}$, where λ_n is the Poisson 90% upper limit for n observed events, ϵ is the reconstruction efficiency, and N_{D^0} is the number of D^0 mesons in the data, which is obtained from the observed $D^0 \to K^-\pi^+$ yield. We observe 70770 ± 470 events in the decay mode $D^0 \to K^-\pi^+$ for $x_p > 0.5$, and 17300 ± 150 events in the decay chain $D^{*+} \to D^0\pi^+$ with $D^0 \to K^-\pi^+$. This corresponds to 5.22 million D^0 mesons and 1.38 million $D^{*+} \to D^0\pi^+$ decays.

For the FCNC and LFNV modes we compute the D^0 reconstruction efficiency using a phase space decay of $D^0 \to X\ell^+\ell^-$. The efficiencies for $D^0 \to Xe^+e^-$ are about 4–10 times greater than those for $D^0 \to X\mu^+\mu^-$, due to the greater momentum acceptance for electrons. The efficiencies for the $D^0 \to V\ell^+\ell^-$ vector decay modes are also determined using a photon pole amplitude decay in which $D^0 \to V\gamma^* \to V\ell^+\ell^-$. This leads to a dilepton mass distribution of $d\Gamma/dm_{\ell\ell}^2 \propto 1/m_{\ell\ell}^2$. The $D^0 \to Ve^+e^-$ efficiency for the pole model is about 30% less than that of the phase space model, primarily due to low mass e^+e^- pairs that resemble photon conversions. We present upper limits in Table I using both decay model assumptions.

The main sources of systematic error are due to uncertainties in the efficiencies for charged particle tracking (2% per track), π^0 and η reconstruction (5%), lepton identification (6%), K_s^0 reconstruction (5%), and Monte Carlo statistics (4–8%). The total systematic errors are in the range 9–12%, depending on the mode. We incorporate these errors into the upper

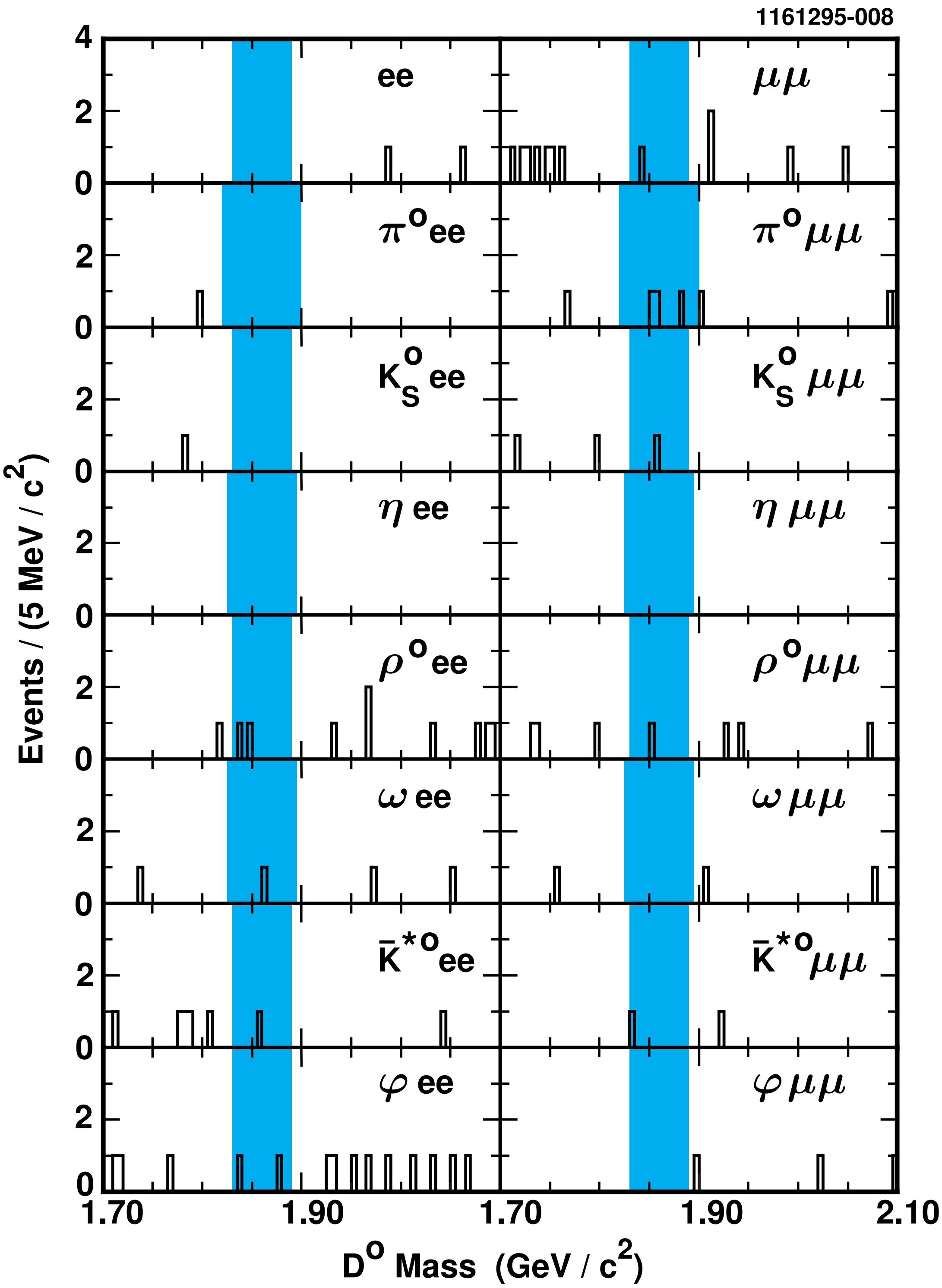

FIG. 3. Invariant mass distribution for FCNC D^0 decays. The signal region for the D^0 decay modes is shaded.

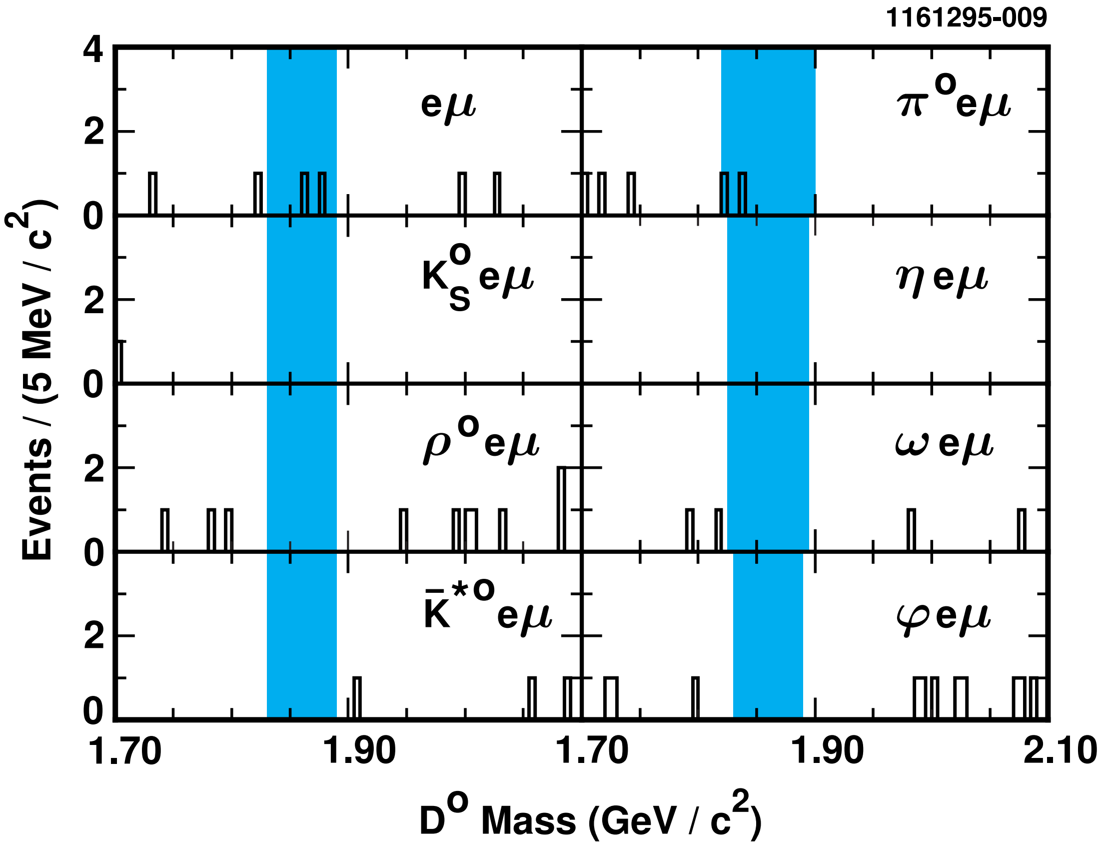

FIG. 4. Invariant mass distribution for LFNV D^0 decays. The signal region for the D^0 decay modes is shaded.

TABLE I. Summary of upper limits on the FCNC and LFNV decay modes $D^0 \to \ell^+\ell^-$ and $D^0 \to X\ell^+\ell^-$. The efficiencies ($\mathcal{E}$) are for the phase space model and do not include branching fractions to the observed final states. The 90% C.L. upper limits are listed separately for the phase space (nonresonant) and photon pole amplitude decay models, together with previous limits.

Decay	Signal	$\mathcal{E}(\%)$	$\mathcal{B}(10^{-5})$ Upper Limits		
Mode	Events		Nonres.	Pole	Previous
e^+e^-	0	14	1.3	—	13 [7]
$\mu^+\mu^-$	1	9	3.4	—	0.3 [8]
$e^\pm\mu^\mp$	2	11	1.9	—	10 [9]
$\pi^0e^+e^-$	0	4.2	4.5	—	
$\pi^0\mu^+\mu^-$	3	1.0	54	—	18 [10]
$\pi^0e^\pm\mu^\mp$	2	2.5	8.6	—	
$\bar{K}^0e^+e^-$	0	4.7	11	—	170 [11]
$\bar{K}^0\mu^+\mu^-$	1	1.4	67	—	26 [10]
$\bar{K}^0e^\pm\mu^\mp$	0	2.7	10	—	
ηe^+e^-	0	4.2	11	—	
$\eta\mu^+\mu^-$	0	0.9	53	—	
$\eta e^\pm\mu^\mp$	0	2.3	10	—	
$\rho^0e^+e^-$	2	4.2	10	18	45 [12]
$\rho^0\mu^+\mu^-$	1	0.7	49	45	25 [10]
$\rho^0e^\pm\mu^\mp$	0	1.9	4.9	5.0	
ωe^+e^-	1	1.9	18	27	
$\omega\mu^+\mu^-$	0	0.3	83	65	
$\omega e^\pm\mu^\mp$	0	0.9	12	12	
$\bar{K}^{*0}e^+e^-$	1	3.4	14	20	
$\bar{K}^{*0}\mu^+\mu^-$	1	0.4	118	100	
$\bar{K}^{*0}e^\pm\mu^\mp$	0	1.4	10	10	
ϕe^+e^-	2	4.4	5.2	7.6	
$\phi\mu^+\mu^-$	0	0.2	41	24	
$\phi e^\pm\mu^\mp$	0	1.5	3.4	3.3	

limits by decreasing the efficiency by 1σ.

The upper limits on the branching fractions for the flavor changing neutral current and lepton family number violating decay modes are summarized in Table I. The 90% confidence level limits range from a few $\times 10^{-5}$ for $D^0 \to \ell^+\ell^-$, $\pi^0\ell^+\ell^-$, and $\phi\ell^+\ell^-$, to a few $\times 10^{-4}$ for the other decay modes. Although these limits are above the theoretical predictions [2], the limits for $D^0 \to e^+e^-$, $e^\pm\mu^\mp$, and $\bar{K}^0 e^+e^-$ are an order of magnitude more restrictive than previous limits. In addition, the limits for many other decay modes reported here are the first published constraints.

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. This work was supported by the National Science Foundation, the U.S. Department of Energy, the Heisenberg Foundation, the Alexander von Humboldt Stiftung, the Natural Sciences and Engineering Research Council of Canada, and the A.P. Sloan Foundation. One of us (D.F.) would like to thank Gustavo Burdman and Sandip Pakvasa for stimulating discussions.

REFERENCES

[1] S.L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D **2**, 1285 (1970).

[2] J.L. Hewett, preprint SLAC-PUB-95-6821; S. Pakvasa, preprint UH-511-787-94; A.J. Schwartz, Mod. Phys. Lett. A **8**, 967 (1993).

[3] Particle Data Group, L. Montanet *et al.*, Phys. Rev. D **50**, 1173 (1994).

[4] E. Golowich and S. Pakvasa, Phys. Rev. D **51**, 1215 (1995); J. Soares, preprint TRI-PP-95-6; A. Khodjamirian *et al.*, Phys. Lett. B **358**, 129 (1995).

[5] Y. Kubota *et al.* (CLEO), Nucl. Inst. and Meth. **A320**, 66 (1992).

[6] In this Letter the charge conjugate states are implied.

[7] J. Adler *et al.* (Mark III), Phys. Rev. D **37**, 2023 (1988).

[8] T. Alexopoulos *et al.* (E771), preprint FERMILAB-PUB-95-297-E; M. Adamovich *et al.* (WA92), Phys. Lett. B **353**, 563 (1995); W.C. Louis *et al.* (E615), Phys. Rev. Lett. **56**, 1027 (1986).

[9] H. Albrecht *et al.* (ARGUS), Phys. Lett. B **209**, 380 (1988).

[10] K. Kodama *et al.* (E653), Phys. Lett. B **345**, 85 (1995).

[11] J. Adler *et al.* (Mark III), Phys. Rev. D **40**, 906 (1989).

[12] P. Haas *et al.* (CLEO), Phys. Rev. Lett. **60**, 1614 (1988).