Study of P-Wave D Mesons

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Abstract

Using data from the CLEO II detector at the Cornell Electron Storage Ring, we have investigated properties of two $L = 1$ charmed mesons, $D_1(2420)^0$ and $D_2^*(2460)^0$. We observe the two mesons in the charmed continuum by studying $D^+\pi^-$ and $D^{*+}\pi^-$ final states. We reconstruct the $D_2^*(2460)^0$ in the two decay modes $D_2^{*0} \to D^{*+}\pi^-$ and $D_2^{*0} \to D^+\pi^-$ and measure the ratio of the two associated branching fractions. Previously, this ratio was very poorly known. We reconstruct the $D_1(2420)^0$ in the decay mode $D_1 \to D^{*+}\pi^-$. We obtain 2420 ± 1 MeV/c^2 and 29 ± 4 MeV/c^2 for the mass and width of $D_1(2420)^0$, respectively; and 2465 ± 2 MeV/c^2 and 38 ± 6 MeV/c^2 for the mass and width of the $D_2^*(2460)^0$, respectively. These results are preliminary and all errors are statistical only. We also obtain a value of $\mathcal{B}(D^+\pi^-)/\mathcal{B}(D^{*+}\pi^-) = 1.48 \pm 0.27 \pm 0.14$ for the ratio of the $D_2^*(2460)^0$ branching fractions; this value is consistent with the expectation from Heavy Quark Effective Theory. In this case the first error is the statistical error and the second is the systematic error due to the uncertainties in the D^{*+} and D branching fractions. Other systematic errors for these measurements have not yet been evaluated.

Introduction

The D^{**} mesons are composed of one charmed quark (Q) and one light quark ($\bar{q}$) with relative angular momentum $L = 1$. They are separated into four states with spin-parity $J^P = 0^+,\ 1^+,\ 1^+$, and 2^+. Three states, belonging to a triplet, carry total quark spin $S = 1$, while the remaining state, a singlet, carries $S = 0$. In spectroscopic notation, the four states are identified as:

$$^{2S+1}L_J = \begin{cases} ^3P_0, \quad ^3P_0, \quad ^3P_2 & \text{(triplet)} \\ ^1P_1 & \text{(singlet)} \end{cases}$$

The Particle Data Group [1] labels these states D_0^*, D_1, D_2^*, where the subscript is the spin J of the state. The D_2^* state is allowed to decay via $D_2^{*0} \to D^{*+}\pi^-$ or $D_2^{*0} \to D^+\pi^-$ through D-wave decays. On the other hand, $D_1^0 \to D^{*+}\pi^-$ is the only allowed decay mode for the D_1^0 states, although both S-wave and D-wave decays are allowed. The two D_1^0 states are expected to mix in such a manner that one mixed state decays essentially only via D waves and the other decays primarily via S waves. The D_1^0 state that decays via S waves and the D_0^{*0} state that also decays via S waves are expected to have very large widths and have not been observed. The observed [1] two narrow D^{**0} states are thought to be the D_2^{*0} and D_1^0 states that decay via D waves. These expectations were originally based on potential models, but are now understood to be consequences of Heavy Quark Effective Theory (HQET) [2, 3, 4, 5].

The helicity angle, α, is defined as the angle between the π^- from the decay $D^{**0} \rightarrow D^{*+}\pi^-$ and the π^+ from the decay $D^{*+} \rightarrow D^0\pi^+$, both measured in the D^{*+} rest frame. The predicted helicity angular distributions for the D^{**0} states are:

$$\frac{d\ N}{d\ \cos\alpha} \propto \begin{cases} \sin^2\alpha & (2^+ \text{ state}) \\ 1 & (\text{pure S-wave } 1^+ \text{ state}) \\ 1+3\cos^2\alpha & (\text{pure D-wave } 1^+ \text{ state}) \end{cases} \tag{1}$$

The two meson states have been observed by various groups, including ARGUS, CLEO 1.5, E687, and, most recently, by CLEO II [1].

Data Sample and Event Selection

The data used in this analysis were from hadronic events arising from e^+e^- annihilations at CESR and collected by the CLEO II detector. A detailed description of the detector is available elsewhere [6]. The center-of-mass energies for the data are at the mass of the $\Upsilon(4S)$, $E_{C.M.} = 10.580$ GeV, and in the nearby continuum. The data represent an integrated luminosity of 4.7 fb^{-1}, about 2.5 times that of the integrated luminosity of the data used in the last CLEO II analysis studying the same D^{**} states. Only hadronic events were selected, using the following criteria based on an earlier CLEO paper [7]: We required a minimum of 3 tracks, a total visible energy greater than 15% of the center-of-mass energy (to reduce contamination from two-photon events and beam-gas events), and a primary vertex within ± 2 cm in the $r-\phi$ plane and ± 5 cm in the z-direction of the nominal collision point. All tracks (pions and kaons) were required to come within ± 5 mm of the origin in $r-\phi$ and ± 5 cm in z. For particle identification, all tracks used were required to have ionization (dE/dx) information, and time-of-flight information was used when available.

$D_2^{*0} \rightarrow D^+\pi^-$

We first reconstructed the D^+ in the mode [8] $K^-\pi^+\pi^+$. The kaon decay angle θ_K, the angle between the direction of the D^+ momentum and the direction of the K^- momentum in the D^+ rest frame, was required to satisfy $\cos\theta_K < 0.8$ in order to reduce the background, since the signal distribution is expected to be flat, while the background peaks near 1. Each D^+ candidate is then combined with each π^- in the event. To reduce combinatorial background, we used the cut $x_p(D_2^{*0}) > 0.6051$, where

$$x_p(D_2^{*0}) = p(D_2^{*0}/p_{max}) \tag{2}$$

and

$$p_{max} = \sqrt{E_{beam}^2 - M(D_2^{*0})^2}. \tag{3}$$

We found that the distribution of decay angle $\cos\theta_\pi$, where θ_π is the angle between the direction of the D_2^{*0} momentum and the direction of the π^- momentum in the D_2^{*0} rest frame, has a significant peak at $\cos\theta_\pi = 1$. This peak results from combinations of the D^+ with the many slow π^- tracks in an event. We accordingly made a cut of $\cos\theta_\pi > -0.8387$ to reduce this background contribution. A cut of $|M(K^-\pi^+\pi^+) - 1869.4\ \text{MeV}/c^2| \leq 0.029\ \text{MeV}/c^2$ (about a 2σ cut) is also imposed on the reconstructed D^+ mass to purify the sample. A total probability, P_{tot}, of the candidate using the particle identification (dE/dx and time-of-flight) and the reconstructed D^+ mass was calculated. $P_{tot}(\chi^2_{tot}, N_{dof})$ is defined to be the probability of observing $\chi^2 > \chi^2_{tot}$ for N_{dof} degrees of freedom. Since there is a small D^+ signal-to-background ratio, the data sample is highly contaminated, resulting in a large and broad peak at $P_{tot} = 0$ in the P_{tot} distribution. The signal distribution is expected to be flat. Therefore, we impose a cut of $P_{tot} > 0.4055$ to purify the sample.

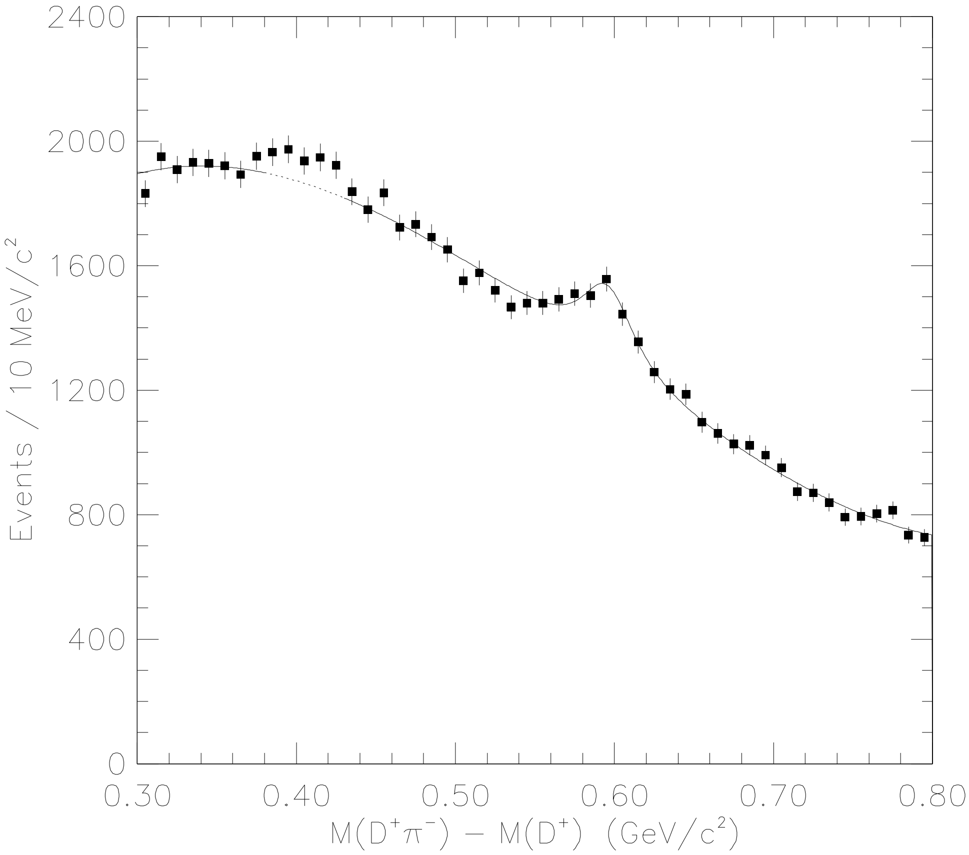

FIGURE 1. The $M(D^+\pi^-) - M(D^+)$ mass-difference distribution for $x_p(D_2^{*0}) > 0.6051$, $\cos\theta_\pi > -0.8387$, and $P_{tot} > 0.4055$.

The $M(D^+\pi^-) - M(D^+)$ mass-difference distribution for all $D^+\pi^-$ combinations that survived the above cuts is shown in Fig. 1. The spectrum was fitted using a third-order Chebychev polynomial for the background and a Breit-Wigner resonance shape convoluted with a Gaussian resolution function for the signal. We fix the σ of the Gaussian resolution function to 4.0 MeV/c^2, as determined from Monte Carlo studies. The region from 380 to 430 MeV/c^2 is excluded from the fit; we expect feed-down in this region from the decays $D^{**0} \to D^{*+}\pi^-$ with the subsequent decay $D^{*+} \to D^+\pi^0$ or $D^+\gamma$, where the neutrals have not been reconstructed in the decay chain. We obtained 1548 ± 224 signal events with a value $M(D^+\pi^-) - M(D^+) = 596 \pm 2$ MeV/c^2, corresponding to a D_2^{*0} mass of 2465 ± 2 MeV/c^2 and an intrinsic width $\Gamma = 38 \pm 6$ MeV/c^2. The systematic error has not been included in these values. Our measurements of the mass and width of this state, along with previous measurements, are listed in Table 1.

TABLE 1. $D_2^*(2460)^0$ mass and width

Experiment	Mass (MeV/c^2)	Width (MeV/c^2)
CLEO II	2465 ± 2	38 ± 6
CLEO II	$2465 \pm 3 \pm 3$	28^{+8+6}_{-7-6}
CLEO 1.5	$2461 \pm 3 \pm 1$	20^{+9+9}_{-12-10}
ARGUS	$2455 \pm 3 \pm 5$	15^{+13+5}_{-10-10}
E691	$2459 \pm 3 \pm 2$	$20 \pm 10 \pm 5$
E687	$2453 \pm 3 \pm 2$	$25 \pm 10 \pm 5$

$D^{**0} \to D^{*+}\pi^-$

We first reconstructed D^0's in the decay modes $K^-\pi^+$ and $K^-\pi^+\pi^+\pi^-$. We made a purifying cut on the reconstructed mass of $|M(K^-\pi^+(\pi^+\pi^-)) - 1864.6\ \mathrm{MeV}/c^2| \leq 18\ \mathrm{MeV}/c^2$ (about a 2σ cut). Each D^0 candidate is then combined with each remaining π^+ in the event to reconstruct the D^{*+} candidates. A purifying cut of $|[M(D^0\pi+) - M(D^0)] - 145.42\ \mathrm{MeV}/c^2| \leq 1.62\ \mathrm{MeV}/c^2$ was made on the mass-difference (about a 2σ cut). Finally, each D^{*+} candidate is combined with each remaining π^- in the event to reconstruct D^{**0} candidates. A cut of $x_p(D^{**0}) > 0.58$ is imposed in order to reduce combinatorial background. After studying the distribution of $\cos\theta_\pi$, where θ_π is the angle between the direction of the π^- momentum and the direction of the D^{**0} momentum in the D^{**0} rest frame, we found a large peak at $\cos\theta_\pi = -1$, which results from random combinations of the D^+ and a slow π^-. Therefore, a cut of $\cos\theta_\pi > -0.66$ was imposed in order to reduce this background. A P_{tot} was calculated for the D^{**0} candidate by using the particle identification (dE/dx and time-of-flight), the D^0 mass, the π^0 mass, and the mass-difference $M(D^{*+}) - M(D^0)$. We made a cut of $P_{tot} > 0.095$ to purify the data sample.

We can use the expected helicity angular distributions to separate the two D^{**0} states. We made a cut of $|\cos\alpha| > 0.75$ in order to suppress the D_2^{*0} signal and improve the signal-to-background ratio for the D_1^0 state. The $M(D^{*+}\pi^-) - M(D^{*+})$ mass-difference spectrum for all combinations that survive the above cuts is shown in Fig. 2. The prominent peak is from the D_1^0 state, while the higher-mass D_2^{*0} peak has been virtually completely suppressed. We fitted the distribution with a fourth-order Chebychev polynomial for the background and two Breit-Wigner resonance shapes convoluted with Gaussian resolution functions for the signals. The σ's of these resolution functions were fixed to 4.0 MeV/c^2, as determined from Monte Carlo studies. We also fix the mass and width of the higher-mass convoluted Breit-Wigner to the values obtained from analysis of the decay $D_2^{*0} \to D^+\pi^-$; the parameters of the other convoluted Breit-Wigner were allowed to float free. We obtained 52 ± 53 signal events for the D_2^{*0} state. For the D_1^0 state, we obtained 837 ± 60 signal events, $M(D_1^0\pi-) - M(D^{*+}) = 410 \pm 1\ \mathrm{MeV}/c^2$, and $\Gamma = 29 \pm 4\ \mathrm{MeV}/c^2$. The mass-difference corresponds to a D_1^0 mass of $2420 \pm 1\ \mathrm{MeV}/c^2$. No systematic errors have been included in these results. Our measurements of the mass and width of this state, along with previous measurements, are listed in Table 2.

TABLE 2. $D_1(2420)^0$ mass and width

Experiment	Mass (MeV/c^2)	Width (MeV/c^2)
CLEO II	2420 ± 1	29 ± 4
CLEO II	2421^{+1+2}_{-2-2}	20^{+6+3}_{-5-3}
CLEO 1.5	$2428 \pm 3 \pm 2$	23^{+8+10}_{-6-4}
ARGUS	$2414 \pm 2 \pm 5$	13^{+6+10}_{-6-5}
E691	$2459 \pm 8 \pm 5$	$58 \pm 14 \pm 10$
E687	$2453 \pm 2 \pm 2$	$15 \pm 8 \pm 4$

The $M(D^{*+}\pi^-) - M(D^{*+})$ mass-difference spectrum with no helicity angle cut is shown in Fig. 3. A fit to the spectrum yielded $M(D_1^0\pi^-) - M(D^{*+}) = 412 \pm 1$ MeV/c^2, and $\Gamma = 29 \pm 3$ MeV/c^2 (with no systematic errors included), in excellent agreement with those obtained above.

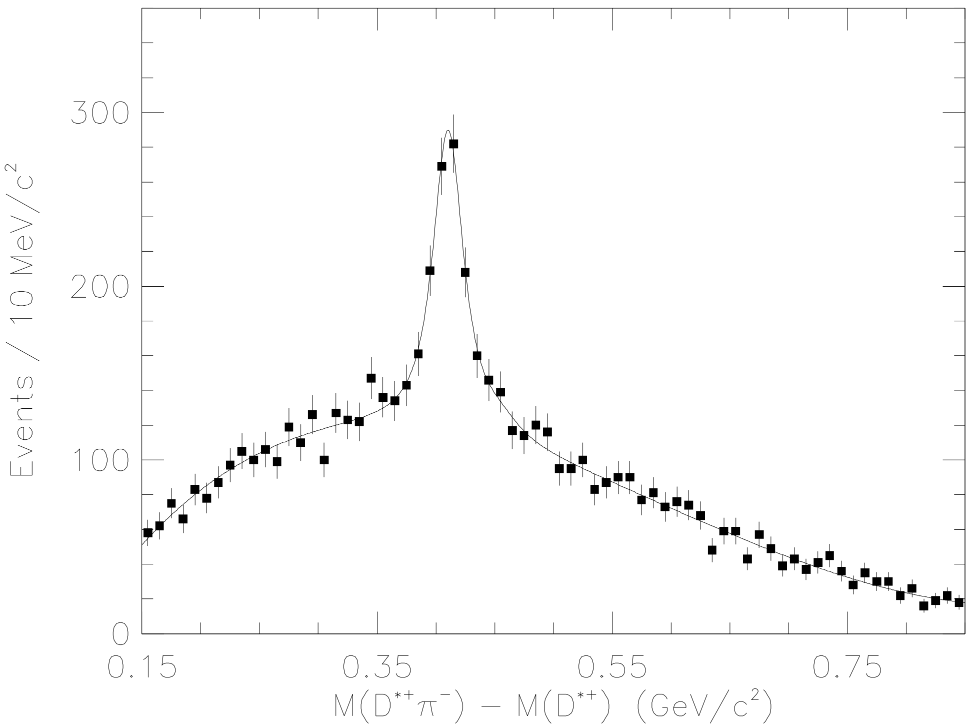

FIGURE 2. The $M(D^{*+}\pi-) - M(D^{*+})$ mass-difference distribution for $|\cos\alpha| > 0.75$.

Ratio of Branching Fractions for D_2^{*0}

For the decay $D^{**0} \rightarrow D^{*+}\pi^-$, we made a helicity angle cut of $|\cos\alpha| < 0.645$, in addition to the other cuts outlined in the previous section, in order to suppress the D_1^0 state and improve the signal-to-background ratio for the D_2^{*0} state. The $M(D^{*+}\pi-) - M(D^{*+})$ mass-difference spectrum for all combinations that survive the above cuts is shown in Fig. 4. We again fitted the spectrum with a fourth-order Chebychev polynomial for the background

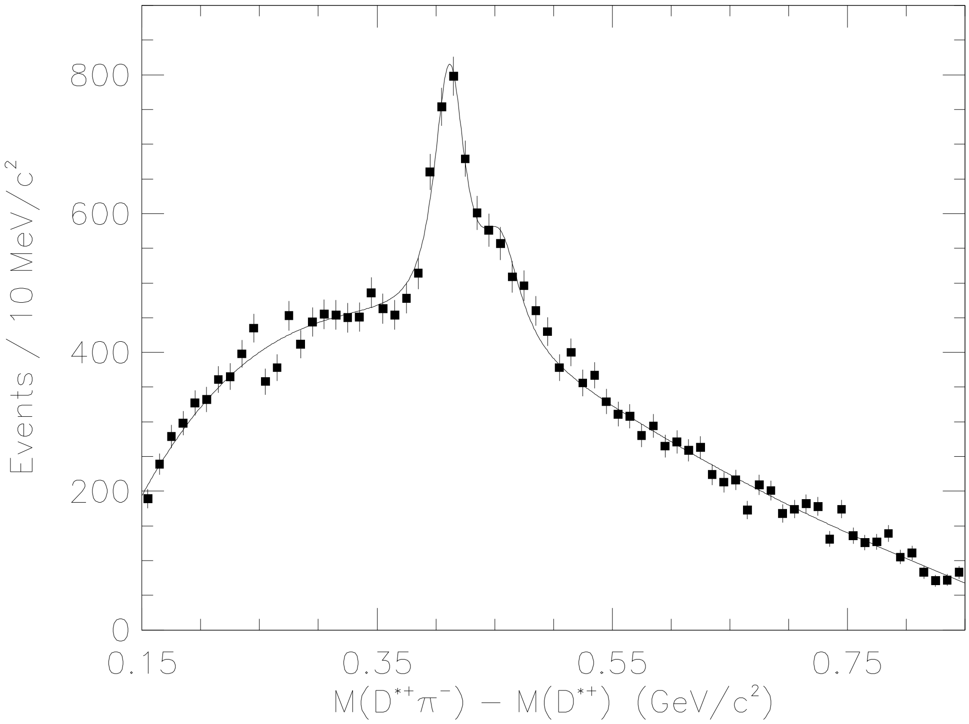

FIGURE 3. The $M(D^{*+}\pi-) - M(D^{*+})$ mass-difference distribution for $-1 \leq \cos\alpha\ \leq +1$.

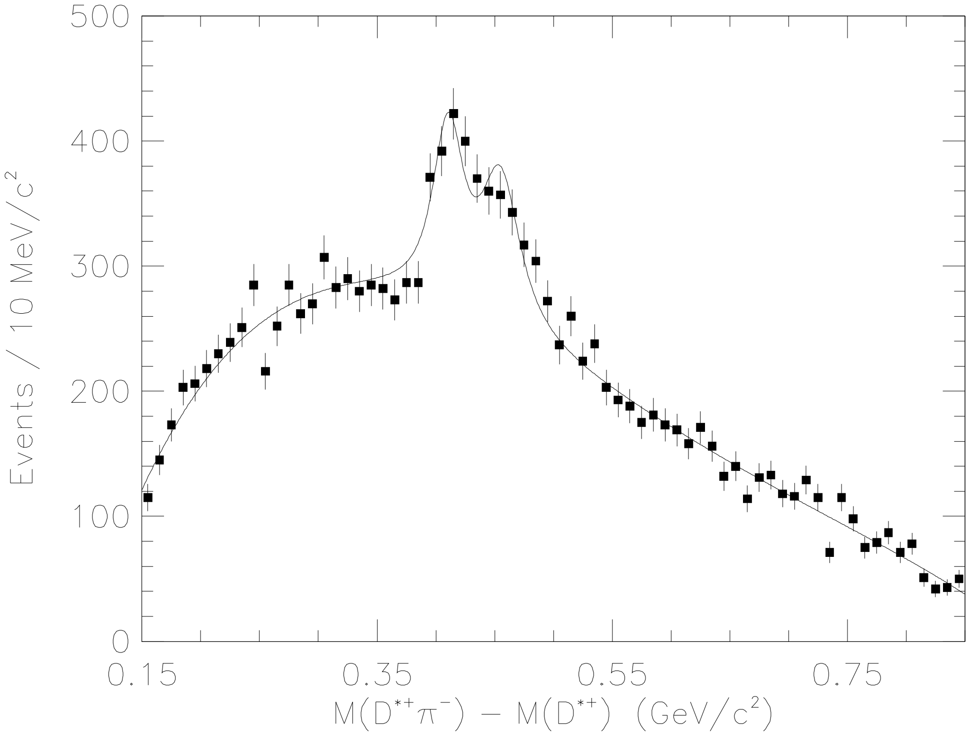

FIGURE 4. The $M(D^{*+}\pi-) - M(D^{*+})$ mass-difference distribution for $|\cos\alpha| < 0.645$

and two Breit-Wigner resonance shapes convoluted with Gaussian resolution functions for the signals. The σ's of the resolution functions are fixed to the same values as before. We constrained the parameters of the lower-mass convoluted Breit-Wigner to the ones obtained above from the analysis of the decay $D_1^0 \to D^{*+}\pi^-$. We allowed the parameters of the other convoluted Breit-Wigner to float free. This fit yielded 742 ± 75 signal events for the D_2^{*0} state in the decay mode $D_1^0 \to D^{*+}\pi^-$. We obtained 1548 ± 224 signal events above for the D_2^{*0} state in the decay mode $D_2^{*0} \to D^+\pi^-$. Using Monte Carlo studies, we calculated efficiencies for the cuts associated with the two values for the number of signal events above. Thus, we were able to calculate the ratio of the branching fractions, $B[D_2^*(2460)^0 \to D^+\pi^-]/B[D_2^*(2460)^0 \to D^{*+}\pi^-]$, for the D_2^{*0} state associated with the two decay modes studied in this analysis. We determined the ratio to be

$$\frac{B(D_2^*(2460)^0 \to D^+\pi^-)}{B(D_2^*(2460)^0 \to D^{*+}\pi^-)} = 1.48 \pm 0.27 \pm 0.14. \tag{4}$$

ARGUS [9], CLEO 1.5 [10], and CLEO II [11] have measured this ratio to be $3.0 \pm 1.1 \pm 1.5$, 2.3 ± 0.8, and $2.2 \pm 0.7 \pm 0.6$, respectively . Our new result agrees with the predictions of Heavy Quark Effective Theory (HQET) [2, 3], which lie approximately in the range 1.5 to 2.3 for the D_2^{*0} state.

Conclusions

We have obtained preliminary new values of the masses and widths of the two p-wave charmed mesons, $D_1(2420)^0$ and $D_2^*(2460)^0$, based on the entire CLEO II data sample. We have measured the masses of the $D_1(2420)^0$ and $D_2^*(2460)^0$, to be 2420 ± 1 MeV/c^2 and 2465 ± 2 MeV/c^2, respectively. We have measured the widths of $D_1(2420)^0$ and $D_2^*(2460)^0$ to be 29 ± 4 MeV/c^2 and 38 ± 6 MeV/c^2, respectively. We have also determined the ratio of the branching fractions of the two decay modes of $D_2^*(2460)^0$ to be, $B(D_2^*(2460)^0 \to D^+\pi^-)/B(D_2^*(2460)^0 \to D^{*+}\pi^-) = 1.48 \pm 0.27 \pm 0.14$, a value consistent with the predictions of HQET [2, 3, 4, 5]. Systematic errors have not been evaluated for these preliminary results and the errors quoted are statistical only, except that the second error on the ratio of the branching fractions is the contribution from the uncertainties in the underlying D and D^* decay branching fractions.

Acknowledgments

I would like to thank Prof. David Cassel of Cornell University, who proposed this Research Experience for Undergraduates project and has so kindly and generously given his time and shared his wealth of knowledge with me. This project would not have been possible without his help. I would also like to thank Mr. Naresh Menon of Purdue University, who never tired of my constant barrage of questions and offered tremendous assistance in my Monte Carlo studies. This work was supported by National Science Foundation grant PHY-9310764 and NSF REU grant PHY-9731882.

Footnotes and References

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