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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.

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 $e^+e^- \to c\bar{c} \to D^{(*)}\pi X$, where X is any additional system. We use an event sample consisting of approximately 590 million $e^+e^- \to c\bar{c}$ 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 $e^+e^- \to B\bar{B}$ 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

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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:

$$B(x) = P(x) \times \begin{cases} e^{c_1 x + c_2 x^2} & \text{for } x \le x_0, \\ e^{d_0 + d_1 x + d_2 x^2} & \text{for } x > x_0, \end{cases} \tag{1}$$

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 I.

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 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.

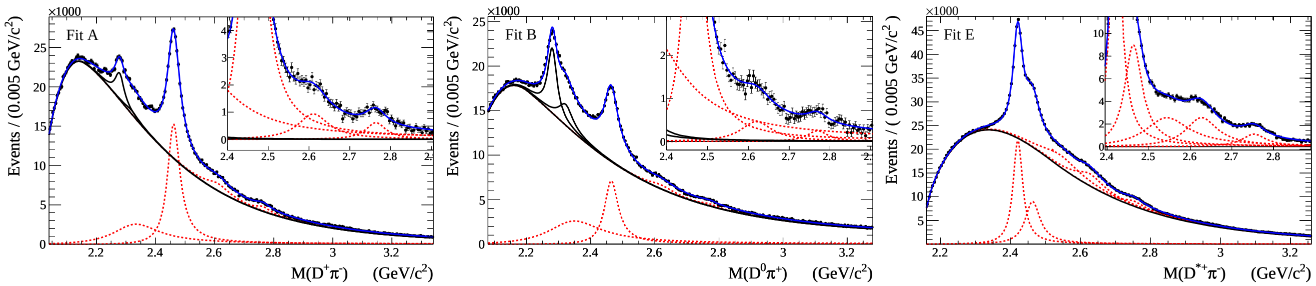

Figure 1: Mass distribution for $D^+\pi^-$, $D^0\pi^+$, and $D^{*+}\pi^-$ candidates. Points correspond to data, with the total fit overlaid as a solid curve. The lower solid curve is the background, and the dotted curves are the signal components. The inset plots show the distributions after subtraction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

- 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. (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).

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

Table I: 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)

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 $D^1_0(2S)$ and $D^3_1(2S)$. 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.

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