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Charmed Hadron Physics at *BABAR*

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We present a study of the $D^+\pi^-$, $D^0\pi^+$, and $D^{*+}\pi^-$ systems in inclusive $e^+e^- \to c\bar{c}$ interactions in a search for new excited D meson states. We use a dataset, consisting of $\sim$454 fb^{-1}, collected at center-of-mass energies near 10.58 GeV by the *BABAR* detector at the SLAC PEP-II asymmetric-energy collider. We observe, for the first time, candidates for the radial excitations of the D^0, D^{*0}, and D^{*+}, as well as the $L = 2$ excited states of the D^0 and D^+, where L is the orbital angular momentum of the quarks.

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1. Introduction

The spectrum of mesons consisting of a charm and an up or a down quark is poorly known. The spectrum of quark-antiquark systems was predicted in 1985 using a relativistic chromodynamic potential model [1]. Besides the ground states (D, D^*), only two L=1 states, known as the $D_1(2420)$ and $D_2^*(2460)$ [2], are well-established experimentally since they have relatively narrow widths ($\sim$30 MeV). To search for states not yet observed, we analyze the *inclusive* production of the $D^+\pi^-$, $D^0\pi^+$, and $D^{*+}\pi^-$ [3] final states in the reaction $e^+e^- \to c\overline{c} \to D^{(*)}\pi X$, where X is any additional system. We use an event sample consisting of approximately 590 million $e^+e^- \to c\overline{c}$ events (454 fb^{-1}) produced at e^+e^- center-of-mass (CM) energies near 10.58 GeV and collected with the *BABAR* detector at the SLAC PEP-II asymmetric-energy collider. Our signal yield for the $L = 1$ resonances is more than ten times larger than the best previous study [4], resulting in much greater sensitivity to higher resonances.

2. Event Reconstruction

The *BABAR* detector is described in detail in Ref. [5]. Charged-particle momenta are measured with a 5-layer, double-sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) inside a 1.5-T superconducting solenoidal magnet. A calorimeter consisting of 6580 CsI(Tl) crystals is used to measure electromagnetic energy. A ring-imaging Cherenkov radiation detector (DIRC), aided by measurements of ionization energy loss, dE/dx, in the SVT and DCH, is used for particle identification (PID) of charged hadrons.

The $D\pi$ system is reconstructed in the $D^+\pi^-$ and $D^0\pi^+$ modes, where $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+$. For all channels we perform a vertex fit for the D^+ and D^0 daughters. To improve the signal to background ratio for $D^+ \to K^-\pi^+\pi^+$, we require that the measured flight distance of the D^+ candidate from the e^+e^- interaction region be greater than 5 times its uncertainty. To improve the signal purity for $D^0 \to K^-\pi^+$ we require $\cos\theta_K > -0.9$ where θ_K is the angle formed by the K^- in the D^0 candidate rest frame with respect to the prior direction of the D^0 candidate in the CM reference frame. The $D\pi$ candidates for both D^+ and D^0 are then reconstructed by performing a vertex fit with an additional charged *primary* pion, which originates from the e^+e^- interaction region. In the $D^0\pi^+$ sample, we veto D^0 candidates from D^{*+} or D^{*0} decays.

The $D^{*+}\pi^-$ system is reconstructed using the $D^0 \to K^-\pi^+$ and $D^0 \to K^-\pi^+\pi^-\pi^+$ decay modes. A D^0 candidate is accepted if its invariant mass is within 30 MeV/c^2 of the mean value. A D^{*+} candidate is reconstructed by requiring an additional slow pion (π_s^+) originating from the e^+e^- interaction region. We select a D^{*+} candidate if the mass difference $\Delta m = m(K^-\pi^+(\pi^+\pi^-)\pi_s^+) - m(K^-\pi^+(\pi^+\pi^-))$ is within 2.0 MeV/c^2 of the mean value. Finally, we reconstruct a $D^{*+}\pi^-$ candidate by combining a D^{*+} candidate with an additional charged track identified as a π^- and applying a vertex fit.

Background from $e^+e^- \to B\overline{B}$ events, and much of the combinatorial background, are removed by requiring the CM momentum of the $D^{(*)}\pi$ system to be greater than 3.0 GeV/c. In addition, we remove fake primary pion candidates originating mainly from the opposite side of the event by requiring $\cos\theta_\pi > -0.8$. The angle θ_π is defined in the $D^{(*)}\pi$ rest frame as the angle between the primary pion direction and the prior direction of the $D^{(*)}\pi$ system in the CM frame.

3. The $D^+\pi^-$ and $D^0\pi^+$ Mass Spectra

To extract the resonance parameters we define the variables $M(D^+\pi^-) = m(K^-\pi^+\pi^+\pi^-) - m(K^-\pi^+\pi^+) + m_{D^+}$ and $M(D^0\pi^+) = m(K^-\pi^+\pi^+) - m(K^-\pi^+) + m_{D^0}$, where m_{D^+} and m_{D^0} are the values of the D^+ and D^0 mass [2]. We remove the contribution due to fake D^+ and D^0 candidates by subtracting the $M(D\pi)$ distributions obtained by selecting events in the D^+ or D^0 candidate mass sidebands.

The $D^+\pi^-$ and $D^0\pi^+$ mass spectra are presented in Fig. 1 (left and middle) and show similar features.

- Prominent peaks for $D_2^*(2460)^0$ and $D_2^*(2460)^+$.
- The $D^+\pi^-$ mass spectrum shows a peaking background (feeddown) at about 2.3 GeV/c^2 due to decays from the $D_1(2420)^0$ and $D_2^*(2460)^0$ to $D^{*+}\pi^-$. The D^{*+} in these events decays to $D^+\pi^0$ and the π^0 is missing in the reconstruction. The missing π^0 has very low momentum because the D^{*+} decay is very close to threshold. Therefore, these decays have a mass resolution of only 5.8 MeV/c^2 and a bias of -143.2 MeV/c^2. Similarly, $D^0\pi^+$ shows peaking backgrounds due to the decays of the $D_1(2420)^+$ and $D_2^*(2460)^+$ to $D^{*0}\pi^+$ where the D^{*0} decays to $D^0\pi^0$.
- Both $D^+\pi^-$ and $D^0\pi^+$ mass distributions show new structures around 2.6 and 2.75 GeV/c^2. We call these enhancements $D^*(2600)$ and $D^*(2760)$.

We have compared these mass spectra with those obtained from generic $e^+e^- \to \bar{c}c$ Monte Carlo (MC) events. In addition, we study $D\pi$ mass spectra from the D^+ and D^0 candidate mass sidebands, as well as mass spectra for wrong-sign $D^+\pi^+$ and $D^0\pi^-$ samples. We find no backgrounds or reflections that can cause the structures at 2.6 and 2.76 GeV/c^2.

The smooth background is modeled using the function:

$$B(x) = P(x) \times \begin{cases} e^{c_1 x + c_2 x^2} & \text{for } x \le x_0, \\ e^{d_0 + d_1 x + d_2 x^2} & \text{for } x > x_0, \end{cases} \tag{3.1}$$

where $P(x) \equiv \frac{1}{2x}\sqrt{[x^2 - (m_D + m_\pi)^2][x^2 - (m_D - m_\pi)^2]}$ is a two-body phase-space factor and $x = M(D\pi)$. Only four parameters are free in the piece-wise exponential: c_1, c_2, d_2, and x_0. The parameters d_0 and d_1 are fixed by requiring that $B(x)$ be continuous and differentiable at the transition point x_0.

The $D_2^*(2460)$ is modeled using a relativistic BW function with the appropriate Blatt-Weisskopf centrifugal barrier factor [2]. The $D^*(2600)$ and $D^*(2760)$ are modeled with relativistic BW functions [2]. Finally, although not visible in the $M(D^+\pi^-)$ mass distribution, we include a BW function to account for the known resonance $D_0^*(2400)$, which is expected to decay to this final state. This resonance is very broad and is present together with the feeddown and $D_2^*(2460)^0$; therefore we restrict its mass and width parameters to be within 2σ of the known values [6]. The results of this fit are shown in Table 1.

The fit to the $D^0\pi^+$ mass spectrum is similar to that described for the $D^+\pi^-$ system. Because the feeddown is larger and the statistical precision of the resonances is not as good as for $D^+\pi^-$, we

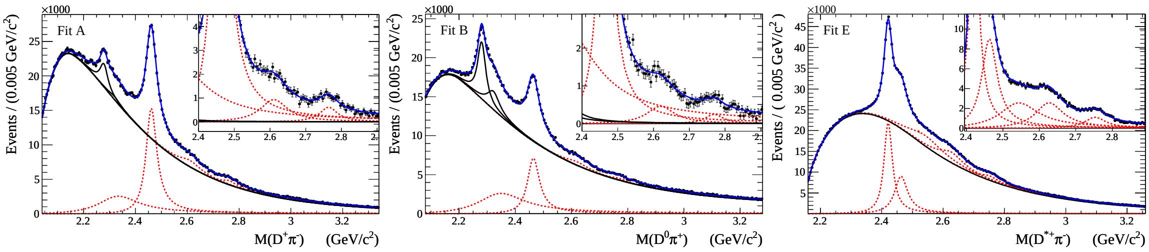

Figure 1: Mass distribution for $D^+\pi^-$, $D^0\pi^+$, and $D^{*+}\pi^-$ candidates. Points correspond to data, with the total fit overlaid as a solid curve. The lower solid curve is the background, and the dotted curves are the signal components. The inset plots show the distributions after subtraction of the combinatoric background.

fix the width parameters of all resonances to the values determined from $D^+\pi^-$ assuming isospin symmetry.

4. The $D^{*+}\pi^-$ Mass Spectrum

We now search for these new states in the $D^{*+}\pi^-$ decay mode. We define the variable $M(D^{*+}\pi^-) = m(K^-\pi^+(\pi^+\pi^-)\pi_s^+\pi^-) - m(K^-\pi^+(\pi^+\pi^-)\pi_s^+) + m_{D^{*+}}$ where $m_{D^{*+}}$ is the value of the D^{*+} mass [2]. The $D^{*+}\pi^-$ mass distribution is shown in Fig. 1 (right) and shows the following features.

- Prominent $D_1(2420)^0$ and $D_2^*(2460)^0$ peaks.
- Two additional enhancements at $\sim$2.60 GeV/c^2 and $\sim$2.75 GeV/c^2, which we initially denote as $D^*(2600)^0$ and $D(2750)^0$.

Studies of the generic MC simulation as well as studies of the D^{*+} sidebands and the wrong-sign sample ($D^{*+}\pi^+$) show no peaking backgrounds in this mass spectrum.

We fit $M(D^{*+}\pi^-)$ by parametrizing the background with the function in Eq. (3.1). The $D_1(2420)^0$ and $D_2^*(2460)^0$ resonances are modeled using relativistic BW functions with appropriate Blatt-Weisskopf form factors. The $D^*(2600)^0$ and $D(2750)^0$ are modeled with relativistic BW functions.

We define the *helicity* angle θ_H as the angle between the primary pion π^- and the slow pion π^+ from the D^{*+} decay in the rest frame of the D^{*+}. The signal yields as a function of θ_H depend on the spin-parity quantum numbers of the resonance. Initially, we have attempted to fit the $M(D^{*+}\pi^-)$ distribution incorporating only two new signals at $\sim$2.6 GeV/c^2 and at $\sim$2.75 GeV/c^2. However, when we extract the yields as a function of $\cos\theta_H$ we find that the mean value of the peak at $\sim$2.6 GeV/c^2 increases by $\sim$70 MeV/c^2 between $\cos\theta_H = -1$ and $\cos\theta_H = 0$, and decreases again as $\cos\theta_H \to +1$. This behaviour suggests two resonances with different helicity-angle distributions are present in this mass region. To proceed we incorporate a new component, which we call $D(2550)^0$, into our model at $\sim$2.55 GeV/c^2, the parameters of the $D(2550)^0$ are obtained from a fit where we require $|\cos\theta_H| > 0.75$. The final fit to the total $D^{*+}\pi^-$ sample is shown in Fig. 1 (right).

Table 1: Summary of the results. The first error is statistical and the second is systematic; "fixed" indicates the parameters were fixed to the values from $D^+\pi^-$.

Resonance	Channel	Yield (x10^3)	Mass (MeV/c^2)	Width (MeV)
$D(2550)^0$	$D^{*+}\pi^-$	98.4±8.2±38	2539.4±4.5±6.8	130±12±13
$D^*(2600)^0$	$D^+\pi^-$	26.0±1.4± 6.6	2608.7±2.4±2.5	93±6±13
	$D^{*+}\pi^-$	71.4±1.7±7.3	2608.7(fixed)	93(fixed)
$D(2750)^0$	$D^{*+}\pi^-$	23.5±2.1±5.2	2752.4±1.7±2.7	71±6±11
$D^*(2760)^0$	$D^+\pi^-$	11.3±0.8±1.0	2763.3±2.3±2.3	60.9±5.1±3.6
$D^*(2600)^+$	$D^0\pi^+$	13.0±1.3±4.5	2621.3±3.7±4.2	93(fixed)
$D^*(2760)^+$	$D^0\pi^+$	5.7±0.7±1.5	2769.7±3.8±1.5	60.9(fixed)

5. Conclusions

In summary, we have analyzed the inclusive production of the $D^+\pi^-$, $D^0\pi^+$, and $D^{*+}\pi^-$ systems in search of new D meson resonances using 454 fb^{-1} of data collected by the *BABAR* experiment. We observe for the first time four signals, which we denote $D(2550)^0$, $D^*(2600)^0$, $D(2750)^0$, and $D^*(2760)^0$. We also observe the isospin partners $D^*(2600)^+$ and $D^*(2760)^+$. The $D(2550)^0$ and $D^*(2600)^0$ have mass values and $\cos\theta_H$ distributions that are consistent with the predicted radial excitations $D_0^1(2S)$ and $D_1^3(2S)$. The $D^*(2760)^0$ signal observed in $D^+\pi^-$ is very close in mass to the $D(2750)^0$ signal observed in $D^{*+}\pi^-$; however, their mass and width values differ by 2.6σ and 1.5σ, respectively. Four $L=2$ states are predicted to lie in this region [1], but only two are expected to decay to $D^+\pi^-$. This may explain the observed features.

References

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