Charm Meson Spectroscopy at *BABAR* and CLEO-c

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In this mini-review we report on the most recent progress in charm meson spectroscopy. We discuss the precision measurements performed by the *BABAR* and CLEO-c experiments in the non strange charm meson part and we present the newly discovered strange charmed meson excited states.

1. Introduction

During the last few years many new D, D_s, charmonium, and charmed baryon excited states have been discovered. Some of these states were not expected theoretically; their masses, widths, quantum numbers, and decay modes did not fit the existing spectroscopic classification, which was based mostly on potential model calculations. The theoretical models had to be improved and new approaches have been developed to explain the data; the possibility of a non-quark-antiquark interpretation of these states has also been widely discussed. Charmonium, and charmed baryon excited states results are discussed elsewhere in these proceedings. In this report an overview of recent results on non strange charm mesons production is presented. Then, recent results on excited D_{sJ} meson production will be presented and their behavior will be discussed.

2. Non Strange Charm Mesons

2.1. Measurement of the Absolute Branching Fractions $B \to D\pi, D^*\pi, D^{**}\pi$ with a Missing Mass Method

Our understanding of hadronic B-meson decays has improved considerably during the past few years with the development of models based on the Heavy Quark Effective Theory (HQET), where collinear [1, 2] or k_T [3, 4] factorization theorems are considered. Models such as the QCD-improved Factorization (QCDF) [5, 6] and the Soft Collinear Effective Theory (SCET) [1, 7] use the collinear factorization, while the perturbative QCD (pQCD) approach [8, 9] uses the k_T factorization. In these models the amplitude of the $B \to D^{(*)}\pi$ two-body decay carries information about the difference δ between the strong-interaction phases of the two isospin amplitudes $A_{1/2}$ and $A_{3/2}$ that contribute [10, 11]. A non-zero value of δ provides a measure of the departure from the heavy-quark limit and the importance of the final-state interactions in the $D^{(*)}\pi$ system. With the measurements by the *BABAR* [12] and BELLE [13] experiments of the color-suppressed B decay $\overline{B}^0 \to D^{(*)0}\pi^0$

providing evidence for a sizeable value of δ, an improved measurement of the color-favored decay amplitudes ($B^- \to D^{(*)0}\pi^-$ and $\overline{B}^0 \to D^{(*)+}\pi^-$) is of renewed interest. In addition, the study of B decays into D, D^*, and D^{**} mesons will allow tests of the spin symmetry [14–17] imbedded in HQET and of non-factorizable corrections [18] that have been assumed to be negligible in the case of the excited states D^{**} [19].

A measurement of the branching fractions is presented for the decays $B^- \to D^0 \pi^-$, $D^{*0} \pi^-$, $D^{**0}\pi^-$ and $\overline{B}^0 \to D^+ \pi^-$, $D^{*+} \pi^-$, $D^{**+}\pi^-$ [20] with a missing mass method, based on a sample of 231 million $\Upsilon(4S) \to B\overline{B}$ pairs collected by the *BABAR* detector at the PEP-II e^+e^- collider. One of the B mesons is fully reconstructed and the other one decays to a reconstructed π and a companion charmed meson identified by its recoil mass, inferred by the kinematics of the two body B decay. This method, compared to the previous exclusive measurements [21], does not imply that the $\Upsilon(4S)$ decays into B^+ and B^0 with equal rates, nor rely on the D, D^*, or D^{**} decay branching fractions. The number of fully reconstructed B mesons $B_{\mathrm{rec'd}}$ is extracted from a fit to its mass distribution. In the decay $\Upsilon(4S) \to B_{\mathrm{rec'd}}\overline{B}_{\mathrm{X}\pi}$ where $\overline{B}_{\mathrm{X}\pi}$ is the recoiling $\overline{B}$ which decays into π^-X, the invariant mass of the X system is derived from the missing 4-momentum p_X applying the energy-momentum conservation:

$$p_X = p_{\Upsilon(4S)} - p_{B_{\mathrm{rec'd}}} - p_{\pi^-}.$$

The 4-momentum of the $\Upsilon(4S)$, $p_{\Upsilon(4S)}$, is computed from the beam energies and p_π and $p_{B_{\mathrm{rec'd}}}$ are the measured 4-momenta of the pion and of the reconstructed $B_{\mathrm{rec'd}}$, respectively. The $B_{\mathrm{rec'd}}$ energy is constrained by the beam energies. The $\overline{B} \to D\pi^-$, $\overline{B} \to D^*\pi^-$, or $\overline{B} \to D^{**}\pi^-$ signal yields peak at the D, D^*, and D^{**} masses in the missing mass spectrum, respectively. The signal yield of the different modes, is extracted from the missing mass spectra. The $D\pi$ and $D^*\pi$ signal yields are extracted by a χ^2 fit to the background subtracted missing mass distribution in the range $1.65 - 2.20$ GeV/c^2. The D^{**} yield is obtained by counting the candidates in excess in the missing mass range $2.2 - 2.8$ GeV/c^2. This range is chosen in order to keep most of the excess and no

further assumption on D^{**} resonance composition is made. The following branching fractions [22] are measured:

$$\mathcal{B}(B^- \to D^0\pi^-) = (4.49 \pm 0.21 \pm 0.23) \times 10^{-3}$$
$$\mathcal{B}(B^- \to D^{*0}\pi^-) = (5.13 \pm 0.22 \pm 0.28) \times 10^{-3}$$
$$\mathcal{B}(B^- \to D^{**0}\pi^-) = (5.50 \pm 0.52 \pm 1.04) \times 10^{-3}$$
$$\mathcal{B}(\overline{B}^0 \to D^+\pi^-) = (3.03 \pm 0.23 \pm 0.23) \times 10^{-3}$$
$$\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-) = (2.99 \pm 0.23 \pm 0.24) \times 10^{-3}$$
$$\mathcal{B}(\overline{B}^0 \to D^{**+}\pi^-) = (2.34 \pm 0.65 \pm 0.88) \times 10^{-3}$$

and the branching ratios:

$$\mathcal{B}(B^- \to D^{*0}\pi^-)/\mathcal{B}(B^- \to D^0\pi^-) = 1.14 \pm 0.07 \pm 0.04$$
$$\mathcal{B}(B^- \to D^{**0}\pi^-)/\mathcal{B}(B^- \to D^0\pi^-) = 1.22 \pm 0.13 \pm 0.23$$
$$\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-)/\mathcal{B}(\overline{B}^0 \to D^+\pi^-) = 0.99 \pm 0.11 \pm 0.08$$
$$\mathcal{B}(\overline{B}^0 \to D^{**+}\pi^-)/\mathcal{B}(\overline{B}^0 \to D^+\pi^-) = 0.77 \pm 0.22 \pm 0.29$$

The first uncertainty is statistical and the second is systematic. This result is published [23].

2.2. Precision Measurement of D^0 mass by CLEO-c

The D^0 ($c\overline{u}$) and $D^\pm$ ($d\overline{c}, c\overline{d}$) mesons form the ground states of the open charm system. The knowledge of their masses is important for its own sake, but a precision determination of the D^0 mass has become more important because of the recent discovery of a narrow state known as X(3872) [24–27]. Many different theoretical models have been proposed [28–31] to explain the nature of this state, whose present average of measured masses is $M(X) = 3871.2 \pm 0.5$ MeV [32]. A provocative and challenging theoretical suggestion is that X(3872) is a loosely bound molecule of D^0 and D^{*0} mesons [31]. This suggestion arises mainly from the closeness of $M[X(3872)]$ to $M(D^0) + M(D^{*0}) = 2M(D^0) + [M(D^{*0}) - M(D^0)] = 2(1864.1 \pm 1.0) + (142.12 \pm 0.07)$ MeV $= 3870.32 \pm 2.0$ MeV based on the PDG [32] average value of the measured D^0 mass, $M(D^0) = 1864.1 \pm 1.0$ MeV. This gives the binding energy of the proposed molecule, $E_b[X(3872)] = M(D^0) + M(D^{*0}) - M[X(3872)] = -0.9 \pm 2.1$ MeV. Although the negative value of the binding energy would indicate that X(3872) is not a bound state of D^0 and D^{*0}, its ± 2.1 MeV error does not preclude this possibility. It is necessary to measure the masses of both D^0 and X(3872) with much improved precision to reach a firm conclusion. Recently, CLEO-c reported a precision measurement of the D^0 mass, and provided a more constrained value of the binding energy of X(3872) as a molecule. Several earlier measurements of the D^0 mass exist. The PDG [32] resulting average D^0 mass is based on the measured D^0 masses as $M(D^0)_{AVG} = 1864.1 \pm 1.0$ MeV. They also list a fitted mass, $M(D^0)_{FIT} = 1864.5 \pm 0.4$ MeV,

based on the updated results of measurements of $D^\pm$, D^0, $D_s^\pm$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ masses and mass differences. In its recent measurement, CLEO-c analyzes 281 pb^{-1} of e^+e^- annihilation data taken at the $\Psi(3770)$ resonance at the Cornell Electron Storage Ring (CESR) with the CLEO-c detector to measure the D^0 mass using the reaction $\Psi(3770) \to D^0\overline{D}^0$, with $D^0 \to K_S^0\Phi$, $K_S^0 \to \pi^+\pi^-$ and $\Phi \to K^+K^-$. The choice of the $D^0 \to K_S^0\Phi$ mode is motivated by the determination of the D^0 mass not depending on the precision of the determination of the beam energy. Since $M(\Phi)+M(K_S^0)=1517$ MeV is a substantial fraction of $M(D^0)$, the final state particles have small momenta and the uncertainty in their measurement makes a small contribution to the total uncertainty in $M(D^0)$. This consideration favors $D^0 \to K_S^0\Phi$ over the more prolific decays $D^0 \to K^-\pi^+$ and $D^0 \to K^-\pi^+\pi^-\pi^+$ in which the decay particles have considerably larger momenta and therefore greater sensitivity to the measurement uncertainties. An additional advantage of the $D^0 \to K_S^0\Phi$ reaction is that in fitting for $M(D^0)$ the mass of K_S^0 can be constrained to its value which is known with precision [32]. The final result of this measurement is $M(D^0) = 1864.847 \pm 0.150$ (stat) $\pm$ 0.095 (syst) MeV. Adding the errors in quadrature, $M(D^0)=1864.847 \pm 0.178$ MeV is obtained. This is significantly more precise than the current PDG average [32]. This result for $M(D^0)$ leads to $M(D^0 D^{*0})=$ 3871.81 $\pm$ 0.36 MeV. Thus, the binding energy of X(3872) as a $D^0 \overline{D}^{*0}$ molecule is $E_b = (3871.81 \pm 0.36)$ - (3871.2 ± 0.5) = $+0.6 \pm 0.6$ MeV. This result provides a strong constraint for the theoretical predictions for the decays of X(3872) if it is a $D^0 \overline{D}^{*0}$ molecule [31]. The error in the binding energy is now dominated by the error in the X(3872) mass measurement, which will hopefully improve as the results from the analysis of larger luminosity data from various experiments become available. This analysis is published [33].

3. Strange charm mesons

Much of the theoretical work on the $c\overline{s}$ system has been performed in the limit of heavy c quark mass using potential models [34–37] that treat the $c\overline{s}$ system much like a hydrogen atom. Prior to the discovery of the $D_{sJ}^*(2317)^+$ meson, such models were successful at explaining the masses of all known D and D_s states and even predicting, to good accuracy, the masses of many D mesons (including the $D_{s1}(2536)^+$ and $D_{s2}(2573)^+$) before they were observed (see Fig. 1). Several of the predicted D_s states were not confirmed experimentally, notably the lowest mass $J^P = 0^+$ state (at around 2.48 GeV/c^2) and the second lowest mass $J^P = 1^+$ state (at around 2.58 GeV/c^2). Since the predicted widths of these two states were large, they would be hard to observe, and thus the lack of
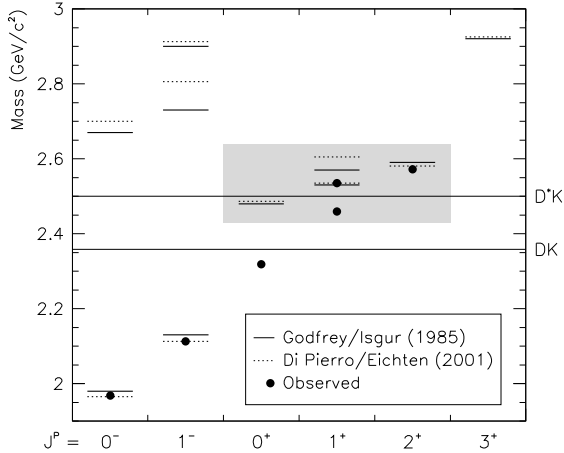
Figure 1: The $c\bar{s}$ meson spectrum, as predicted by Godfrey and Isgur [34] (solid lines) and Di Pierro and Eichten [37] (dashed lines) and as observed by experiment (points). The DK and D^*K mass thresholds are indicated by the horizontal lines spanning the width of the plot.

experimental evidence was not a concern.

3.1. $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$

The $D_{sJ}^*(2317)^+$ meson has been observed in the decay $D_{sJ}^*(2317)^+ \to D_s^+\pi^0$ [38–42]. The mass is measured to be around 2.32 GeV/c^2, which is below the DK threshold. Thus, this particle is forced to decay either electromagnetically, of which there is no experimental evidence, or through the observed isospin-violating $D_s^+\pi^0$ strong decay. The intrinsic width is small enough that only upper limits have been measured (the best limit previous to this analysis being $\Gamma < 4.6$ MeV at 95% CL as established by BELLE [40]). If the $D_{sJ}^*(2317)^+$ is the missing 0^+ $c\bar{s}$ meson state, the narrow width could be explained by the lack of an isospin-conserving strong decay channel. The low mass (160 MeV/c^2 below expectations) is more surprising and has led to the speculation that the $D_{sJ}^*(2317)^+$ does not belong to the D_s^+ meson family at all but is instead some type of exotic particle, such as a four-quark state [43].

The $D_{sJ}(2460)^+$ meson has been observed decaying to $D_s^+\pi^0\gamma$ [38–42], $D_s^+\pi^+\pi^-$ [40], and $D_s^+\gamma$ [40–42]. The intrinsic width is small enough that only upper limits have been measured (the best limit previous to this analysis being $\Gamma < 5.5$ MeV at 95% CL as established by BELLE [40]). The $D_s^+\gamma$ decay implies a spin of at least one, and so it is natural to assume that the $D_{sJ}(2460)^+$ is the missing 1^+ $c\bar{s}$ meson state. Like the $D_{sJ}^*(2317)^+$, the $D_{sJ}(2460)^+$ is substantially lower in mass than predicted for the normal $c\bar{s}$ meson. This suggests that a similar mechanism is deflating the masses of both mesons, or that both the states belong

to the same family of exotic particles.

The spin-parity of the $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ mesons has not been firmly established. The decay mode of the $D_{sJ}^*(2317)^+$ alone implies a spin-parity assignment from the natural J^P series $\{0^+, 1^-, 2^+, \ldots\}$, assuming parity conservation. Because of the low mass, the assignment $J^P = 0^+$ seems most reasonable, although experimental data have not ruled out higher spin. It is not clear whether electromagnetic decays such as $D_s^*(2112)^+\gamma$ can compete with the strong decay to $D_s^+\pi^0$, even with isospin violation. Thus, the absence of experimental evidence for radiative decays such as $D_{sJ}^*(2317)^+ \to D_s^*(2112)^+\gamma$ is not conclusive.

Experimental evidence for the spin-parity of the $D_{sJ}(2460)^+$ meson is somewhat stronger. The observation of the decay to $D_s^+\gamma$ alone rules out $J = 0$. Decay distribution studies in $B \to D_{sJ}(2460)^+ D_s^{(*)-}$ [41, 42] favor the assignment $J = 1$. Decays to either $D_s^+\pi^0$, D^0K^+, or D^+K^0 would be favored if they were allowed. Since these decay channels are not observed, this suggests, when combined with the other observations, the assignment $J^P = 1^+$. In this case, the decay to $D_{sJ}^*(2317)^+\gamma$ is allowed, but it may be small in comparison to the $D_s^+\gamma$ decay mode.

An updated analysis of the $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ mesons using 232 fb^{-1} of $e^+e^- \to c\bar{c}$ data is presented here. Established signals from the decay $D_{sJ}^*(2317)^+ \to D_s^+\pi^0$ and $D_{sJ}(2460)^+ \to D_s^+\pi^0\gamma$, $D_s^+\gamma$, and $D_s^+\pi^+\pi^-$ are confirmed. A detailed analysis of invariant mass distributions of these final states including consideration of the background introduced by reflections of other $c\bar{s}$ decays produces the following mass values:

$$m(D_{sJ}^*(2317)^+) = (2319.6 \pm 0.2 \pm 1.4)\,\text{MeV}/c^2$$
$$m(D_{sJ}(2460)^+) = (2460.1 \pm 0.2 \pm 0.8)\,\text{MeV}/c^2,$$

where the first error is statistical and the second systematic. Upper 95% CL limits of $\Gamma < 3.8$ MeV and $\Gamma < 3.5$ MeV are calculated for the intrinsic $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ widths. All results are consistent with previous measurements.

The following final states are investigated: $D_s^+\pi^0$, $D_s^+\gamma$, $D_s^*(2112)^+\pi^0$, $D_{sJ}(2317)^+\gamma$, $D_s^+\pi^0\pi^0$, $D_s^*(2112)^+\gamma$, $D_s^+\gamma\gamma$, $D_s^+\pi^\pm$, and $D_s^+\pi^+\pi^-$. No statistically significant evidence of new decay modes is observed. The following branching ratios are measured:

$$\frac{\mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\gamma)}{\mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\pi^0\gamma)} = 0.337 \pm 0.036 \pm 0.038$$
$$\frac{\mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\pi^+\pi^-)}{\mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\pi^0\gamma)} = 0.077 \pm 0.013 \pm 0.008,$$

where the first error is statistical and the second systematic. The data are consistent with the decay

$D_{sJ}(2460)^+ \rightarrow D_s^+ \pi^0 \gamma$ proceeding entirely through $D_s^*(2112)^+ \pi^0$.

Since the results presented here are consistent with $J^P = 0^+$ and $J^P = 1^+$ spin-parity assignments for the $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ mesons, these two states remain viable candidates for the lowest lying p-wave $c\bar{s}$ mesons. The lack of evidence for some radiative decays, in particular $D_{sJ}^*(2317)^+ \rightarrow D_s^*(2112)^+\gamma$ and $D_{sJ}(2460)^+ \rightarrow D_s^*(2112)^+\gamma$, are in contradiction with this hypothesis according to some calculations, but large theoretical uncertainties remain. No state near the $D_{sJ}^*(2317)^+$ mass is observed decaying to $D_s^+\pi^\pm$. If charged or neutral partners to the $D_{sJ}^*(2317)^+$ exist (as would be expected if the $D_{sJ}^*(2317)^+$ is a four-quark state), some mechanism is required to suppress their production in e^+e^- collisions. This analysis is realized in inclusive $c\bar{c}$ production using 232 fb^{-1} of data collected by the *BABAR* experiment near $\sqrt{s} = 10.6$ GeV and is published in [45].

3.2. The $D_{s1}(2536)^+$ Case

For a complete understanding of the charmed strange meson spectrum, a comprehensive knowledge of the parameters of all known D_s^+ mesons is mandatory. In this part of the presentation, a precision measurement of the mass and the decay width of the meson $D_{s1}(2536)^+$ is presented. The mass is currently reported by the PDG with a precision of 0.6 MeV/c^2, while only an upper limit of 2.3 MeV/c^2 is given for the decay width [32]. These values are based on measurements with 20 times fewer reconstructed D_{s1}^+ candidates compared to this one. The *BABAR* experiment, in addition to its excellent tracking and vertexing capabilities, provides a rich source of charmed hadrons, enabling an analysis of the D_{s1}^+ with high statistics and small errors.

Since the uncertainty of the D^{*+} mass is large (0.4 MeV/c^2 [32]), a measurement of the mass difference defined by

$$\Delta m(D_{s1}^+) = m(D_{s1}^+) - m(D^{*+}) - m(K_S^0),$$

is performed. Additionally, due to the correlation between the masses, the D_{s1}^+ signal in the mass difference spectrum is much more narrow than the one from the D_{s1}^+ mass spectrum alone leading to a high precision measurement of the mass and the decay width of the meson $D_{s1}(2536)^+$ using the decay mode $D_{s1}^+ \rightarrow D^{*+}K_S^0$. The mass difference between D_{s1}^+ and $D^{*+}K_S^0$ for the two reconstructed decay modes is measured to be

$$\Delta\mu(D_{s1}^+)_{K4\pi} = 27.209 \pm 0.028 \pm 0.031 \text{ MeV}/c^2,$$
$$\Delta\mu(D_{s1}^+)_{K6\pi} = 27.180 \pm 0.023 \pm 0.043 \text{ MeV}/c^2,$$

with the first error denoting the statistical uncertainty and the second one the systematic uncertainty. These results correspond to a relative error of 0.15% for the

mass difference. This lies within the range of precision achievable with the *BABAR* detector: the J/ψ mass has been reconstructed with a relative error of 0.05% [46].

Combining the results, while taking the systematic errors including the uncertainties of the D^{*+} mass (± 0.4 MeV/c^2) and of the K_S^0 mass (± 0.022 MeV/c^2) into account, yields a final value for the D_{s1}^+ mass of

$$m(D_{s1}^+) = 2534.85 \pm 0.02 \pm 0.40 \text{ MeV}/c^2,$$

while the PDG value for the mass is given as $2535.35 \pm 0.34 \pm 0.50$ MeV/c^2. The error on the measured D_{s1}^+ mass is dominated by the uncertainty of the D^{*+} mass. The mass difference between the D_{s1}^+ and the D^{*+} follows from these results as

$$\Delta m = m(D_{s1}^+) - m(D^{*+}) =$$
$$524.85 \pm 0.02 \pm 0.04 \text{ MeV}/c^2.$$

The decay width is measured to be

$$\Gamma(D_{s1}^+)_{K4\pi} = 1.112 \pm 0.068 \pm 0.131 \text{ MeV}/c^2,$$
$$\Gamma(D_{s1}^+)_{K6\pi} = 0.990 \pm 0.059 \pm 0.119 \text{ MeV}/c^2.$$

The final combined value for decay width is

$$\Gamma(D_{s1}^+) = 1.03 \pm 0.05 \pm 0.12 \text{ MeV}/c^2.$$

The result for the mass difference $\Delta m = m(D_{s1}^+) - m(D^{*+})$ represents an improvement in precision by a factor of 14 compared with the current PDG value of $525.3 \pm 0.6 \pm 0.1$ MeV/c^2. It deviates by 1σ from the larger PDG value. The precision achieved is comparable with other recent high precision analyses performed at *BABAR* like the Λ_c mass measurement ($m(\Lambda_c) = 2286.46 \pm 0.04 \pm 0.14$ MeV/c^2) [47]. Furthermore, this analysis presents for the first time a direct measurement of the D_{s1}^+ decay width with small errors rather than just an upper limit, which is currently stated by the PDG as 2.3 MeV/c^2. This analysis is also realized in inclusive $c\bar{c}$ production using 232 fb^{-1} of data collected by the *BABAR* experiment near $\sqrt{s} = 10.6$ GeV and is detailed in [48].

3.3. $D_{s2}(2573)^+$ and New Strange Charmed Mesons

Here, a new $c\bar{s}$ state and a broad structure observed in the decay channels D^0K^+ and $D^+K_S^0$ are reported. This analysis is based on a 240 fb^{-1} inclusive $c\bar{c}$ data sample recorded near the $\Upsilon(4S)$ resonance by the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage rings.

Three inclusive processes [20] are reconstructed:

$$e^+e^- \rightarrow D^0K^+X, D^0 \rightarrow K^-\pi^+ \qquad (1)$$
$$e^+e^- \rightarrow D^0K^+X, D^0 \rightarrow K^-\pi^+\pi^0 \qquad (2)$$
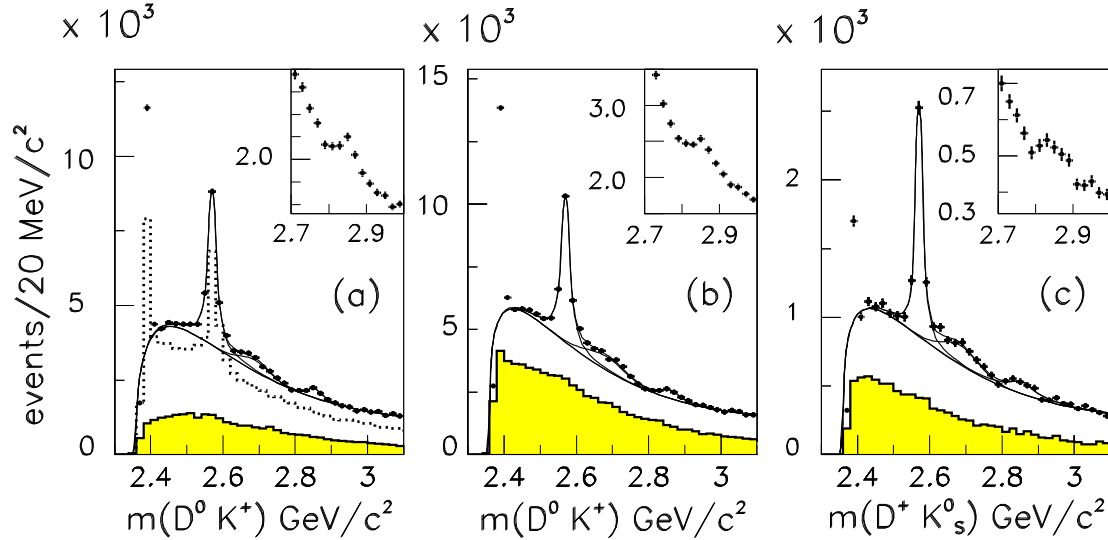$$e^+e^- \rightarrow D^+K_S^0X, D^+ \rightarrow K^-\pi^+\pi^+, K_S^0 \rightarrow \pi^+\pi^- (3)$$

Figure 2: The DK invariant mass distributions for (a) $D^0_{K^-\pi^+}K^+$, (b) $D^0_{K^-\pi^+\pi^0}K^+$ and (c) $D^+_{K^-\pi^+\pi^+}K^0_s$. The shaded histograms are for the D-mass sideband regions. The dotted histogram in (a) is from $e^+e^- \to c\bar{c}$ Monte Carlo simulations incorporating previously known D_s states with an arbitrary normalization. The insets show an expanded view of the 2.86 GeV/c^2 region. The solid curves are the fitted background threshold functions from the three separate fits.

Selecting events in the D signal regions, Fig. 2 shows the D^0K^+ invariant mass distributions for channels (1) and (2), and the $D^+K^0_S$ invariant mass distribution for channel (3). To improve mass resolution, the nominal D mass and the reconstructed 3-momentum are used to calculate the D energy for channels (1) and (3). Since channel (2) has a poorer D^0 resolution, each $K^-\pi^+\pi^0$ candidate is kinematically fit with a D^0 mass constraint and a χ^2 probability greater than 0.1% is required.

The fraction of events having more than one DK combination per event is 0.9% for channels (1) and (3) and 3.4% for channel (2). In the following, the term reflection will be used to describe enhancements produced by two or three body decays of narrow resonances where one of the decay products is missed.

The three mass spectra in Fig. 2 present similar features:

- A single bin peak at 2.4 GeV/c^2 due to a reflection from the decays of the $D_{s1}(2536)^+$ to $D^{*0}K^+$ or $D^{*+}K^0_S$ in which the π^0 or γ from the D^* decay is missed. This state, if $J^P = 1^+$, cannot decay to DK.

- A prominent narrow signal due to the $D_{s2}(2573)^+$.

- A broad structure peaking at a mass of approximately 2.7 GeV/c^2.

- An enhancement around 2.86 GeV/c^2. This can be seen better in the expanded views shown in the insets of Fig. 2.

Different background sources are examined: combinatorial, possible reflections from D^* decays, and particle misidentification.

Backgrounds come both from events in which the candidate D meson is correctly identified and from events in which it is not. The first case can be studied combining a reconstructed D meson with a kaon from another $\bar{D}$ meson in the same event, using data with fully reconstructed $D\bar{D}$ pairs or Monte Carlo simulations. No signal near 2.7 or 2.86 GeV/c^2 is seen in the DK mass plots for these events. The second case can be studied using the D mass sidebands. The shaded regions in Fig. 2 show the DK mass spectra for events in the D sideband regions normalized to the estimated background in the signal region. No prominent structure is visible in the sideband mass spectra. The dotted histogram in (a) is from $e^+e^- \to c\bar{c}$ Monte Carlo simulations incorporating previously known D_s states with an arbitrary normalization.

The possibility that the features at 2.7 and 2.86 GeV/c^2 could be a reflection from D^* or other higher mass resonances is considered. Candidate DK pairs where the D is a D^*-decay product are identified by forming $D\pi$ and $D\gamma$ combinations and requiring the invariant-mass difference between one of those combinations and the D to be within $\pm 2\sigma$ of the known $D^* - D$ mass difference. No signal near 2.7 or 2.86 GeV/c^2 is seen in the DK mass plots for these events. Events belonging to these possible reflections (except for the $D^{*0} \to D^0\gamma$ events, which could not be isolated cleanly) have been removed from the mass distributions shown in Fig. 2 (corresponding to $\approx 8\%$

of the final sample).

The presence of resonant structures can be visually enhanced by subtracting the fitted background threshold function from the data. Fig. 3 shows the background-subtracted $D^0_{K^-\pi^+}K^+$, $D^0_{K^-\pi^+\pi^0}K^+$, and $D^+_{K^-\pi^+\pi^+}K^0_s$ invariant mass distributions in the 2.86 GeV/c^2 mass region. Fig. 3(d) shows the sum of the three mass spectra.

In the following, the structure in the 2.86 GeV/c^2 mass region is labelled $D_{sJ}(2860)^+$ and the one in the 2.7 GeV/c^2 mass region is labelled $X(2690)^+$. The three DK mass spectra shown in Fig. 2 from 2.42 GeV/c^2 to 3.1 GeV/c^2 (excluding the $D_{s1}(2536)^+$ reflection) are first fitted separately using a binned χ^2 minimization. The background for the three DK mass distributions is described by a threshold function: $(m-m_{\rm th})^\alpha\, e^{-\beta m-\gamma m^2-\delta m^3}$ where $m_{\rm th}=m_D+m_K$. A fit to the Monte Carlo distribution shown in Fig. 2(a) using this background expression and one spin-2 relativistic Breit-Wigner for the $D_{s2}(2573)^+$ gives a good 32 % χ^2 probability. In the fit to the data, the $D_{s2}(2573)^+$ and $D_{sJ}(2860)^+$ peaks are described with relativistic Breit-Wigner lineshapes where spin-2 is assumed for the $D_{s2}(2573)^+$ and spin 0 is used for the $D_{sJ}(2860)^+$. The $D_{sJ}(2860)^+$ parameters are found insensitive to the choice of the spin. The best description of the $X(2690)^+$ structure is obtained using a Gaussian distribution. The fits give consistent values for the parameters of the three structures.

When the three mass distributions of Fig. 2 are fitted simultaneously, the resulting resonance parameters are also found consistent with those obtained with previous separate fits. For $D_{s2}(2573)^+$ resonance, mass and width are:

$$m(D_{s2}(2573)^+) = (2572.2 \pm 0.3 \pm 1.0)\ {\rm MeV}/c^2$$
$$\Gamma(D_{s2}(2573)^+) = (27.1 \pm 0.6 \pm 5.6)\ {\rm MeV}/c^2,$$

where the first errors are statistical and the second systematic. For the new states, the following values are obtained:

$$m(D_{sJ}(2860)^+) = (2856.6 \pm 1.5 \pm 5.0)\ {\rm MeV}/c^2$$
$$\Gamma(D_{sJ}(2860)^+) = (47 \pm 7 \pm 10)\ {\rm MeV}/c^2.$$

$$m(X(2690)^+) = (2688 \pm 4 \pm 3)\ {\rm MeV}/c^2$$
$$\Gamma(X(2690)^+) = (112 \pm 7 \pm 36)\ {\rm MeV}/c^2.$$

In summary, in 240 fb^{-1} of data collected by the *BABAR* experiment, a new D_s^+ state is observed in the inclusive DK mass distribution near 2.86 GeV/c^2 in three independent channels. The decay to two pseudoscalar mesons implies a natural spin-parity for this state: $J^P = 0^+, 1^-, \ldots$. It has been suggested that this new state could be a radial excitation of $D_{sJ}^*(2317)$ [49] although other possibilities cannot be ruled out. In the same mass distributions a broad enhancement around 2.69 GeV/c^2 is also observed, it is not possible to associate it to any known reflection or background. This analysis is published [50]. Another *BABAR* analysis[51], has searched for resonances in $B \to D^{(*)}D^{(*)}K$ decays in 22 decay modes using 347 fb^{-1} data sample recorded at the $\Upsilon(4S)$ resonance. The DK and D^*K invariant mass distributions are built with 8 decay modes each. Both distributions show a resonant enhancement around 2700 MeV/c^2. However, due to an unknown structure at low mass in the DK invariant mass distribution and to the possible additional resonances in the signal region in the D^*K invariant mass distribution, a full Dalitz analysis in necessary and is ongoing in order to extract the $D_{sJ}(2700)^+$ parameters.

4. Conclusion

Although the nature of the newly discovered charm resonances is not yet fully understood, the resonances are interpreted as molecular or hybrid states in most theoretical papers. It will be interesting to see if these interpretations are confirmed by future measurements and analyses.

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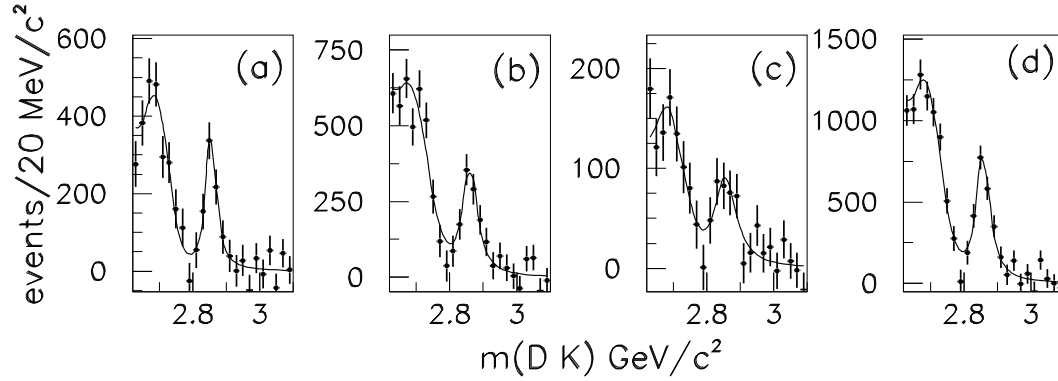[14] T. Mannel *et al.* , Phys. Lett. B **259**, 359 (1991).

Figure 3: Fitted background-subtracted DK invariant mass distributions for (a) $D^0_{K^-\pi^+}K^+$, (b) $D^0_{K^-\pi^+\pi^0}K^+$, (c) $D^+_{K^-\pi^+\pi^+}K^0_s$, and (d) the sum of all modes in the 2.86 GeV/c^2 mass region. The curves are the fitted functions described in the text.

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