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Rare and Forbidden Decays of the D^0 Meson

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We report the observation of the rare charm decay $D^0 \to K^-\pi^+e^+e^-$, a search for nine lepton-number-violating (LNV) and three lepton-flavor-violating (LFV) neutral charm decays of the types $D^0 \to h^-h'^-l^+l'^+$ and $D^0 \to h^-h'^+l^+l'^-$, where h and h' represent a K or π meson, l and l' an electron or muon, and a search for seven lepton-number-violating decays of the type $D^0 \to X^0e^\pm\mu^\mp$, where X^0 is a π^0, K^0_S, K^{*0}, ρ^0, ϕ, ω, or η meson. The results are based on 468 fb^{-1} of e^+e^- collision data collected with the BABAR detector at the SLAC National Accelerator Laboratory. In the invariant mass range $0.675 < m(e^+e^-) < 0.875\ \text{GeV/c}^2$, we find $\mathcal{B}(D^0 \to K^-\pi^+e^+e^-) = (4.0\pm0.5\pm0.2\pm0.1)\times10^{-6}$, where the errors are, respectively, statistical, systematic, and due to uncertainty of the branching fraction of the decay used for normalization. In other invariant mass regions where long-distance effects are potentially small, we obtain a 90% confidence level (C.L.) upper limit on the branching fraction $\mathcal{B}(D^0 \to K^-\pi^+e^+e^-) < 3.1\times10^{-6}$. We observe no evidence for any LFV or LNV modes and establish 90% C.L. upper limits on the branching fractions in the range $(1.0 - 30.6)\times10^{-7}$. Individual limits are one to three orders of magnitude more stringent than previous measurements.

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1. Introduction

Conservation laws are central to physics and correspond to symmetries in the corresponding physical theories. Lepton number conservation and lepton flavor conservation are empirically observed symmetries, but the associated local symmetries are not elucidated. Lepton number conservation is familiar to most physics students as arising from the explanation of beta decay: the anti-neutrino hypothesized to explain the energy spectrum of electrons in the decays can also be used to balance the net lepton number before and after the decay. So the decay is $n \to p + e^- + \bar{\nu}_e$ rather than $n \to p + e^-$. Similarly, lepton flavor conservation is familiar from the most common form of muon decay, $\mu^- \to e^- \bar{\nu}_e \nu_\mu$, which would be a direct conversion, $\mu^- \to e^-$, without the introduction of the neutrinos to both balance the lepton flavor on both sides of the interaction and to explain the 3-body spectrum of electron energy.

These conservation laws hold at the level of our current observations. The Standard Model only allows violation through complicated short-distance Feynman diagrams with typical branching fractions of order 10^{-50} or less. However, neutrino oscillation demonstrates lepton flavor violation (LFV) readily – neutrinos flip flavor in the process. Many New Physics (NP) theories allow for LFV or lepton number violating (LNV) processes that may be within current experimental reach [1–5]. Baryon asymmetry in the Universe can be explained via leptogenesis, which requires LNV. If neutrinos are Majorana particles, they are their own antiparticles, and some LNV processes become automatically tenable [6]. Observation of either type of violation would provide evidence of and insight into NP.

Even modes that do not explicitly violate any of the conservation rules can provide insight. For instance, the decay $D^0 \to K^-\pi^+l^+l^-$ cannot occur at tree level and is expected to be suppressed [7]. This mode exhibits a tension between expected dominant long-distance contributions at $O(10^{-6})$, such as $D^0 \to XV \to Xl^+l^-$ in a vector meson dominance model [8], and suppressed short-distance contributions such as loop and box diagrams at $O(10^{-9})$ [1].

2. Overview of Searches

We report here on the search for nine decays of the type $D^0 \to h^-h'^-l^+l'^+$, all of which exhibit both lepton number violation and lepton flavor violation, and five decays of the type $D^0 \to h^-h'^+l^+l'^-$, where h and h' represent a K or π meson, including the first observation of the mode $D^0 \to K^-\pi^+e^+e^-$, as shown in Table 1 [9–12]. We also report on the search for the explicitly LFV decays $D^0 \to X^0\mu^\pm e^\mp$, where X^0 represents a π^0, K^0_S, K^{*0}, ρ^0, ϕ, ω, or η meson [13]. Data for these searches were collected with the BABAR detector at the PEP-II asymmetric-energy electron-positron collider at the SLAC National Accelerator Laboratory in Stanford, California [14]. The data used in all of the analyses consisted of 424 fb^{-1} recorded at the center-of-mass energy of the $\Upsilon(4S)$ resonance (on-peak) and 44 fb^{-1} recorded at a 40 MeV lower CM energy (off-peak), resulting in approximately 6×10^8 events of the type $e^+e^- \to c\bar{c}$, which provides a large sample of D^0 mesons for these searches. [15]. Events are required to contain at least five charged tracks, two of which must be identified as leptons. For the modes $D^0 \to \pi^0 e^\pm\mu^\mp$ and $D^0 \to \eta(\to \gamma\gamma)e^\pm\mu^\mp$, only three charged tracks are required in the event selection. Branching fractions are measured relative to normalization modes $D^0 \to \pi^-\pi^+\pi^+\pi^-$, $D^0 \to K^-\pi^+\pi^+\pi^-$, and $D^0 \to K^-K^+\pi^+\pi^-$ for signal modes with zero, one, or two kaons, respectively, in the final state, except for the modes involving π^0 and η, which are normalized against the $D^0 \to K^-\pi^+\pi^+\pi^-$ due to its higher statistics.

Mode	e^+e^-	$\mu^+\mu^-$	$e^+\mu^-$
K^-K^+	Allowed	Allowed, Found [11]	LFV
$\pi^-\pi^+$	Allowed	Allowed, Found [12]	LFV
$K^\mp\pi^\pm$	Allowed, Found [10]	Allowed, Found [12]	LFV

Table 1: Search modes of type $D^0 \to h^-h'^+l^+l'^-$. Charge conjugates are implied. The mode in the lower left corner of the table is reported in this paper while the modes in the center column were found by the LHCB Experiment [11, 12]. The four modes represented in the rightmost column are all lepton flavor violating.

3. D^0 Selection

Candidate D^0 mesons are formed from four charged tracks, except in the modes $D^0 \to \pi^0 e^\pm\mu^\mp$ and $D^0 \to \eta(\to \gamma\gamma)e^\pm\mu^\mp$ in which they are formed from two charged tracks and two photons. Particle identification for each charged track must be consistent with the particle type assumed in forming the D^0 candidate. The tracks must meet at a good-quality vertex with χ^2 probability greater than 0.005. A bremsstrahlung energy recovery algorithm is applied to electrons to correct for losses in the detector material. In the $D^0 \to \pi^0 e^\pm\mu^\mp$ and $D^0 \to \eta(\to \gamma\gamma)e^\pm\mu^\mp$ modes, photons are required to pass minimum energy thresholds and the CM momentum of the
pi^0 or η must be at least 0.045 GeV/c. All intermediate particles must have invariant masses consistent with nominal values. The D^0 candidate must have momentum in the center of mass frame greater than 2.4 GeV/c, consistent with production via $e^+e^- \to c\bar{c}$. To increase the purity of the sample, D^0 candidates are required to originate from the decay $D^{*\pm} \to D^0\pi^\pm$: the charged pion must have laboratory momentum greater than 0.1 GeV/c and the vertex fit, with the D^0 mass constrained to nominal value, must have χ^2 probability greater than 0.005. The $D^{*\pm}$ vertex must be consistent with origin from the primary interaction point of the event.

4. Observation of $D^0 \to K^-\pi^+e^+e^-$

For the observation of $D^0 \to K^-\pi^+e^+e^-$, extended unbinned maximum likelihood fits are made to the four-body invariant mass, $m(K^-\pi^+e^+e^-)$, and independently to the mass difference $\Delta m = m_{D^*} - m_D$. Normalization is achieved by performing a parallel analysis on decays of type $D^0 \to K^-\pi^+\pi^+\pi^-$ from a 39.3 fb^{-1} dataset. The fits find 68 ± 9 signal decays, corresponding to a significance of 9.7 σ, and 260870 ± 520 normalization decays. The projection of the fits onto the invariant mass of the electron-positron pair is shown in Figure 1. The shaded bands correspond to ranges of e^+e^- mass associated with vector mesons and thus long-distance effects. The non-shaded regions are referred to as "continuum" and correspond to regions in which short-distance effects should dominate. In the mass region $0.675 < m(e^+e^-) < 0.875$ GeV/c^2, we determine the branching fraction $\mathcal{B}(D^0 \to K^-\pi^+e^+e^-) = (4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$, where the first uncertainty is statistical, the second systematic, and the third due to the uncertainty in the normalization mode. In the continuum region, we find no evidence of signal and set a 90% C.L. upper limit $\mathcal{B}(D^0 \to K^-\pi^+e^+e^-) < 3.1 \times 10^{-6}$.

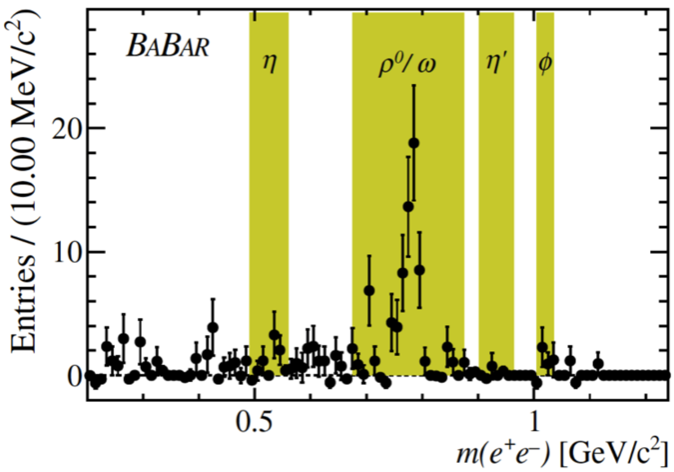

Figure 1: Projection of the fits to the $D^0 \to K^-\pi^+e^+e^-$ data distributions onto $m(e^+e^-)$ for candidates with $m(e^+e^-) > 0.2$ GeV/c^2, with backgrounds subtracted. The shaded bands are regions in which long-distance effects should dominate and are not included in the short-distance dominated "continuum" regions.

5. Search for Forbidden Modes $D^0 \to hh'll'$

In the searches for four-body LNV and LNF modes of the type $D^0 \to hh'll'$, semi-leptonic charm decays and other charm decays with additional particles present possibly significant backgrounds. We reduce these backgrounds using a Fischer discriminant in nine variables, including thrust and sphericity, Fox-Wolfram moments, momentum of the D^0 daughters, and angles of the $D^{*\pm}$ in the event. In simulation studies, the Fisher discriminant retains 90% of the signal while removing 30-50% of the background. Normalization is performed using the mode $D^0 \to \pi^-\pi^+\pi^+\pi^-$, $D^0 \to K^-\pi^+\pi^+\pi^-$, or $D^0 \to K^-K^+\pi^+\pi^-$, depending on the number of kaons in the final state. A two-dimensional fit is performed on the invariant mass of the D^0 candidate and the mass difference $\Delta m = m_{D^*} - m_D$. Projections of sample fits are shown in Figure 2. No significant signals are found and 90% C.L. upper limits are set for the branching fraction for each mode, ranging from 1.0×10^{-7} to 30.6×10^{-7}. These upper limits are all more stringent than previous limits, by as much as three orders of magnitude.

6. Search for Forbidden Modes $D^0 \to X^0 e^\pm \mu^\mp$

Backgrounds to these explicitly LFV modes come from events in which child particles are either lost or selected from elsewhere in the event and are suppressed using a Boosted Decision Tree (BDT) in 8 variables. Input to the BDT includes lepton and meson momenta, invariant mass of the X^0 candidate, maximum angle between the D^0 and its daughters, and event variables. The requirement on the discriminant retains 70-90% of signal while rejecting 50-90% of background. For this search, a maximum likelihood fit is performed on the variable $\Delta m = m_{D^*} - m_D$, as shown in Figure 3. No significant signals are found and 90% C.L. upper limits are set for the branching fraction for each mode, ranging from 5.0×10^{-7} to 43.0×10^{-7}. Each result is roughly two orders of magnitude more stringent than previous limits.

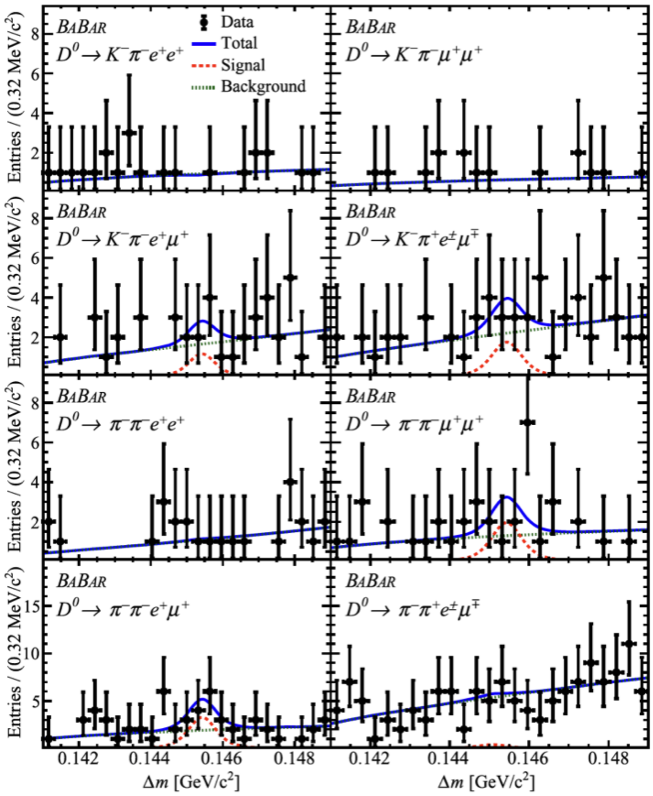

Figure 2: Projections onto Δm of two-dimensional fits for $D^0 \to hh'll'$ signals for a sample of modes.

7. Conclusion

Rare and forbidden decays in the charm sector provide an interesting window on possible New Physics. The BABAR Collaboration has reported the first observation of the rare mode $D^0 \to K^-\pi^+e^+e^-$ and found it to be consistent with long-distance interactions. We have searched for nineteen LNV and/or LFV D^0 decay modes and set upper limits on all that are up to three orders of magnitude more stringent than previous limits.

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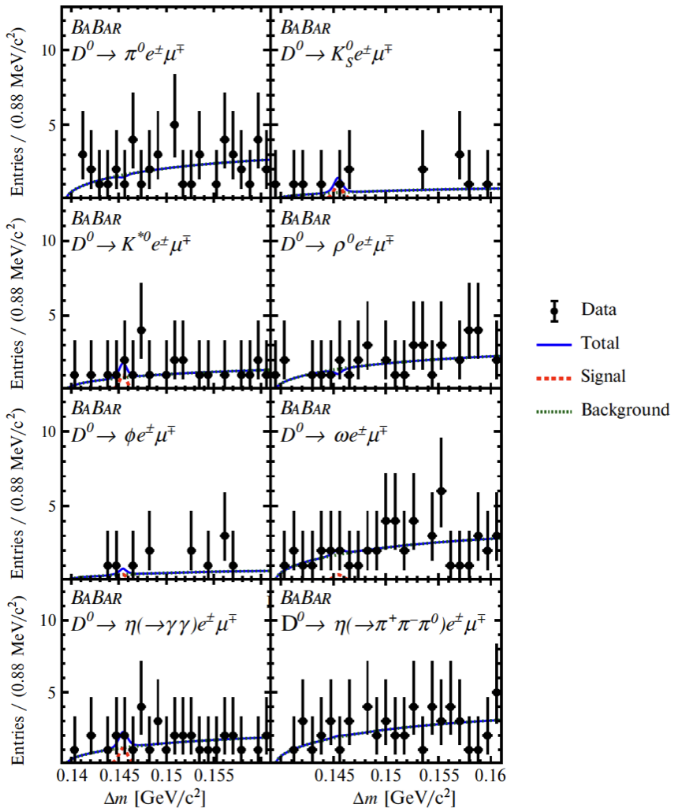

Figure 3: Projections onto Δm of two-dimensional fits for $D^0 \to hh'll'$ signals for each of the searched modes.

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