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Observation of Excited Charmed Mesons

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Using the Tagged Photon Spectrometer and a high-energy photon beam, we have searched for excited states of charm in Fermilab experiment E691. We have found evidence for a state of mass 2459 ± 3 (stat.) ± 2 (syst.) MeV/c^2 and width $20 \pm 10 \pm 5$ MeV/c^2 which decays to $D^+\pi^-$. The fraction of D^+ coming from $D^{**0}(2459)$ is $0.07 \pm 0.02 \pm 0.02$. We also confirm the $D^{**0}(2420) \to D^{*+}\pi^-$ decay observed previously in e^+e^- experiments and present evidence for its charged counterpart.

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While the S-wave charmed mesons, the D, $D^*(2010)$, D_s, and $D_s^*(2110)$, are well established, it has proved more difficult to detect charm states with $L > 0$. There should be four $L = 1$ states (the D^{**} states) have spin-parities (J^P) of 0^+, 1^+, 1^+, and 2^+. Many models have been put forward predicting the masses and widths of these states.[1] The mass values give information on the spin structure of the quark-antiquark potential at relatively long distances. The 2^+ can decay to both $D^*\pi$ and $D\pi$ while, because of spin-parity constraints, the 1^+ states can only decay to $D^*\pi$ and the 0^+ to $D\pi$. Although the predicted mass for the 2^+ varies from 2.3 to 2.5 GeV/c^2, all the models contend that the 2^+ is at least 100 MeV/c^2 more massive than the 0^+. Hence, the $D\pi$ channel is attractive because the 2^+ should be well isolated. The ARGUS and CLEO Collaborations have previously reported on a candidate state at a mass of about 2420 MeV/c^2 decaying to $D^{*+}\pi^-$,[2-4] but, since its spin could not be unambiguously determined, this state could be the 2^+, either of the 1^+'s, or some combination of all three. In this paper we report on signals found in the $D^+\pi^-$, $D^{*+}\pi^-$, and $D^0\pi^+$ channels using the full data set from Fermilab experiment E691. (The charge-conjugate states are implicitly included throughout the paper.)

The D signals are culled from the $\sim 10^8$ events written to tape during experiment E691. The data were collected using a photon beam of mean energy 145 GeV and the Tagged Photon Spectrometer. The spectrometer has been described in detail elsewhere.[5] The elements of the spectrometer most relevant for this analysis are the 35 drift-chamber planes and two magnets for tracking and momentum resolution, the two threshold Čerenkov counters for particle identification, and the silicon-microstrip vertex detector for high-resolution tracking near the interaction point.

Our sample of D^{*+} decaying to $D^0\pi^+$ is used to search for the previously reported $D^{**0}(2420) \to D^{*+}\pi^-$ mode. The D^0 is observed in both the $K^-\pi^+$ and $K^-\pi^+\pi^+\pi^-$ channels. The criteria for selecting D and D^* signals have been described elsewhere.[5,6] The actual values of the cuts used in this paper were chosen so as to maximize $S/\sqrt{B}$, where S is the number of Monte Carlo–generated D^{**} events and B is the number of D^{**} background events (simulated using the wings of the data distributions). The cuts include limitations on the following: the minimum distance between a secondary charm vertex and the primary interaction vertex, how close any other track in the event comes to the charm vertex, how well the charm momentum vector points back to the primary vertex, and the certainty with which it is known that any track in the secondary vertex belongs only to that vertex. The final D^{*+} sample consists of 2908 ± 66 signal events (all quoted errors are statistical unless stated otherwise) over a background (within $\pm 2.5\sigma$ of the measured D^{*+}

mass) of about 460 events.

The D^{*+} candidates are then combined with each π^- in the same event. The pions are required to have passed through both magnets for good momentum resolution and to have been identified as pions using the Čerenkov information. In addition, the distance of closest approach of the π^- and D^0 momentum vectors is required to be less than 90 μm and the momentum of the $D^{*+}\pi^-$ state is required to be greater than 50 GeV/c. The resultant Δm plot [where $\Delta m = m(D^{*+}\pi^-) - m(D^{*+})$] is shown in Fig. 1 where there is a significant effect around Δm of 420 MeV/c^2. The distribution is fitted using a function consisting of a background term of the form $(\Delta m - m_\pi)^\alpha e^{-\beta \Delta m}$, and a signal term whose form is that of a Breit-Wigner form convoluted with a Gaussian resolution function. This background parametrization was found to describe well both the wrong-sign (i.e., $D^{*+}\pi^+$) distribution and the distribution using the wings of the D^0. The experimental resolution is found using the Monte Carlo data to be 8 MeV/c^2 (rms). We find 171^{+43}_{-58} events at a mass difference of 419 ± 8 MeV/c^2 and with a width of 58 ± 14 MeV/c^2. The χ^2 for the fit was 41.7 for 44 degrees of freedom and the statistical significance of the signal (as measured by the change in χ^2 when the signal amplitude is set to zero[7]) is 4 standard deviations. The mass is 2428 ± 8 MeV/c^2. Systematic errors of 5 MeV/c^2 in Δm and 10 MeV/c^2 in the width are estimated by observing the response of the signal to varied cuts and background shapes. The wrong-sign and D^0-wings distributions show no evidence of a similar enhancement.

The product of the efficiency for finding the π^- and the efficiencies of the distance-of-closest-approach and D^{**0}-momentum cuts is (45 ± 3)%. Using this and the numbers of D^{*+} and $D^{**0}(2420)$ events, we calculate the fraction of D^{*+} coming from $D^{**0}(2420)$ to be $0.13^{+0.03}_{-0.04}$(stat.) ± 0.02(syst.). The systematic error is dominated by the error in the background-shape estimation. The CLEO Collaboration found this ratio to be $0.12 \pm 0.04 \pm 0.03$ (Ref. 4) and the most recent value from the ARGUS Collaboration is $0.09^{+0.03}_{-0.02} \pm 0.03$.[3] Although the production mechanisms are different in photoproduction and e^+e^- annihilation, this ratio depends on the fragmentation of the high-energy charmed-quark jet and so it is perhaps not surprising that the ratios are essentially equal in this case.

The D^+ is observed through its decay to $K^-\pi^+\pi^+$. The cuts were again chosen to maximize $S/\sqrt{B}$ but now using the Monte Carlo-generated $D^{**} \rightarrow D^+\pi^-$ events to simulate the signal and the wings of the D^+ for the background. The resulting $K^-\pi^+\pi^+$ mass spectrum is shown in Fig. 2. There are 4135 ± 73 events in the peak over a background of approximately 740 events.

The D^+ candidates are then combined with each π^- in the same event. The pions are required to pass the same cuts as were used on the pions in the $D^{*+}\pi^-$ analysis except that there is no requirement on the momentum of the $D^+\pi^-$ state. The resulting $m(D^+\pi^-) - m(D^+)$ distribution is shown in Fig. 3 where there is a clear peak at a mass difference (Δm) of around 590 MeV/c^2. The "wrong-sign" distribution (i.e., $D^+\pi^+$) and that obtained using the wings of the D^+ show no evidence of a similar enhancement. The background function used in the fit to the Δm plot contains two elements: an exponential to describe phase space, and a broad peak around 420 MeV/c^2 due to $D^{**0}(2420) \rightarrow D^{*+}\pi^-$ events where the D^{*+} decays to a D^+ and either a π^0 or a photon which goes undetected. The magnitude of this second contribution can be inferred from D^{*+} branching ratios and the measured

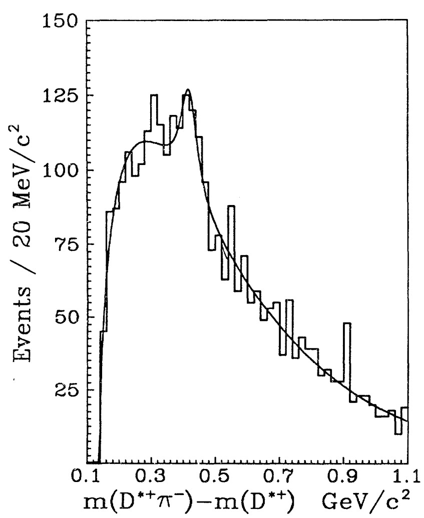

FIG. 1. The $m(D^{*+}\pi^-) - m(D^{*+})$ plot showing the fit for the $D^{**0}(2420)$.

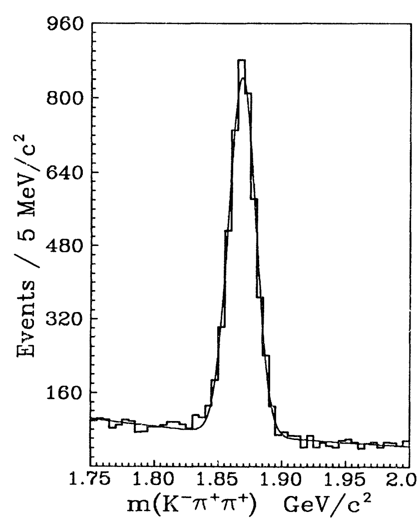

FIG. 2. The D^+ mass plot.

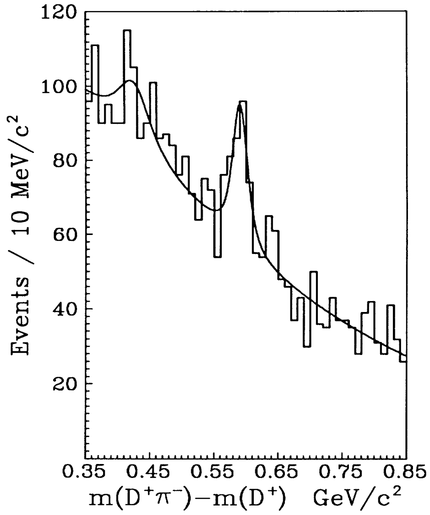

FIG. 3. The $m(D^+\pi^-)-m(D^+)$ plot showing the fit for the $D^{**0}(2459)$.

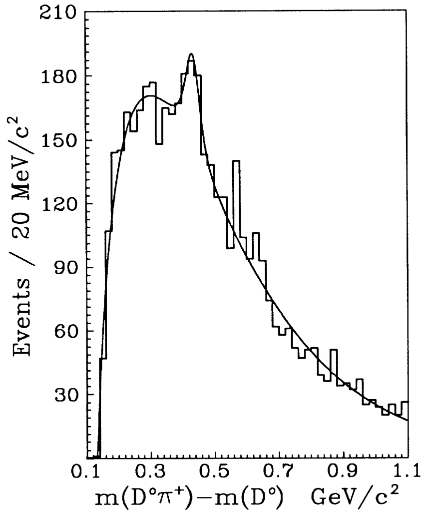

FIG. 4. The $m(D^0\pi^+)-m(D^0)$ plot showing the fit for the charged counterpart of the $D^{**0}(2420)$.

D^{**0}/D^{*+} production ratio. The signal is fitted with a Breit-Wigner form convoluted with a Gaussian resolution function. The resolution is found from the Monte Carlo data to be 6.5 MeV/c^2. This fit gives 153^{+42}_{-37} events at a Δm of 590.7 ± 3.2 MeV/c^2 and a width of 20^{+11}_{-8} MeV/c^2. The peak has a statistical significance of 5 standard deviations and the χ^2 for the fit is 41.6 for 45 degrees of freedom. The corresponding mass for this state is 2459 ± 3 MeV/c^2. The parameters are relatively insensitive to the amount of $D^{*+}\pi^-$ feedthrough put into the fit. By observing changes in the signal due to varying background shapes and cuts, we estimate that the systematic error in Δm is 2 MeV/c^2 and in the width is 5 MeV/c^2. The product of the efficiencies for finding the π^- and of the distance-of-closest-approach cut is $(56\pm3)\%$. Using this and the number of D^+ events, we find the fraction of D^+ coming from $D^{**0}(2459)$ to be $0.07\pm0.02(\text{stat.})\pm0.02(\text{syst.})$.

It is expected that the 2^+ will be the heaviest of the P-wave D mesons. Also, the other state which decays to $D^+\pi^-$, the 0^+, should be produced with a factor of 5 less cross section than the 2^+ due to spin multiplicity. While the fact that the state observed in the $D^+\pi^-$ spectrum is more massive than the $D^{*+}\pi^-$ state suggests that it might be the 2^+, there is no direct evidence for this. The statistics are also not good enough to measure the spin of the $D^{*+}\pi^-$ state from the angular distribution. Although the branching fractions for the 2^+ to decay to $D^+\pi^-$ and $D^{*+}\pi^-$ are not well predicted, the $D^+\pi^-$ mode is expected to dominate because of the larger Q value and the 2 units of angular momentum in the decay. The fraction of $D^{**0}(2420)$ events in the $D^+\pi^-$ spectrum is small, indicating that the $D^{**0}(2420)$ is not the 2^+. On the other hand, a substantial fraction of the $D^{**0}(2459)$ could be included in the tail of the peak at $\Delta m \sim 420$ MeV/c^2 in the $D^{*+}\pi^-$ spectrum.

To search for the charged counterparts of the $D^{**0}(2459)$ and the $D^{**0}(2420)$ we use D^0 candidates which were found not to come from a D^{*+} [i.e., did not survive the $m(D^0\pi^+)-m(D^0)$ cut]. The D^0 is again observed in both the $K^-\pi^+$ and the $K^-\pi^+\pi^+\pi^-$ channels. The invariant mass distribution combining both channels includes a signal of 4295 ± 81 events over a background of ~1550 events.

We estimate the size of the expected D^{**+} signals in the $D^0\pi^+$ spectrum as follows. Assuming the charged and neutral D^{**} states are produced equally, then isospin symmetry predicts that there should be equal numbers of $D^{**0}\rightarrow D^+\pi^-$ and $D^{**+}\rightarrow D^0\pi^+$ decays. However, the D^{*0} always decays to D^0 and a neutral (either a π^0 or a photon) while less than half of the D^{*+} decays are to D^++neutral.[8] A simple calculation using the D^*:D production rate (which we have measured[9] to be consistent with the expected value of 3:1) shows that about 80% of the reconstructed D^0 events come from D^* decays as opposed to 60% in the D^+ case. Therefore, a 5σ effect in the D^+D^- spectrum, combined with the fact that there is more background under the D^0 than under the D^+, leads one to expect about a 2σ effect in the $D^0\pi^+$ spectrum, with roughly half the number of signal events as in the $D^+\pi^-$ case. On the other hand, the feedthrough from $D^*\pi$ to $D\pi$ is expected to be greater in the $D^0\pi^+$ spectrum than in the $D^+\pi^-$ spectrum since more of the D^0 signal comes from D^* decays.

The D^0 candidates are combined with π^+'s in the same event that survived the same cuts as were used on the π^-'s in the $D^{*+}\pi^-$ analysis. The $m(D^0\pi^+)-m(D^0)$ plot is shown in Fig. 4 where there is no clear evidence for the charged counterpart of the $D^{**0}(2459)$.

However, there is a significant peak around a mass difference (Δm) of 430 MeV/c^2 due to $D^{**+} \to D^{*0}\pi^+$ decays (where the neutral from the $D^{*0} \to D^0 +$neutral decay goes undetected). The Δm spectrum is fitted with a function which consists of a background term of the form $(\Delta m - m_\pi)^\alpha e^{-\beta \Delta m}$ and a signal term which is a Breit-Wigner form convoluted with a Gaussian resolution function. The resolution for the signal was found using Monte Carlo data to be 12 MeV/c^2. This is wider than for the $D^{*+}\pi^-$ peak because the missing neutral tends to smear out the signal. We find 190^{+77}_{-44} events at a mass difference of 434 ± 7 MeV/c^2 and a width of 41 ± 19 MeV/c^2. The statistical significance of the signal is 4 standard deviations. The corresponding mass is 2443 ± 7 MeV/c^2 and the systematic errors are estimated to be 5 MeV/c^2 in the mass and 8 MeV/c^2 in the width. The number of $D^{**+}(2443)$ candidates is consistent with the observed D^{**0}/D^{*+} production ratio.

To summarize, we observe a 5σ effect in the $D^+\pi^-$ decay channel at a mass of 2459 ± 3(stat.)± 2(syst.) MeV/c^2 and with a width of $20 \pm 10 \pm 5$ MeV/c^2. The fraction of D^+ coming from $D^{**0}(2459)$ is $0.07 \pm 0.02 \pm 0.02$. We also see evidence for the $D^{**0}(2420)$ decaying to $D^{*+}\pi^-$ at a mass of $2428 \pm 8 \pm 5$ MeV/c^2 and a width of $58 \pm 14 \pm 10$ MeV/c^2. The fraction of D^{*+} coming from $D^{**0}(2420)$ is found to be $0.13^{+0.03}_{-0.04} \pm 0.02$. Finally, we observe evidence for the D^{**+} decaying to $D^{*0}\pi^+$ with a mass and width of $2443 \pm 7 \pm 5$ and $41 \pm 19 \pm 8$ MeV/c^2, respectively.

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