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Search for Rare and Forbidden Decays $D^+ \to h^\pm e^\mp e^+$

Q. He,[1] H. Muramatsu,[1] C. S. Park,[1] E. H. Thorndike,[1] T. E. Coan,[2] Y. S. Gao,[2] F. Liu,[2] M. Artuso,[3] C. Boulahouache,[3] S. Blusk,[3] J. Butt,[3] O. Dorjkhaidav,[3] J. Li,[3] N. Menaa,[3] R. Mountain,[3] R. Nandakumar,[3] K. Randrianarivony,[3] R. Redjimi,[3] R. Sia,[3] T. Skwarnicki,[3] S. Stone,[3] J. C. Wang,[3] K. Zhang,[3] S. E. Csorna,[4] G. Bonvicini,[5] D. Cinabro,[5] M. Dubrovin,[5] R. A. Briere,[6] G. P. Chen,[6] J. Chen,[6] T. Ferguson,[6] G. Tatishvili,[6] H. Vogel,[6] M. E. Watkins,[6] J. L. Rosner,[7] N. E. Adam,[8] J. P. Alexander,[8] K. Berkelman,[8] D. G. Cassel,[8] V. Crede,[8] J. E. Duboscq,[8] K. M. Ecklund,[8] R. Ehrlich,[8] L. Fields,[8] R. S. Galik,[8] L. Gibbons,[8] B. Gittelman,[8] R. Gray,[8] S. W. Gray,[8] D. L. Hartill,[8] B. K. Heltsley,[8] D. Hertz,[8] C. D. Jones,[8] J. Kandaswamy,[8] D. L. Kreinick,[8] V. E. Kuznetsov,[8] H. Mahlke-Krüger,[8] T. O. Meyer,[8] P. U. E. Onyisi,[8] J. R. Patterson,[8] D. Peterson,[8] E. A. Phillips,[8] J. Pivarski,[8] D. Riley,[8] A. Ryd,[8] A. J. Sadoff,[8] H. Schwarthoff,[8] X. Shi,[8] M. R. Shepherd,[8] S. Stroiney,[8] W. M. Sun,[8] D. Urner,[8] T. Wilksen,[8] K. M. Weaver,[8] M. Weinberger,[8] S. B. Athar,[9] P. Avery,[9] L. Breva-Newell,[9] R. Patel,[9] V. Potlia,[9] H. Stoeck,[9] J. Yelton,[9] P. Rubin,[10] C. Cawlfield,[11] B. I. Eisenstein,[11] G. D. Gollin,[11] I. Karliner,[11] D. Kim,[11] N. Lowrey,[11] P. Naik,[11] C. Sedlack,[11] M. Selen,[11] E. J. White,[11] J. Williams,[11] J. Wiss,[11] D. M. Asner,[12] K. W. Edwards,[12] D. Besson,[13] T. K. Pedlar,[14] D. Cronin-Hennessy,[15] K. Y. Gao,[15] D. T. Gong,[15] J. Hietala,[15] Y. Kubota,[15] T. Klein,[15] B. W. Lang,[15] S. Z. Li,[15] R. Poling,[15] A. W. Scott,[15] A. Smith,[15] S. Dobbs,[16] Z. Metreveli,[16] K. K. Seth,[16] A. Tomaradze,[16] P. Zweber,[16] J. Ernst,[17] H. Severini,[18] S. A. Dytman,[19] W. Love,[19] S. Mehrabyan,[19] J. A. Mueller,[19] V. Savinov,[19] Z. Li,[20] A. Lopez,[20] H. Mendez,[20] J. Ramirez,[20] G. S. Huang,[21] D. H. Miller,[21] V. Pavlunin,[21] B. Sanghi,[21] I. P. J. Shipsey,[21] G. S. Adams,[22] M. Cravey,[22] J. P. Cummings,[22] I. Danko,[22] and J. Napolitano[22]

(CLEO Collaboration)

[1]*University of Rochester, Rochester, New York 14627*
[2]*Southern Methodist University, Dallas, Texas 75275*
[3]*Syracuse University, Syracuse, New York 13244*
[4]*Vanderbilt University, Nashville, Tennessee 37235*
[5]*Wayne State University, Detroit, Michigan 48202*
[6]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213*
[7]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*
[8]*Cornell University, Ithaca, New York 14853*
[9]*University of Florida, Gainesville, Florida 32611*
[10]*George Mason University, Fairfax, Virginia 22030*
[11]*University of Illinois, Urbana-Champaign, Illinois 61801*
[12]*Carleton University, Ottawa, Ontario, Canada K1S 5B6 and the Institute of Particle Physics, Canada*
[13]*University of Kansas, Lawrence, Kansas 66045*
[14]*Luther College, Decorah, Iowa 52101*
[15]*University of Minnesota, Minneapolis, Minnesota 55455*
[16]*Northwestern University, Evanston, Illinois 60208*
[17]*State University of New York at Albany, Albany, New York 12222*
[18]*University of Oklahoma, Norman, Oklahoma 73019*

[19]*University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[20]*University of Puerto Rico, Mayaguez, Puerto Rico 00681*
[21]*Purdue University, West Lafayette, Indiana 47907*
[22]*Rensselaer Polytechnic Institute, Troy, New York 12180*
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Abstract

Using 0.8×10^6 D^+D^- pairs collected with the CLEO-c detector at the $\psi(3770)$ resonance, we have searched for flavor-changing neutral current and lepton-number-violating decays of D^+ mesons to final states with dielectrons. We find no indication of either, obtaining 90% confidence level upper limits of $\mathcal{B}(D^+ \to \pi^+ e^+ e^-) < 7.4 \times 10^{-6}$, $\mathcal{B}(D^+ \to \pi^- e^+ e^+) < 3.6 \times 10^{-6}$, $\mathcal{B}(D^+ \to K^+ e^+ e^-) < 6.2 \times 10^{-6}$, and $\mathcal{B}(D^+ \to K^- e^+ e^+) < 4.5 \times 10^{-6}$.

Searches for rare-decay processes have played an important role in the development of the Standard Model (SM). The absence of flavor-changing neutral currents (FCNCs) in kaon decays led to the prediction of the charm quark [1], and the observation of B^0–$\bar{B}^0$ mixing, a FCNC process, signaled the very large top-quark mass [2]. To date, rare and forbidden charm decays have been less informative and less extensively studied. In this Letter we present searches for the FCNC decays [3, 4] $D^+ \to \pi^+ e^+ e^-$ and $D^+ \to K^+ e^+ e^-$, and the lepton-number-violating (LNV) decays [5] $D^+ \to \pi^- e^+ e^+$ and $D^+ \to K^- e^+ e^+$. (Charge-conjugate modes are implicit throughout this Letter.) Short-distance FCNC processes in charm decays are much more highly suppressed by the Glashow-Iliopoulos-Maiani mechanism [6] than the corresponding down-type quark decays because of the range of masses of the up-type quarks. Observation of D^+ FCNC decays could therefore provide indication of non-SM physics or of unexpectedly large rates for long-distance SM processes like $D^+ \to \pi^+ V$, $V \to e^+ e^-$, with a real or virtual vector meson V. The LNV decays $D^+ \to \pi^- e^+ e^+$ and $D^+ \to K^- e^+ e^+$ are forbidden in the SM. They could be induced by a Majorana neutrino, but with a branching fraction only of order 10^{-30}. Any observation at experimentally accessible levels would be clear evidence of physics beyond the SM. Past searches have set upper limits for the four dielectron decay modes in our study that are of order 10^{-4} [7]. The limits for corresponding dimuon modes are about an order of magnitude more stringent.

The CLEO-c detector [8–11] was used to collect a sample of 1.8 million $e^+e^- \to \psi(3770) \to D\bar{D}$ events (1.6 million $D^\pm$ mesons) from an integrated luminosity of 281 pb^{-1} provided by the Cornell Electron Storage Ring (CESR). From the interaction point out, CLEO-c consists of a six-layer low-mass drift chamber, a 47-layer central drift chamber, a ring-imaging Cherenkov detector (RICH), and a cesium iodide electromagnetic calorimeter, all operating inside a 1.0-T magnetic field provided by a superconducting solenoidal magnet. The detector provides acceptance of 93% of the full 4π solid angle for both charged particles and photons. Charged particle identification (PID) is based on information from the RICH detector, the specific ionization (dE/dx) measured by the drift chamber, and the ratio of electromagnetic shower energy to track momentum (E/p). Background processes and the efficiency of signal-event selection are estimated with a GEANT-based [12] Monte Carlo (MC) simulation program. Physics events are generated by EvtGen [13] and final-state radiation (FSR) is modeled by the PHOTOS [14] algorithm. Signal events are generated with a phase-space model as a first approximation of non-resonant FCNC and LNV decays.

Candidate signal decays are reconstructed from well-measured charged-particle tracks that are consistent in three dimensions with production at the e^+e^- collision point. Electrons with momenta of at least 200 MeV are identified with a likelihood ratio that combines E/p, dE/dx, and RICH information. Charged kaons and pions with momenta of 50 MeV or greater are selected based on dE/dx and RICH information. For each candidate decay of the form $D^+ \to h^\pm e^\mp e^+$, where h is either π or K, we compute the energy difference $\Delta E = E_{\rm cand} - E_{\rm beam}$ and the beam-constrained mass difference $\Delta M_{\rm bc} = \sqrt{E_{\rm beam}^2 - |\vec{p}_{\rm cand}|^2} - M_{D^+}$, where $E_{\rm cand}$ and $\vec{p}_{\rm cand}$ are the measured energy and momentum of the $h^\pm e^\mp e^+$ candidate, $E_{\rm beam}$ is the beam energy, and M_{D^+} is the nominal mass of the D^+ meson [7]. The resolution for these quantities is improved by recovering bremsstrahlung photons that are detected in the calorimeter within 100 mrad of electron trajectories. This provides a signal-efficiency increase of $13\% - 18\%$, depending on decay mode.

Events with D^+ candidates satisfying -30 MeV $\leq \Delta M_{\rm bc} < 30$ MeV and -100 MeV $\leq \Delta E < 100$ MeV are selected for further study. Within this region we define the "signal box" to be -5 MeV $\leq \Delta M_{\rm bc} < 5$ MeV and -20 MeV $\leq \Delta E < 20$ MeV, corresponding to $\pm 3\sigma$

in each variable, as determined by MC simulation. The remainder of the candidate sample was used to assess backgrounds.

The expected branching fraction for the long-distance decay $D^+ \to \pi^+\phi \to \pi^+e^+e^-$ is within the sensitivity of this analysis ($\sim 10^{-6}$). We subdivide our candidates based on the mass squared of the final-state e^+e^- (equal to the q^2 of the decay), with 0.9973 GeV^2 $\leq m^2_{e^+e^-} <$ 1.0813 GeV^2 defining the ϕ-resonant region. We use this region both to veto the long-distance $D^+ \to \phi\pi^+ \to \pi^+e^+e^-$ contribution and to measure its branching fraction.

Backgrounds in the $D^+ \to h^\pm e^\mp e^+$ candidate sample arise from both $D\bar{D}$ and non-$D\bar{D}$ sources. In $D\bar{D}$ events double semileptonic decays are dominant. These typically have four or fewer tracks (including two real electrons) and large missing energy. Potential peaking backgrounds from three-body hadronic D^+ decays, such as $K^-\pi^+\pi^+$, $\pi^+\pi^+\pi^-$, and $K^+K^0_S$, are negligible because of the very small probability of misidentifying charged hadrons as electrons in CLEO-c ($\sim$ 0.1% per track), and because incorrect mass assignments result in ΔE outside the signal box. In non-$D\bar{D}$ events, including continuum $e^+e^- \to q\bar{q}$ with $q \neq c$, τ-pair events, and radiative return to $\psi(2S)$, non-peaking backgrounds arise from γ-conversion and Dalitz decays of π^0 and η.

We have performed a "blind analysis." Signal-selection and background-suppression criteria were optimized using MC simulation before we open the signal box by minimizing the sensitivity variable

$$\mathcal{S} = \frac{\sum_{n=0}^{\infty} \mathcal{C}(n;N) \cdot \mathcal{P}(n;N)}{\epsilon \cdot N_{D^+}(\mathcal{L})}, \tag{1}$$

where n is the observed number of events, N is the expected number of background events, $\mathcal{C}$ is the 90% confidence coefficient upper limit on the signal, $\mathcal{P}$ is the Poisson probability, N_{D^+} is the number of charged D mesons (as a function of integrated luminosity $\mathcal{L}$), and ϵ is the signal-selection efficiency. The sensitivity variable $\mathcal{S}$ represents the average upper limit on the branching fraction that would be obtained from an ensemble of experiments if the true mean for the signal were zero. Sideband studies demonstrate that the MC simulation provides a good description of background events.

Background associated with D semileptonic decays, mainly double semileptonic events with typically 4 or fewer tracks in the event with large missing energy (or semileptonic decay accompanied with γ-conversion or π^0 and η Dalitz decays in the other side), is suppressed by a requirement on the energy $E_{\rm other}$, the sum of the energies of all particles other than those making up the signal candidate. Small values of $E_{\rm other}$ correspond to large values of missing energy in the event and are indicative of semileptonic decays in which neutrinos account for significant undetected energy. Optimization leads to different requirements on $E_{\rm other}$ for different signal modes: $E_{\rm other} >$ 1.0 GeV for the $\pi^+e^+e^-$ final state, $E_{\rm other} >$ 1.3 GeV for $K^+e^+e^-$, and $E_{\rm other} >$ 0.5 GeV for the LNV modes if the number of tracks in the event is 4 or fewer.

Background events from γ-conversion and from π^0 and η Dalitz decays are suppressed by rejecting D^+ candidates with low effective dielectron mass. We use two kinds of dielectron effective mass squared variables for this purpose: $m^2_{e^+e^-}$ is computed for oppositely charged signal-side electrons and $\acute{m}^2_{e^+e^-}$ is computed for all combinations of one signal electron with any unused oppositely charged track. We veto candidates if $m^2_{e^+e^-} <$ 0.01 GeV^2 or $\acute{m}^2_{e^+e^-} <$ 0.0025 GeV^2.

The decay mode $D^+ \to \pi^+e^+e^-$ is susceptible to background from $D^+ \to K^0_S e^+\nu_e$ accompanied by a semileptonic decay of the other D. This is suppressed by rejecting candidates when the signal π^+ and an oppositely charged track combine to give a mass $M_{\pi^+\pi^-}$ that

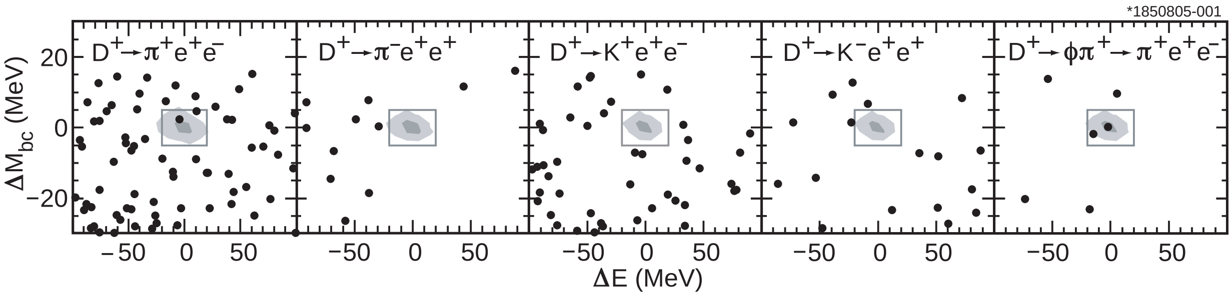

FIG. 1: Scatter plots of $\Delta M_{\rm bc}$ vs. ΔE obtained from data for each decay mode. The signal region, defined by -20 MeV $\leq \Delta E < 20$ MeV and -5 MeV $\leq \Delta M_{\rm bc} < 5$ MeV, is shown as a box. The two contours for each mode enclose regions determined with signal MC simulations to contain 50% and 85% of signal events, respectively.

satisfies -5 MeV $\leq M_{\pi^+\pi^-} - M_{K^0_S} < 5$ MeV, where $M_{K^0_S}$ is the nominal K^0_S mass [7].

After application of all background-suppression criteria, our intention was to eliminate multiple candidates (candidates in excess of one per mode per charge per event) by selecting the smallest $|\Delta M_{\rm bc}|$ among all that satisfy -5 MeV $\leq \Delta M_{\rm bc} < 5$ MeV and -100 MeV $\leq \Delta E < 100$ MeV. However, it turns out that there were *no* multiple candidate events.

The residual background and the efficiencies after application of all selection criteria have been determined by MC simulation and are given for the four signal modes in Table I. The model used to describe FCNC and LNV decays is phase space. The efficiency is observed to be quite uniform over the Dalitz plot, with the exception of the two corners at low m^2_{ee}, which are depleted by the 200-MeV minimum-momentum requirement for electron identification.

Scatter plots of $\Delta M_{\rm bc}$ vs. ΔE for data events surviving all other cuts are shown in Fig. 1. For $D^+ \to \pi^+ e^+ e^-$, two events lie in the signal box, with an expected background of 1.99. For all other FCNC or LNV modes there are zero events in the signal box. With no evidence of a signal, we calculate 90% confidence level (CL) upper limits (UL) on the branching fraction for each mode from the observed number of events (n) in the signal box, the signal-detection efficiency (ϵ), and the MC-estimated number of background events (N). We follow the Poisson procedure [7] to calculate the 90% confidence level coefficient ($\mathcal{C}(n;N)$) upper limit on signal in the presence of expected background:

$$\mathrm{UL} = \frac{\mathcal{C}(n;N)}{\epsilon \cdot (2 \cdot \sigma_{D^+D^-} \cdot \mathcal{L})}, \tag{2}$$

where $\sigma_{D^+D^-}$ [15] is the $e^+e^- \to \psi(3770) \to D^+D^-$ cross section, $\mathcal{L}$ is the integrated luminosity, and $2 \cdot \sigma_{D^+D^-} \cdot \mathcal{L} = 1.6$ million is the number of charged D mesons in our data sample. Results are given in Table I: we find no evidence of either FCNC or LNV decays. We separately measure the branching fraction for the resonant decay $D^+ \to \pi^+\phi \to \pi^+ e^+ e^-$, finding two events in the signal region with an expected background of 0.04.

Systematic uncertainties in these results can be divided into two categories: those related to background estimation and those arising from the signal-efficiency determination.

For the background uncertainty, only the $D^+ \to \pi^+ e^+ e^-$ mode needs to be considered, as the other modes have zero observed events and the uncertainty in the expected number of background events does not affect their upper limits. For $D^+ \to \pi^+ e^+ e^-$, we compared the background estimate from the MC simulations with that of data from the ΔE-$\Delta M_{\rm bc}$

TABLE I: Efficiencies (ϵ), background estimates (N), observed yields (n), combined systematic uncertainties ($\sigma_{\rm syst}$), and branching fraction results for four FCNC and LNV decay modes and for the resonant decay $D^+ \to \pi^+\phi \to \pi^+e^+e^-$. Branching-fraction UL values are all at 90% CL.

Mode	ϵ (%)	N	n	$\sigma_{\rm syst}$ (%)	$\mathcal{B}$ (10^{-6})
$\pi^+e^+e^-$	36.41	1.99	2	8.7	< 7.4
$\pi^-e^+e^+$	43.85	0.48	0	7.1	< 3.6
$K^+e^+e^-$	26.18	1.47	0	10.0	< 6.2
$K^-e^+e^+$	35.44	0.50	0	7.2	< 4.5
$\pi^+\phi(e^+e^-)$	46.22	0.04	2	7.4	$2.7^{+3.6}_{-1.8} \pm 0.2$

sideband. The sideband estimate of the background in the signal box is about one standard deviation (σ) higher than the MC estimate. Therefore our upper limit based on the MC background estimate is conservative; the upper limit with the sideband-estimated background would be 5% lower.

Sources of uncertainties that are common to all results are the number of D^+ (-3.2%, $+4.5\%$), tracking ($\pm1\%$ per track or $\pm3\%$ total), PID ($\pm2.3\%$), and FSR ($\pm4.0\%$ for $\pi^\pm e^\mp e^+$, $\pm3.3\%$ for $K^+e^+e^-$, $\pm3.5\%$ for $K^-e^+e^+$, and $\pm4.4\%$ for $\pi^+\phi \to \pi^+e^+e^-$, estimated by comparing the efficiency before and after bremsstrahlung recovery).

Uncertainties in signal efficiency due to background-suppression cuts are estimated by comparing the efficiency before and after the cuts are applied: $\pm5.2\%$ ($\pi^+e^+e^-$), $\pm1.1\%$ ($\pi^-e^+e^+$), $\pm7.3\%$ ($K^+e^+e^-$), $\pm1.0\%$ ($K^-e^+e^+$), and $\pm0.9\%$ ($\pi^+\phi \to \pi^+e^+e^-$).

Uncertainty from using the phase-space model (as a first approximation for non-resonant decays) for the FCNC and LNV signal efficiency estimation is assessed by (somewhat arbitrarily) taking one quarter of the fraction of phase space which has non-uniform efficiency due to the electron identification momentum cut-off (200 MeV): $\pm2.8\%$ ($\pi^\pm e^\mp e^-$) and $\pm3.8\%$ ($K^\pm e^\mp e^-$).

For the results in Table I, we increase the upper limits to account for systematic uncertainties by decreasing the efficiency by $1\sigma_{\rm syst}$ (combined systematic uncertainty).

In summary, we find no evidence for non-Standard-Model physics. There is no evidence either for the two rare (FCNC) decays or for the two forbidden (LNV) decays of charged D mesons to three-body final states with dielectrons. Finding no evidence for signals, we set 90% confidence level upper limits:

$$\begin{aligned}
\mathcal{B}(D^+ \to \pi^+e^+e^-) &< 7.4 \times 10^{-6} \\
\mathcal{B}(D^+ \to \pi^-e^+e^+) &< 3.6 \times 10^{-6} \\
\mathcal{B}(D^+ \to K^+e^+e^-) &< 6.2 \times 10^{-6} \\
\mathcal{B}(D^+ \to K^-e^+e^+) &< 4.5 \times 10^{-6}
\end{aligned}$$

Our results for these dielectron modes are significantly more restrictive than previous limits, and reflect sensitivity comparable to the searches for dimuon modes [7]. Due to the dominance of long-distance effects in FCNC modes, we separately measure the branching fraction of the resonant decay $D^+ \to \pi^+\phi \to \pi^+e^+e^-$, obtaining $\mathcal{B}(D^+ \to \phi\pi^+ \to \pi^+e^+e^-) = (2.7^{+3.6}_{-1.8} \pm 0.2) \times 10^{-6}$. This is consistent with the product of known world average [7] branching fractions, $\mathcal{B}(D^+ \to \phi\pi^+ \to \pi^+e^+e^-) = \mathcal{B}(D^+ \to \phi\pi^+) \times \mathcal{B}(\phi \to e^+e^-) = [(6.2 \pm 0.6) \times 10^{-3}] \times [(2.98 \pm 0.04) \times 10^{-4}] = (1.9 \pm 0.2) \times 10^{-6}$.

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