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Charm Spectroscopy from B Factories

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A brief review of the excited D_s and D mesons is presented. A precision measurement of the $D_{s1}(2536)$ mass and width parameters is reported by *BABAR*. Finally, a recent *BABAR* study of the $D\pi$ and $D^*\pi$ final states shows first observations of 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 bound states consisting of a charm quark and a light u, d, or s quark have been predicted since 1985 using a relativistic chromodynamic potential model [1], but many of the bound states predicted using this technique still remain unobserved. The B factories have collected samples of events containing charm mesons which are orders of magnitude larger that previous experiments and this has allowed for the first observation of excited states both in the D and D_s sectors.

Within the B factory experiments, the interest on charm meson spectroscopy was sparked by the *BABAR* discovery of the $D_s(2317)$ decaying into $D_s\pi^0$ in 2003[2]. Several studies by both *BABAR* and *BELLE* followed which tried to understand this unexpectedly narrow state [3]. Later studies by *BABAR* and *BELLE* led to the observation of more charm-strange excited states decaying to the DK and D^*K final states [4, 5]. While the $D_s(2317)$ is likely to be the spin-0 state of the $L = 1$ group, the enhancements observed in DK and D^*K are likely due to the $L = 2$ states and the radial excitations. The $D_{s1}(2536)$ is a state which was discovered since 1989, but its width remained unknown due to its low value which made it hard to deconvolve from the detector resolution. A first measurement of the width performed by *BABAR*[6] is presented below.

In the excited D meson sector (c-u or c-d systems) there have also been recent advancements. Previously, only the $L = 1$ states had been observed. Two, the $D_1(2420)$ and $D_2^*(2460)$, were well established since they have relatively narrow widths, while the others, the $D_0^*(2400)$ and $D_1'(2430)$, have been hard to study because of their very large widths of order 300 MeV [8, 9]. Recently, *BABAR* has released an analysis of the $D\pi$ and $D^*\pi$ final states which shows first observations of the $L = 2$ and radial excitations [10], the results are presented below.

2. Precision measurement of the $D_{s1}(2536)^+$ mass and width

The measurement of the $D_{s1}(2536)^+$ mass and width parameters is based on a data sample of 384 fb^{-1} collected by *BABAR* [6]. The $D_{s1}(2536)^+$ is reconstructed inclusively via its decay to $D^{*+}K_S$ with $K_S \to \pi^+\pi^-$ and $D^{*+} \to D^0\pi^+$ in reactions of the kind $e^+e^- \to c\bar{c} \to D^{*+}K_SX$, where X is any additional system. The D^0 is reconstructed using two high yield modes: $D^0 \to K^-\pi^+$ ($K4\pi$) and $D^0 \to K^-\pi^+\pi^-\pi^+$ ($K6\pi$). The total signal yield consists of about 8000 events which is about 40 times larger than previous studies. In order to determine the D_{s1}^+ mass and width parameters the variable $\Delta m(D_{s1}^+)$ = m(D_{s1}^+) - m(D^{*+}) - m(K_S) is defined. The reconstructed data samples are shown in Fig. 1. The detector resolution has been studied in this variable using dedicated monte carlo (MC) samples and is found to have a half-width-at-half max (HWHM) of about 0.55 MeV. The signal samples have been fit using a Breit-Wigner (BW) function (written in terms of the mass difference $\Delta m(D_{s1}^+)_0$) convolved with a function which parametrizes the detector resolution. The backgrounds in $\Delta m(D_{s1}^+)$ are parametrized using a linear function. The results of the fit, shown in Fig. 1, are

$$\Delta m(D_{s1}^+)_0 = (27.23 \pm 0.02 \pm 0.03) MeV/c^2 (K4\pi),$$
$$\Delta m(D_{s1}^+)_0 = (27.21 \pm 0.02 \pm 0.04) MeV/c^2 (K6\pi).$$

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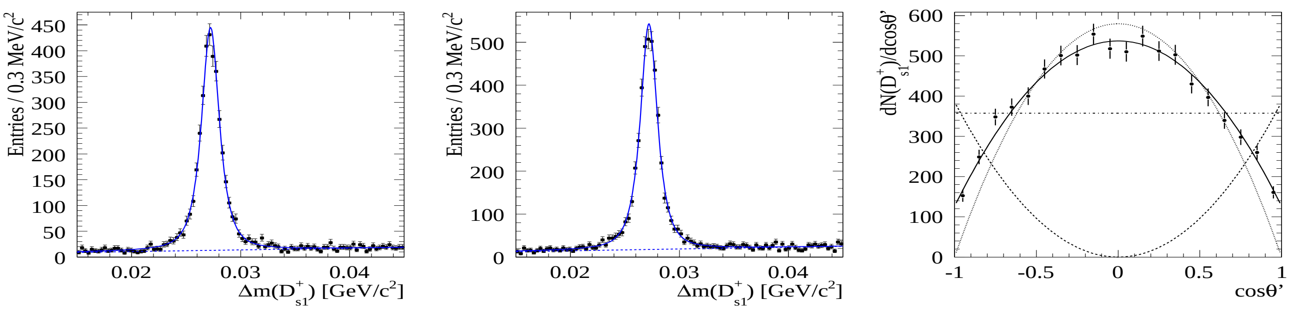

Figure 1: Fit of a relativistic Breit-Wigner convolved with the resolution function to the D^+_{s1} candidate spectra in data for the $K4\pi$ (left) and $K6\pi$ (middle) sample. The dotted line shows the background. The distribution of signal yield as a function of $\cos(\theta')$ (right) is fit using three models: $\sin^2(\theta') + s\cos^2(\theta')$ (solid line), $\cos^2(\theta')$ (dash-dotted curve), and $\sin^2(\theta')$ (dotted curve).

Combining these results, and adding the nominal D^{*+} and K_S masses [7], the final value for the D^+_{s1} mass is $m(D^+_{s1}) = (2535.08 \pm 0.01 \pm 0.15) MeV/c^2$. For the decay width, the measured values are

$$\Gamma(D^+_{s1}) = (0.95 \pm 0.05 \pm 0.05) MeV (K4\pi),$$
$$\Gamma(D^+_{s1}) = (0.89 \pm 0.05 \pm 0.05) MeV (K6\pi),$$

Combining the two values gives $\Gamma(D^+_{s1}) = (0.92 \pm 0.03 \pm 0.04) MeV$ as the total decay width of the D^+_{s1}.

In addition a study of the angular distribution has been performed as a test of the spin-parity quantum numbers $J^P = 1^+$ which are assigned to this state. The signal yield is determined as a function of the angle θ' defined as the angle between D^0 and K_S in the rest frame of the D^{*+}. The signal yield for the combined samples is shown in Fig. 1 (right). This distribution is consistent with un-natural spin-parity ($J^P = 1^+, 2^-, 3^+, ...$) and rules out natural spin-parity ($J^P = 1^-, 2^+, 3^-, ...$) as well as 0^-.

3. Study of the inclusive production of $D\pi$ and $D^*\pi$ final states

A study of the inclusive $D^+\pi^-$, $D^0\pi^+$, and $D^{*+}\pi^-$ mass spectra was performed by *BABAR* using 454 fb^{-1} [10]. The final states are reconstructed from reactions of the kind $e^+e^- \to c\bar{c} \to D^{(*)}\pi X$, where X is any additional system. In the $D^+\pi^-$ final state the D^+ was reconstructed using the $D^+ \to K^-\pi^+\pi^+$ mode and in the $D^0\pi^+$ final state the $D^0 \to K^-\pi^+$ mode was used. For $D^{*+}\pi^-$ the D^{*+} was reconstructed via $D^{*+} \to D^0\pi^+$ and using the two high yield D^0 decay modes: $D^0 \to K^-\pi^+$ and $D^0 \to K^-\pi^+\pi^-\pi^+$. After the full event selection the D^+, D^0, D^{*+} purities were approximately 65%, 83%, and 89%, respectively.

In order to measure the resonance parameters the following variables were defined: $M(D^+\pi^-) = m(K^-\pi^+\pi^+\pi^-) - m(K^-\pi^+\pi^+) + m_{D^+}$, $M(D^0\pi^+) = m(K^-\pi^+\pi^+) - m(K^-\pi^+) + m_{D^0}$, and $M(D^{*+}\pi^-) = m(K^-\pi^+(\pi^+\pi^-)\pi^+_s\pi^-) - m(K^-\pi^+(\pi^+\pi^-)\pi^+_s) + m_{D^{*+}}$, where m_{D^+}, m_{D^0}, and $m_{D^{*+}}$ are the nominal mass values [7]. The detector resolution using these variables is about 3 MeV/c^2. The mass spectra for the three samples are shown in Fig. 2.

The signal yield obtained for the known $L = 1$ resonances ($D_1(2420)$ and $D_2^*(2460)$) is about 10 times larger than previous experiments. In addition to the known resonances two new enhancements are observed in the higher mass region. In $D^+\pi^-$ and $D^0\pi^+$ these enhancements are labeled $D^*(2600)$ and $D^*(2760)$. These new signals are modeled using relativistic BW functions corrected for efficiency shape and convolved with a function which parametrizes the detector resolution.

In $D^{*+}\pi^-$ the region at about 2.6 GeV/c^2 has been analyzed as a function the helicity angle θ_H defined in the rest frame of the D^{*+} as the angle between the slow pion from the D^{*+} decay and the primary pion. The dependence of this enhancement as a function of $\cos\theta_H$ indicates the presence of two resonances $D(2550)$ and $D^*(2600)$. The parameters of the $D(2550)$ are determined under the assumption that the $D^*(2600)$ is the same signal previously

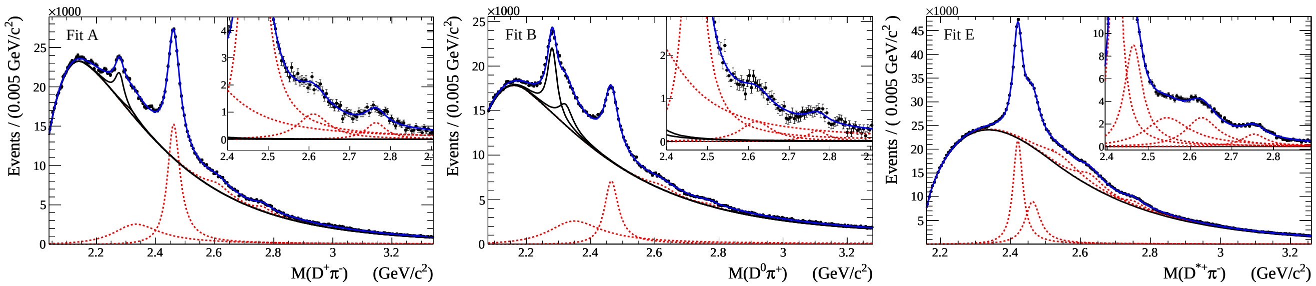

Figure 2: Mass distribution for $D^+\pi^-$, $D^0\pi^+$, and $D^{*+}\pi^-$ candidates. Points correspond to data, with the total fit overlaid as a solid curve. The lower solid curve is the background, and the dotted curves are the signal components. The inset plots show the distributions after subtraction of the combinatorial background.

observed in $D^+\pi^-$ so that its parameters are fixed. The additional enhancement at about 2.75 GeV/c^2 is labeled as $D(2750)$ and has parameters which are different from those of the $D^*(2760)$ in $D^+\pi^-$.

The backgrounds in these final states are mainly combinatorial arising from the additional pions created during the fragmentation processes at the high energy of the collider. In addition, in the $D^+\pi^-$ and $D^0\pi^+$ final states there are peaking backgrounds arsing from the $D_1(2420)$ and $D_2^*(2460)$ decaying to $D^*\pi$ where the slow pion from the D^* decay is missing. The combinatorial background is modeled using an exponential function modified by a threshold factor, the peaking backgrounds are modeled using BW functions corrected by the resolution and bias. The fits are shown in Fig. 2 and the parameters determined for the new signals are listed in Table I.

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)

In addition an angular analysis has been performed to investigate the spin-parity quantum numbers of the resonances. A fit is performed in bins of $\cos\theta_H$ and the signal yields are extracted for each resonance as shown in Fig. 3. The angular distributions obtained for the known resonances are consistent with their assigned quantum numbers of 2^+ for the $D_2^*(2460)$ and 1^+ for the $D_1(2420)$. For the $D(2550)$ the angular distribution is consistent with a 0^- state while for the $D^*(2600)$ the angular distribution is consistent with a 1^- state. The distribution for the $D(2750)$ is inconclusive. These properties together with theoretical expectations indicate that the $D(2550)$ and the $D^*(2600)$ are likely the radial excitations of the D meson while the $D(2750)$ and $D^*(2760)$ may be due to the $L = 2$ states.

4. Conclusions

As a result of the large data samples collected at B factories we have observed several advancements in the understanding of the charm meson spectrum during the last few years. Several new excited states in both the D_s and D sectors have been discovered. These states are generally in qualitative agreement with the old predictions by

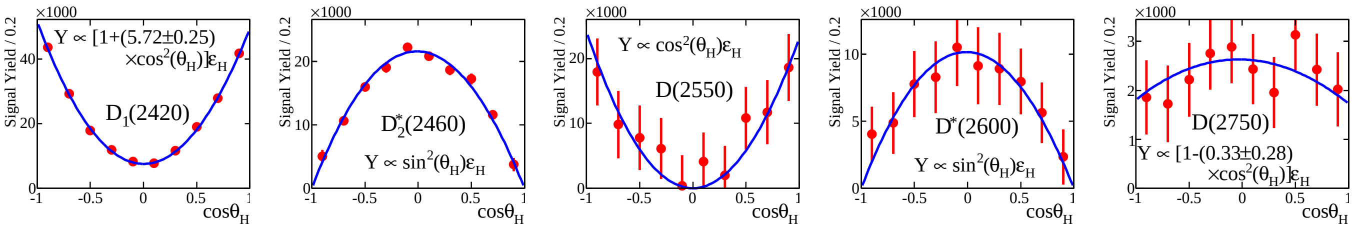

Figure 3: Distribution in $\cos\theta_H$ for each signal in $D^{*+}\pi^-$. The error bars include statistical and correlated systematic uncertainties. The curve is a fit using the function Y shown in the plot; ε_H is the efficiency as a function of $\cos\theta_H$.

Godfrey and Isgur [1], but suffer from significant quantitative differences. This note reports a first time measurement of the D_{s1}^+ width and the observation of new excited D mesons decaying to $D\pi$ and $D^*\pi$.

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