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Evidence for the Decay $D^0 \to K^-\pi^+\pi^-e^+\nu_e$

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Using a 281 pb^{-1} data sample collected at the $\psi(3770)$ with the CLEO-c detector, we present the first absolute branching fraction measurement of the decay $D^0 \to K^-\pi^+\pi^-e^+\nu_e$ at a statistical significance of about 4.0 standard deviations. We find 10 candidates consistent with the decay $D^0 \to K^-\pi^+\pi^-e^+\nu_e$. The probability that a background fluctuation accounts for this signal is less than 4.1×10^{-5}. We find $\mathcal{B}(D^0 \to K^-\pi^+\pi^-e^+\nu_e) = [2.8^{+1.4}_{-1.1}(\mathrm{stat}) \pm 0.3(\mathrm{syst})] \times 10^{-4}$. By restricting the invariant mass of the hadronic system to be consistent with $K_1(1270)$, we obtain the product of branching fractions $\mathcal{B}(D^0 \to K_1^-(1270)e^+\nu_e) \times \mathcal{B}(K_1^-(1270) \to K^-\pi^+\pi^-) = [2.5^{+1.3}_{-1.0}(\mathrm{stat}) \pm 0.2(\mathrm{syst})] \times 10^{-4}$. Using $\mathcal{B}(K_1^-(1270) \to K^-\pi^+\pi^-) = (33 \pm 3)\%$, we obtain $\mathcal{B}(D^0 \to K_1^-(1270)e^+\nu_e) = [7.6^{+4.1}_{-3.0}(\mathrm{stat}) \pm 0.6(\mathrm{syst}) \pm 0.7] \times 10^{-4}$. The last error accounts for the uncertainties in the measured $K_1^-(1270) \to K^-\pi^+\pi^-$ branching fractions.

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The understanding of the hadronic mass spectrum in semileptonic decays of charm mesons sheds light on nonperturbative strong interaction dynamics in weak decays. In particular, an interesting question is whether the charm quark can be considered "heavy," and thus theoretical predictions based upon heavy quark effective theory (HQET) can be applied to describe some features of its decays. *A priori* this seems to be an unlikely scenario as, even in the Cabibbo-favored transition $c \to s e^+ \nu_e$, the daughter quark is too light for HQET to apply. Nonetheless, this effective theory seems to describe these decays relatively well [1].

The decays induced by the quark level process $c \to s e^+ \nu_e$ are dominated by the two final states $D \to \bar{K} e^+ \nu_e$ and $D \to \bar{K}^* e^+ \nu_e$. CLEO-c has measured exclusive D semileptonic branching fractions for all modes observed to date: $\bar{K} e^+ \nu_e$, $\bar{K}^* e^+ \nu_e$, $\pi e^+ \nu_e$, $\rho e^+ \nu_e$, and $D^+ \to \omega e^+ \nu_e$ [2], as well as inclusive $D \to X e^+ \nu_e$ branching fractions [3]. The sum of the exclusive branching fractions and the inclusive branching fractions for D meson semileptonic decays are consistent: $\sum \mathcal{B}(D^0_{\rm excl}) = [6.1 \pm 0.2({\rm stat}) \pm 0.2({\rm syst})]\%$ and $\sum \mathcal{B}(D^+_{\rm excl}) = [15.1 \pm 0.5({\rm stat}) \pm 0.5({\rm syst})]\%$, while $\mathcal{B}(D^0 \to X e^+ \nu_e) = [6.46 \pm 0.17({\rm stat}) \pm 0.13({\rm syst})]\%$ and $\mathcal{B}(D^+ \to X e^+ \nu_e) = [16.13 \pm 0.20({\rm stat}) \pm 0.33({\rm syst})]\%$. Nonetheless, there is some room left for higher multiplicity modes.

The quark model developed by Isgur, Scora, Grinstein, and Wise [4], later updated to include constraints from heavy quark symmetry, hyperfine distortions of wave functions, and form factors with more realistic high recoil behavior [1], is the only one to provide quantitative predictions for the partial width of decays such as $D \to K_1(1270) e^+ \nu_e$. In general, we expect the decay mediated by the quark level process $c \to s e^+ \nu_e$ to be dominated by the ground state pseudoscalar and vector daughter mesons. The low available phase space makes it less likely to produce heavier mesons, such as P-wave or first radial excitations of the $s\bar{u}$ and $s\bar{d}$ quark states. The lightest excited state is the $K_1(1270)$. This model predicts that the partial width $\Gamma(D \to K_1(1270) e^+ \nu_e)$ is 2% of the total $\Gamma(c \to s e^+ \nu_e)$, and that decays to other excited resonances are suppressed by at least a factor of 10 or more.

Little is known about $D^0 \to K_1(1270) e^+ \nu_e$ to date. The fixed target experiment E653 [5] reported a 90% confidence level upper limit of $\mathcal{B}(D^0 \to K^- \pi^+ \pi^- \mu^+ \nu_\mu) < 0.037 \times \mathcal{B}(D^0 \to K^- \mu^+ \nu_\mu)$. This Letter is the first report on a signal for the decay $D^0 \to K^- \pi^+ \pi^- e^+ \nu_e$.

We use a 281 pb^{-1} data sample collected at the $\psi(3770)$ with the CLEO-c detector [6,7]. The three major subsystems of this detector are the charged particle tracking chambers, the CsI electromagnetic calorimeter, and a Ring Imaging Cherenkov (RICH) charged particle identification system. All these components are critical to an efficient and highly selective electron and positron identification algorithm. The CsI calorimeter measures the electron and photon energies with an r.m.s. resolution of 2.2% at $E = 1$ GeV and 5% at $E = 100$ MeV. One of the key variables for e identification, E/p, uses E, the energy measured in the calorimeter and p, the momentum measured in the charged particle tracking system. The tracking system is composed of a 6-layer inner drift chamber and a 47-layer main drift chamber. The main drift chamber also provides specific ionization (dE/dx) measurements for charged particle identification. In addition, charged particles are identified using the RICH detector [8]. Combining information from these detector subsystems, we achieve efficient and selective charged particle identification over the entire momentum region relevant for the decays studied.

We use a tagging technique similar to the one pioneered by the Mark III collaboration [9]. Details on the tagging selection procedure are given in Ref. [10]. We select events containing a fully reconstructed $\bar{D}^0 \to K^+ \pi^-$, $\bar{D}^0 \to K^+ \pi^- \pi^0$, $\bar{D}^0 \to K^+ \pi^- \pi^+ \pi^-$, or $\bar{D}^0 \to K^0_S \pi^+ \pi^-$ decay, which we call a tag. (Mention of a specific mode implies the use of the charge conjugate mode as well throughout this Letter.) Two kinematic variables, namely, energy difference, $\Delta E \equiv E_{\rm tag} - E_{\rm beam}$, and beam-constrained mass, $M_{\rm bc} \equiv \sqrt{E^2_{\rm beam}/c^4 - |\vec{p}_{\rm tag}|^2/c^2}$, are used to select tag candidates, where $E_{\rm beam}$ represents the beam energy and $(E_{\rm tag}, \vec{p}_{\rm tag})$ represents the 4-vector of the $\bar{D}^0$ tag candidate. We first require $|\Delta E|$ to be less than 0.020 to 0.030 GeV, depending upon the mode considered. Figure 1 shows the $M_{\rm bc}$ spectra for events that satisfy the $|\Delta E|$ requirement for the four tagging modes considered. In order to determine the total number of tags, we fit the $M_{\rm bc}$ distribution with a signal shape composed of a crystal ball function [11] and a Gaussian, and an ARGUS function [12] parametrizing the background in the fit. The signal window is chosen as $1.858\ {\rm GeV}/c^2 \le M_{\rm bc} \le 1.874\ {\rm GeV}/c^2$. In order to extract the tag yield, we integrate the signal shape within this $M_{\rm bc}$ interval. Alternatively, we count tag candidates in the $M_{\rm bc}$ signal window and subtract the combinatorial background obtained by integrating the background function from the fit. The total number of tags obtained with the former method is $[257.4 \pm 0.7({\rm stat})] \times 10^3$; the second method gives $[257.7 \pm 0.6({\rm stat})] \times 10^3$. The agreement is excellent and we use the latter number as the total number of tags in our sample. The difference between the two tag yields is included in a systematic uncertainty.

In each event where a tag is found, we search for a set of tracks recoiling against the tag that are consistent with a semileptonic decay. We select tracks that are well measured and have a helical trajectory approaching the event origin within a distance of 5 cm (5 mm) along the beam axis (in the plane perpendicular to the beam axis). Each track must include at least 50% of the main drift chamber wire hits expected for its momentum and have momentum greater than 50 MeV$/c$. We search for a positron among well-reconstructed tracks having a momentum of at least

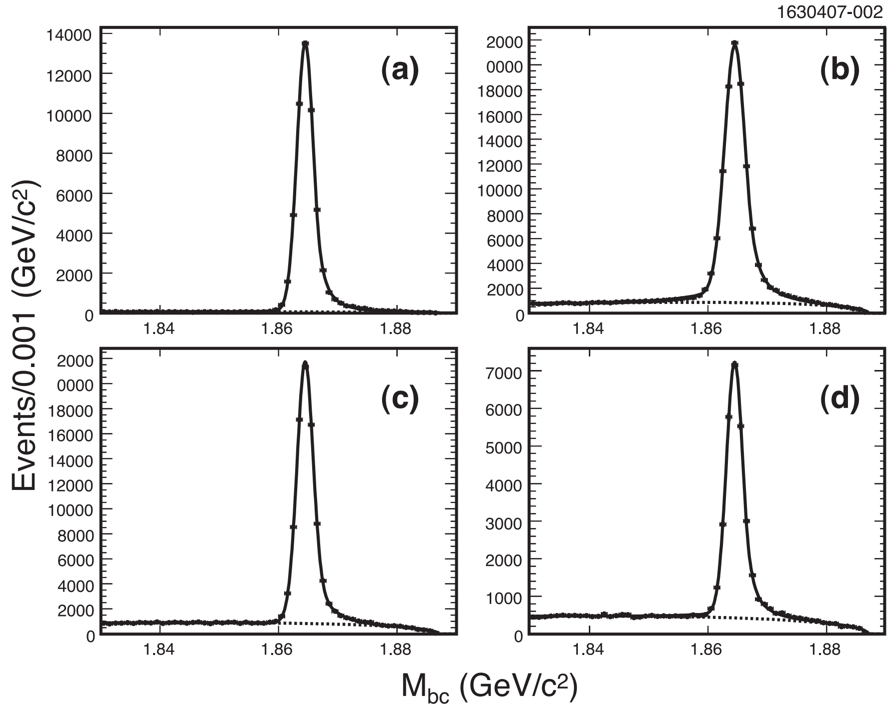

FIG. 1. $M_{\rm bc}$ spectra for (a) $\bar{D}^0 \to K^+\pi^-$, (b) $\bar{D}^0 \to K^+\pi^-\pi^0$, (c) $\bar{D}^0 \to K^+\pi^-\pi^+\pi^-$, (d) $\bar{D}^0 \to K_S^0\pi^+\pi^-$ candidate tags.

200 MeV$/c$, as the electron identification becomes increasingly difficult at low momenta. We also require $|\cos\theta| < 0.90$, where θ is the angle between the positron direction and the beam axis. The positron selection criteria are discussed in Ref. [2]. They have an average efficiency of 95% in the momentum region $[0.3 - 1.0]$ GeV$/c$, and 71% in the region [0.2–0.3] GeV$/c$. The hadron to e^+ misidentification probabilities are of the order of 0.1% over most of the momentum range and below 1% even in the regions where dE/dx separation is less effective. In addition, we search for a good track consistent with a K^- and two oppositely charged tracks consistent with pions. Hadron track identification criteria rely on dE/dx information from the drift chamber for tracks with $p <$ 0.7 GeV$/c$. For tracks with $p \geq 0.7$ GeV$/c$, in addition to dE/dx measurements, information from the RICH detector [8] is used to improve the K-π discrimination. In the momentum range relevant for this analysis the K-π misidentification probability is negligible. The probability of an electron being incorrectly identified as a π, determined experimentally with radiative Bhabhas, has an average value of 17% for electron momenta below 0.2 GeV$/c$, and is about 1% for higher momenta.

As the decay mode that we are investigating is rare, efficient background suppression is critical to achieve adequate sensitivity. Accordingly, we require that only four charged tracks be present in the event in addition to those used in the tag reconstruction. The dominant source of background in this analysis arises from events in which the detected positron comes from a γ conversion ($\gamma \to e^+e^-$), or a π^0 Dalitz decay ($\pi^0 \to e^+e^-\gamma$). This background is equally likely to produce (e^+K^-) combinations, which we call right-sign events (RS), and (e^-K^-) combinations, which we call wrong-sign events (WS). Typically, an e^+e^- pair arising from a conversion γ or a π^0 Dalitz decay has a strong angular correlation with almost collinear angular orientation of the two particles. For signal events, the opening angle between the $e^+\pi^-$ pair tends to be large. We therefore include a requirement that the opening angle be greater than 20°. This requirement eliminates most of the background from conversion γ's or π^0 Dalitz decays, while reducing the signal efficiency by only 1.7%.

In this semileptonic sample, signal candidate events are selected using the missing mass squared MM^2 defined as

$$\mathrm{MM}^2 = \left(E_{\rm beam} - \sum_{i=1}^{4} E_i\right)^2 \Big/ c^4 - \left(-\vec{p}_{\rm tag} - \sum_{i=1}^{4} \vec{p}_i\right)^2 \Big/ c^2, \quad (1)$$

where $\vec{p}_{\rm tag}$ is the momentum of the fully reconstructed tag, and $(E_i, \vec{p}_i)$ represent the energy and momentum of the four tracks in the D^0 candidate. For signal events the MM^2 distribution is centered at zero, as it represents the invariant mass squared of the missing ν_e. According to Monte Carlo simulation of our signal semileptonic channel, the MM^2 distribution has a resolution consistent among the tag modes with a standard deviation (σ) of 0.00594 ± 0.00010 (GeV$/c^2$)^2. Figure 2 shows the measured MM^2 distribution for RS events in the data as well as the estimated background, derived from GEANT-based

Monte Carlo simulation [13] in combination with particle misidentification probabilities derived from data. In addition, we estimate the background directly from the WS events in data. We define a signal window as $|MM^2| \leq 0.02$ $(GeV/c^2)^2$. There are 10 events in the signal window of MM^2 as shown in Fig. 2.

Another interesting observable is the invariant mass of the $K^- \pi^+ \pi^-$ hadron system. Figure 3 shows the invariant mass of the $K^- \pi^+ \pi^-$ system for RS candidate events, compared with the expectation from the ISGW2 model [1], which provides the best representation of our data, where the hadronic system forms the $K_1(1270)$ resonance. The measured distribution is in reasonable agreement with this model.

We have performed several studies to determine possible background sources. A Monte Carlo sample incorporating all the information available on D meson decays and 40 times bigger than our collected data demonstrates that the dominant background comes from conversion γ's or π^0 Dalitz decays. As the e to π misidentification probability may not be modeled accurately by our Monte Carlo simulation, the background from Dalitz decays is evaluated by folding the e spectra from simulated $D^0 \to K^- \pi^+ \pi^0$ decays with the e to π misidentification probability derived from a radiative Bhabha data sample. This study predicts that 1.56 ± 0.22 background events are due to this source if no requirement on the $K^- \pi^+ \pi^-$ invariant mass is applied. A study of the WS data gives one background event, in agreement with the previous estimate. In addition, there are small background components from the decays $D^0 \to K^- \pi^+ \pi^+ \pi^-$ (0.2 ± 0.1) and $D^0 \to K^- \pi^+ \pi^+ \pi^- \pi^0$ (0.1 ± 0.1), both estimated with Monte Carlo samples. We have also studied non-$D\bar{D}$ contributions at this center-of-mass energy, such as those from the continuum ($e^+ e^- \to q\bar{q}$, where q is a u, d, or s quark), radiative return production of $\psi(2S)$, and $e^+ e^- \to \tau^+ \tau^-$ processes, and we do not find any background from these sources. Summing up all background contributions, we find that 1.86 ± 0.25(stat) events are consistent with background. We have also studied this sample with a requirement on the invariant mass of the $K\pi\pi$ system optimized for the decay $D^0 \to K_1^-(1270) e^+ \nu_e$, using the variable $S/\sqrt{S+B}$, where S is the number of signal events predicted from Monte Carlo simulations and B is the number of estimated background events. For the optimal invariant mass interval, [1150–1500] MeV/c^2, we find 8 candidate events and an estimated background of $1.0^{+0.4}_{-0.3}$(stat) events, with no events in the WS sample.

The reconstruction efficiency depends on the invariant mass of the $K^- \pi^+ \pi^-$ system ($M_{\rm had}$). A larger fraction of the electron spectrum is below the momentum cut of 0.2 GeV/c for higher $M_{\rm had}$, and the spin and parity of the final hadronic state influence the electron spectrum shape as well. For example, the ISGW2 model studies all the P-wave $s\bar{u}$ and $d\bar{u}$ hadronic final states, as well as the corresponding radial excitations. Among the P-wave states, the ${}^{3/2}P_1$ are identified with the $K_1(1270)$, and ${}^{1/2}P_1$ are identified with the $K_1(1400)$. The latter has a much softer electron spectrum, and therefore our efficiency for detecting it is smaller. We have studied the signal reconstruction efficiency with the ISGW2 model, including different mixing percentages of the ${}^{3/2}P_1$ and ${}^{1/2}P_1$

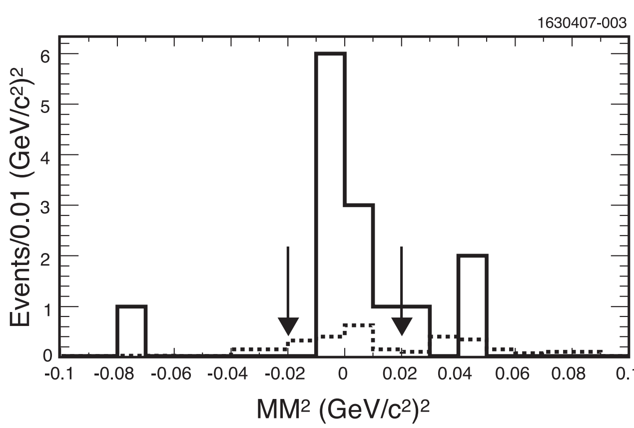

FIG. 2. Missing mass squared (MM^2) distribution for the RS sample $D^0 \to K^- \pi^+ \pi^- e^+ \nu_e$. The dashed histogram represents the estimated background. Events with MM^2 within the two arrows are considered signal candidates.

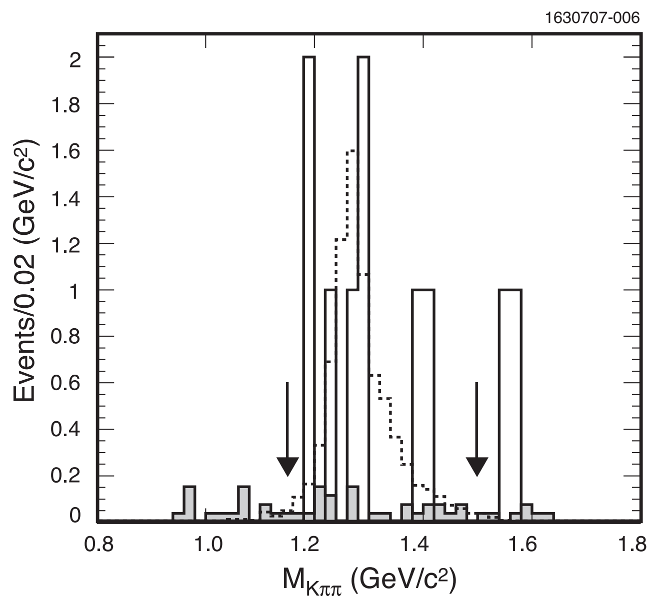

FIG. 3. Invariant mass of the hadronic system in the data for $D^0 \to K^- \pi^+ \pi^- e^+ \nu_e$. The dashed histogram represents the predicted distribution obtained using a Monte Carlo simulation according to the ISGW2 model, assuming all the $K^- \pi^+ \pi^-$ are $K_1(1270)$ decay products. The region within the two arrows defines the invariant mass range used to select the $K_1^-(1270)$ resonance. The shaded histogram represents the background estimate described in the text.

TABLE I. Systematic errors on $D^0 \to K^-\pi^+\pi^-e^+\nu_e$ branching fraction. The first column applies to the analysis without $K_1(1270)$ mass cut, the second to the analysis with the $K_1(1270)$ mass cut as described in the text.

	Systematic errors (%)	
Number of tags	0.5	0.5
Tracking	1.3	1.3
PID Efficiency (hadrons)	1.9	1.9
PID Efficiency (electrons)	1.0	1.0
Opening angle cut	1.5	1.5
$M_{K\pi\pi}$ cut	...	1.7
Model dependence	10.0	4.0
Background	5.3	5.3
Total	11.9	7.5

final states, as well as a phase space model for the distribution of the $M_{\rm had}$. With the Monte Carlo simulation based on the ISGW2 model, we obtain $\epsilon = (10.78 \pm 0.23)\%$ for the full $M_{\rm had}$ range and $\epsilon = (10.53 \pm 0.22)\%$ with the $K_1(1270)$ mass requirement ([1150–1500] MeV/c^2).

The absolute branching fraction for $D^0 \to K^-\pi^+\pi^-e^+\nu_e$ is obtained using $\mathcal{B} \equiv (N_s - N_b)/(\epsilon_{\rm eff}N_{\rm tag})$, where N_s is the number of signal events, N_b is the number of background events, $N_{\rm tag}$ is the number of tags, and $\epsilon_{\rm eff}$ is the effective efficiency for detecting the semileptonic decay in an event with an identified tag. This effective efficiency includes a correction term $C \equiv \epsilon^{\rm sl}_{\rm tag}/\epsilon_{\rm tag}$ accounting for the small difference in tag reconstruction efficiency in events containing the semileptonic signal and in generic $D\bar{D}$ events. The average value of C is 1.036. We obtain $\mathcal{B}(D^0 \to K^-\pi^+\pi^-e^+\nu_e) = (2.8^{+1.4}_{-1.1} \pm 0.3) \times 10^{-4}$, without applying any invariant mass requirement. If we apply the $K_1(1270)$ invariant mass requirement, we obtain $\mathcal{B}(D^0 \to K_1^-(1270)e^+\nu_e) \times \mathcal{B}(K_1^-(1270) \to K^-\pi^+\pi^-) = (2.5^{+1.3}_{-1.0} \pm 0.2) \times 10^{-4}$. The smaller systematic uncertainty is derived by the fact that the model dependence can simply be estimated by varying the form factors in the ISGW2 model. In this case we do not need to model a broader invariant mass distribution for the $K^-\pi^+\pi^-$ system. Note that the probability for 1.86 background events to fluctuate to 10 or more events, taking into account a 0.25 event Gaussian uncertainty, is 4.1×10^{-5}, corresponding to a significance of about 4.0σ. The result with the $K^-\pi^+\pi^-$ mass requirement has similar statistical significance.

The systematic uncertainties for the branching fractions are listed in Table I and are quoted as relative to the measured branching fraction. The uncertainty on the tag yield is estimated from varying the background functions. Systematic uncertainties on track finding and hadron particle identification efficiencies are reported in Ref. [10], while electron identification efficiency is reported in Ref. [3]. The sensitivity to the requirement on the $e^+\pi^-$ opening angle has been evaluated by repeating the analysis after changing the requirement by $\pm 5°$. The model dependence of the efficiency is studied using an alternative invariant mass distribution for the hadronic system governed by phase space. In the analysis where we apply a mass requirement on the $K^-\pi^+\pi^-$ system, the model dependence of the efficiency is estimated by varying the form factors in the ISGW2 model, and the corresponding uncertainty is found to be 4%. The background uncertainty is derived by changing the measured fake probabilities within their errors.

In summary, we have presented the first measurement of the absolute branching fraction $\mathcal{B}(D^0 \to K^-\pi^+\pi^-e^+\nu_e) = [2.8^{+1.4}_{-1.1}(\text{stat}) \pm 0.3(\text{syst})] \times 10^{-4}$. The invariant mass of the hadronic system recoiling against the $e^+\nu_e$ pair is consistent with $K_1^-(1270)$. By requiring $M_{\rm had}$ to be within the [1150–1500] MeV/c^2 mass window, we obtain the product branching fraction $\mathcal{B}(D^0 \to K_1^-(1270)e^+\nu_e) \times \mathcal{B}(K_1^-(1270) \to K^-\pi^+\pi^-) = [2.5^{+1.3}_{-1.0}\text{stat} \pm 0.2] \times 10^{-4}$. The statistical significance is about 4.0 standard deviations. We derive the branching fraction $\mathcal{B}(D^0 \to K_1^-(1270)e^+\nu_e)$, by summing the $K_1^-(1270)$ branching fractions of all the modes that decay to $K\pi\pi$ weighted with the probability that the final state is $K^-\pi^+\pi^-$. By using the branching fractions reported by the PDG [14], we obtain $\mathcal{B}(K_1^-(1270) \to K^-\pi^+\pi^-) = (33 \pm 3)\%$ and $\mathcal{B}[D^0 \to K_1^-(1270)e^+\nu_e] = [7.6^{+4.1}_{-3.0}(\text{stat}) \pm 0.6(\text{syst}) \pm 0.7] \times 10^{-4}$. The last error accounts for the uncertainties in the measured $K_1^-(1270)$ branching fractions. This channel is found to be 1.2% of the total semileptonic width. The ISGW [4] model predicts this fraction to be about 1%, while the ISGW2 model [1] predicts this fraction to be about 2%; hence the measured branching fraction and $K^-\pi^+\pi^-$ invariant mass are consistent with quark model calculations.

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