Charm and Charmonium Spectroscopy at the e^+e^- B-Factories

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Over the past few years, there has been a lot of progress in the areas of charm and charmonium spectroscopy, in large part due to the very large data samples being accumulated at the e^+e^- B-Factories. In this presentation I will focus on results in three areas: the X/Y/Z charmonium-candidate states, the D_{sJ} charmed-strange mesons, and newly-discovered charmed baryons. Note the absence of a section on pentaquarks: all B-Factory searches for pentaquarks, charmed or otherwise, have not yielded any observation of such states.

1. Introduction

The results I am going to present are obtained from data collected by BABAR@PEP-II, Belle@KEK-B, and CLEO@CESR. BABAR and Belle data samples are of the order of 450–650 million (M) $c\bar{c}$ and 380–550M $B\bar{B}$ events, collected at center-of-mass (CM) energies on or just below the $\Upsilon(4S)$ resonance, $\sqrt{s} \approx 10.58\,\mathrm{GeV}$.

Charm and charmonium states at the B-Factories are produced in $e^+e^- \to c\bar{c}$ annihilation events, in $e^+e^- \to e^+e^- c\bar{c}$ two-photon events, and in B decay proceeding through the dominant $b \to c$ transition. Important variations of the annihilation process are *(i)* initial-state-radiation (ISR), which reduces the available CM energy of the $c\bar{c}$ pair (*e.g.*, into the region of the charmonium system), and *(ii)* double-charmonium production, where an additional $c\bar{c}$ pair is pulled out of the vacuum. The annihilation process (with and without ISR) proceeds through a virtual photon, thus fixing the quantum numbers (QNs) of the final state to be $\mathrm{J^{PC}} = 1^{--}$. For production via the collision of two quasi-real photons, the final state has to have positive C-parity and cannot have spin 1, *i.e.*, $\mathrm{J^C} = 0^+, 2^+$. B decay allow access to a multitude of final states with masses below the B meson mass; their spin-parities can be determined from analyzing appropriate decay angular distributions. A particularly interesting B decay is the case of a two-body decay $\bar{B} \to \bar{K}^{(*)} X$[1], where the Cabibbo-Kobayashi-Maskawa (CKM) coupling strengths strongly favor $b \to c$ and $W \to s\bar{c}$ transitions, resulting in the production of a $X = c\bar{c}$ system recoiling against the $\bar{K}^{(*)}$.

2. Charmonium-candidate States

Thanks in large part to the large and steadily increasing data samples at the B-Factories, there has been a steady stream of discoveries of charmonium-candidate states, resulting in somewhat of an alphabet soup of (unimaginatively named) $X/Y/Z$ states. Generally, there has been good progress in determining the properties of those states, not the least because of the ability to pull together information from multiple production mechanisms.

2.1. X(3872)

The first of these states, the X(3872), was discovered by the Belle Collaboration [1] in B decay in the reaction $B \to K\,X(3872)$, $X(3872) \to \pi^+\pi^- J/\psi$, using a data sample of 152M $B\bar{B}$ pairs. Existence of the $X(3872) \to \pi^+\pi^- J/\psi$ decay was quickly confirmed by CDF, D0, and BABAR. Since then, BABAR and Belle have analyzed samples of 232M [2] and 275M [3] $B\bar{B}$ pairs, respectively, and observe relatively clean $X(3872)$ signals of approximately $50-60$ events. They measure an average product branching fraction (BF)

$$\mathcal{B}(B \to K\,X(3872),\ X(3872) \to \pi^+\pi^- J/\psi) = (11.6 \pm 1.9) \times 10^{-6}, \quad (1)$$

where statistical and systematic errors have been combined in quadrature, and a mass and width

$$m_X = (3871.2 \pm 0.6)\,\mathrm{MeV}/c^2, \quad \Gamma_X < 2.3\,\mathrm{MeV} \ @\ 90\%\ \mathrm{C.L.} \quad (2)$$

The measured mass, width, and decay mode make it difficult to accommodate the $X(3872)$ as a conventional charmonium state. Alternative interpretations have been proposed, for example, in terms of a $\bar{D}^0$-D^{*0} molecule [4], or a diquark–antidiquark state [5]. To help establish the nature of the $X(3872)$, additional information on its properties, like spin-parity or other decay modes, is needed—and has been forthcoming with the increasing B-Factory data samples.

BABAR has searched inclusively [6] for $B \to K\,X(3872)$ using a $B\bar{B}$ data sample with one B fully reconstructed. The searched-for two-body decay of the other B meson results in a monochromatic line in the kaon momentum spectrum in the B meson rest frame. BABAR observes signals for a number of well-known charmonium states, with BFs consistent with

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[1]Unless noted otherwise, charge conjugation is implied throughout the text.

exclusive measurements, but no significant $X(3872)$ signal is found, resulting in an upper limit on $X(3872)$ production in charged-B decay

$$\mathcal{B}(B^{\pm} \to K^{\pm} X(3872)) < 3.4 \times 10^{-4} \text{ @ } 90\% \text{ C.L.} \quad (3)$$

Combining this with the (average) product BF in eq. 1 yields a lower limit on the $X(3872)$ decay BF

$$\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) > 0.042 \text{ @ } 90\% \text{ C.L.} \quad (4)$$

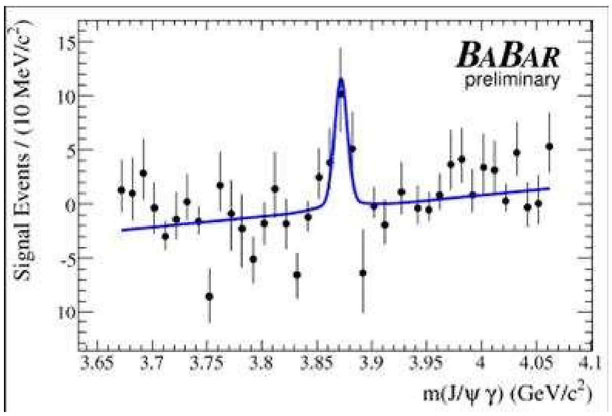

Figure 1: Number of B signal events in bins of $\gamma\, J/\psi$ invariant mass.

Recently, *BABAR* confirmed Belle's observation [7] of the radiative decay $X(3872) \to \gamma\, J/\psi$. The existence of this decay mode determines the C-parity of the $X(3872)$ to be positive. Using 287M $B\bar{B}$ events, *BABAR* observes 19.4 ± 5.7 signal events; see Fig. 1. The corresponding (preliminary) product BF is

$$\mathcal{B}(B \to K\, X(3872),\ X(3872) \to \gamma\, J/\psi) = (3.4 \pm 1.0 \pm 0.3) \times 10^{-6}\,, \quad (5)$$

where the errors are statistical and systematic, respectively. Combining this with Belle's measurement yields

$$\mathcal{B}(B \to K\, X(3872),\ X(3872) \to \gamma\, J/\psi) = (2.2 \pm 0.7) \times 10^{-6}\,, \quad (6)$$

where the error has been scaled by a factor $S = 1.3$ according to the particle data group (PDG) prescription [8]. The resulting ratio of radiative over hadronic decays is

$$\frac{\mathcal{B}(X(3872) \to \gamma\, J/\psi)}{\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)} = 0.19 \pm 0.07\,. \quad (7)$$

The positive C-parity of the $X(3872)$ fixes the QN of the $\pi^+\pi^-$ system to be $\mathrm{I^G(J^{PC})} = 1^+(1^{--})$, *i.e.*, those of the ρ meson. Consequently, one expects the $\pi^+\pi^-$ invariant mass spectrum to peak toward the upper kinematic boundary. That is just what Belle observes in their analysis [3]. The $\pi^+\pi^-$ invariant mass spectrum can also yield clues to the relative angular momentum, L, between the $\pi^+\pi^-$ system and the J/ψ, due to the phase-space suppression that scales with $[q^*_{J/\psi}]^{2L+1}$, where $q^*_{J/\psi}$ is the J/ψ momentum in the $X(3872)$ rest frame. The $\pi^+\pi^-$ spectrum is fitted using a background function (estimated from $X(3872)$ sidebands) plus a ρ Breit-Wigner (B-W) function modified by an S-wave (solid line) or P-wave (dashed line) phase-space factor. The data clearly prefers S-wave; as a consequence positive parity is preferred for the $X(3872)$ [2]. So at this point, the preferred $X(3872)$ spin-parity assignment is among $\mathrm{J^{PC}} = 0^{++},\ 1^{++},\ 2^{++}$.

A short digression on isospin here: the positive C-parity of the $X(3872)$ and the resulting QNs of the $\pi^+\pi^-$ system determine the $\pi^+\pi^- J/\psi$ final state to be an isovector. Using 234M $B\bar{B}$ pairs, *BABAR* has searched for charged partners $X^{\pm}(3872)$ and determines an upper limit [10]

$$\mathcal{B}(B^0 \to K^{\mp} X^{\pm}(3872),\ X^{\pm}(3872) \to \pi^{\pm}\pi^0 J/\psi) < 5.4 \times 10^{-6} \text{ @ } 90\% \text{ C.L.}\,, \quad (8)$$

about a factor 2 lower than the BF observed for the neutral $X(3872)$. Thus, one concludes that the initial-state neutral $X(3872)$ is an isoscalar and its decay into $\pi^+\pi^- J/\psi$ violates isospin symmetry. It is this suppression that causes the very small $X(3872)$ width. One might ask then: what prevents the isospin-allowed decay $X(3872) \to \pi^+\pi^-\pi^0 J/\psi$ from happening all too frequently? Examining the QNs of a neutral 3-pion system resulting from a positive C-parity initial state, one finds $\mathrm{I^G(J^{PC})} = 0^-(1^{--})$, *i.e.*, those of the ω meson. However, at the nominal ω mass of $\sim 782\,\mathrm{MeV}/c^2$, the $\omega J/\psi$ decay is kinematically forbidden. It is only due to the $\sim 8.5\,\mathrm{MeV}$ natural width of the ω that this decay channel is accessible, leaving it (kinematically) suppressed to a level comparable to the isospin-violating decay via the ρ:

$$\frac{\mathcal{B}(X(3872) \to \pi^+\pi^-\pi^0 J/\psi)}{\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)} = 1.0 \pm 0.4 \pm 0.3\,, \quad (9)$$

as measured by Belle [7].

Belle has extensively studied [3] the decay angular distributions in the decay $B \to K\, X(3872)$, $X(3872) \to \pi^+\pi^- J/\psi$, which is relatively straightforward thanks to the initial B meson and the accompanying kaon being spin-less (pseudoscalar) particles. Looking at a particular pair of $X(3872)$ decay angles suggested in ref. [11], they

[2]Note that this conclusion is significantly weakened if a more complicated decay dynamics, *e.g.*, $\rho - \omega$ interference, is considered, as described in a CDF analysis [9].

find their distributions to be entirely consistent with the expectation for $J^{PC} = 1^{++}$, whereas there is poor consistency for the $J^{PC} = 0^{++}$ hypothesis. Unfortunately, the data is inclusive for $J^{PC} = 2^{++}$.

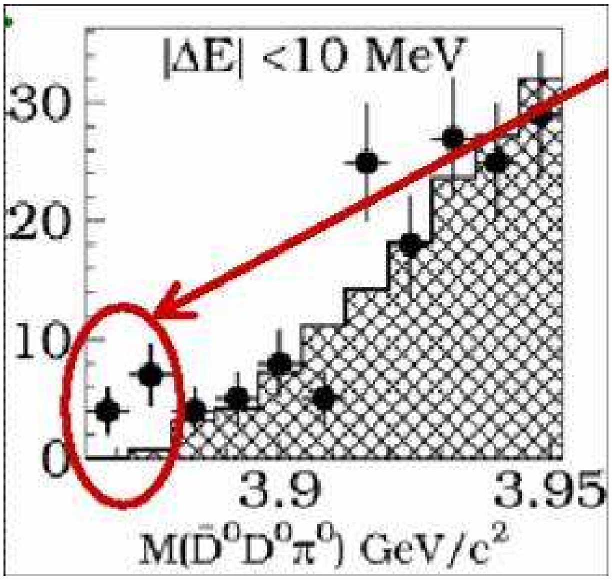

Figure 2: $\bar{D}^0 D^0 \pi^0$ invariant mass distribution in B signal region; cross-hatched: B sideband region.

At a number of conferences earlier this year, Belle has reported (preliminary) results on the observation of the $X(3872) \to \bar{D}^0 D^0 \pi^0$ decay mode. Analyzing a sample of 270M $B\bar{B}$ events, they measure [3]

$$\mathcal{B}(B \to K\, X(3872),\ X(3872) \to \bar{D}^0 D^0 \pi^0) = (1.6 \pm 0.4 \pm 0.3) \times 10^{-4}\,, \quad (10)$$

which is about an order of magnitude larger than the original discovery mode:

$$\frac{\mathcal{B}(X(3872) \to \bar{D}^0 D^0 \pi^0)}{\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)} = 13.8 \pm 4.9\,. \quad (11)$$

Fig. 2 shows the $\bar{D}^0 D^0 \pi^0$ invariant mass distribution, which exhibits an excess of 12.5 ± 3.9 events in the vicinity of $3872\,\mathrm{MeV}/c^2$ that is not present for events in the B sideband region. The existence of this decay mode not only excludes $J^P = 0^+$ on the basis of spin-parity conservation, but it also argues strongly against a $J^P = 2^+$ assignment as that would require a D-wave angular momentum to be present, which is very unlikely for a system within $\sim 8\,\mathrm{MeV}/c^2$ of threshold. Unfortunately, statistics is not sufficient to determine whether this final state really originates from $X(3872) \to \bar{D}^0 D^{*0}$ decay.

The $X(3872)$ has been searched for, but not found, in ISR production [13]

$$\Gamma^X_{ee} \times \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) < 6.2\,\mathrm{eV} \text{ @ } 90\%\ \mathrm{C.L.}\,, \quad (12)$$

confirming that it is not a $J^{PC} = 1^{--}$ state. Similarly, no sign of it was found in quasi-real two-photon collisions [14]

$$\Gamma^X_{\gamma\gamma} \times \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) < \frac{12.9\,\mathrm{eV}}{2\mathrm{J}+1} \text{ @ } 90\%\ \mathrm{C.L.}\,, \quad (13)$$

confirming that it is not a spin-0 or spin-2 state.

In summary, the $X(3872)$ is a very narrow $J^{PC} = 1^{++}$ state with a mass right at $\bar{D}^0 D^{*0}$ threshold (indistinguishable within errors), decaying dominantly into $\bar{D}^0 D^0 \pi^0$. Its properties are perfectly consistent with the interpretation as a $\bar{D}^0$-D^{*0} molecule, whereas it is very difficult to accommodate as a regular charmonium state.

2.2. X(3940)

Using $375\,\mathrm{fb}^{-1}$ of data, Belle has investigated double-charmonium production in $c\bar{c}$ continuum events [15]. They examine the invariant mass of the system recoiling against a reconstructed J/ψ and observe a structure near $3940\,\mathrm{MeV}/c^2$, containing 266 ± 63 events. This $X(3940)$ is produced together with three known charmonium states: η_c, χ_{c0}, and $\eta_c(2S)$ (all of which have positive C-parity). A very natural interpretation of this structure is to identify it as the $\eta_c(3S)$, which would make it a $J^{PC} = 0^{-+}$ (pseudoscalar) state. A charmonium state of this mass is expected to decay dominantly into open charm. Belle has searched for its $D\bar{D}$ and $D^*\bar{D}$ decay by constraining the recoil mass against a reconstructed $J/\psi\,\bar{D}$ system to be either around the D or D^* mass and examining the mass spectrum of the system recoiling against the J/ψ. In the $D^*\bar{D}$ case, they observe a $X(3940)$ signal of 24.5 ± 6.9 events with a mass and width

$$\begin{aligned} m_X &= (3943 \pm 6 \pm 6)\,\mathrm{MeV}/c^2, \\ \Gamma_X &= (15.4 \pm 10.1_{stat})\,\mathrm{MeV} \\ &< 52\,\mathrm{MeV} \text{ @ } 90\%\ \mathrm{C.L.} \end{aligned} \quad (14)$$

The corresponding BF is

$$\begin{aligned} \mathcal{B}(X(3940) \to D^*\bar{D}) &= 0.96^{+0.04}_{-0.32} \pm 0.22 \\ &> 0.45 \text{ @ } 90\%\ \mathrm{C.L.} \end{aligned} \quad (15)$$

[3] It should be noted that this measurement is in poor agreement with a previously published [12] upper limit on this mode, $\mathcal{B}(B \to K\,X(3872),\ X(3872) \to \bar{D}^0 D^0 \pi^0) < 6 \times 10^{-5}$ @ 90% C.L., based on an analysis of 96M $B\bar{B}$ pairs. Resolution of this issue is awaiting a forthcoming publication on the new measurement.

No signal is observed in the $D\bar{D}$ case, resulting in an upper limit

$$\mathcal{B}(X(3940) \to D\bar{D}) \; < \; 0.41 \text{ @ } 90\% \text{ C.L.} \quad (16)$$

The absence of a $D\bar{D}$ decay for the $X(3940)$ is consistent with its assignment as the $\eta_c(3S)$, since a pseudo-scalar cannot decay into two pseudo-scalars.

Belle has also searched for the decay $X(3940) \to \omega J/\psi$, determining an upper limit

$$\mathcal{B}(X(3940) \to \omega J/\psi) \; < \; 0.29 \text{ @ } 90\% \text{ C.L.} \quad (17)$$

The motivation for this will become clear in the next section.

2.3. Y(3940)

Analyzing 275M $B\bar{B}$ decays, Belle has observed a large $\omega J/\psi$ threshold enhancement [16] in the channel $B^{\pm} \to K^{\pm}\, \omega J/\psi$. If interpreted as a S-wave resonance, a premise that should be critically reviewed, a B-W fit yields a signal of 58 ± 11 events with a mass and width

$$\begin{aligned} m_Y &= (3943 \pm 11 \pm 13)\,\text{MeV}/c^2, \\ \Gamma_Y &= (87 \pm 22 \pm 26)\,\text{MeV} \\ &> 20\,\text{MeV @ } 90\% \text{ C.L.} \end{aligned} \quad (18)$$

(The mechanics of this fit should also be reviewed; I find it surprising that a MINOS error evaluation would yield symmetric errors in this (threshold) situation.) The observed number of signal events corresponds to a BF

$$\begin{aligned} &\mathcal{B}(B^{\pm} \to K^{\pm}\, Y(3940),\; Y(3940) \to \omega J/\psi) \\ &\qquad = (7.3 \pm 1.3 \pm 3.1) \times 10^{-5} . \end{aligned} \quad (19)$$

If this threshold enhancement is really a resonance state, its nature is totally unclear. A charmonium state of this mass is expected to decay dominantly into open charm; $\omega J/\psi$ is not a decay mode that readily comes to mind. That decay mode fixes the $Y(3940)$ C-parity to be positive—just like for the $X(3940)$ discussed in the previous section. Given the weak upper limit for the $X(3940) \to \omega J/\psi$ decay and the large uncertainties in the $X(3940)$ and $Y(3940)$ widths, it is not clear (to me) whether these really are different states.

2.4. Z(3930)

In an effort to elucidate the nature of the X/Y states discussed in the previous sections, Belle has searched for $D^0\bar{D}^0$ and D^+D^- production in two-photon interactions [17], using $395\,\text{fb}^{-1}$ of data. As mentioned before, the production mechanism results in positive C-parity final states with spin 0 or spin 2. In case of spin 2, there are two possible helicity states, 0 and 2, with helicity-2 : helicity-0 = 6 : 1 due to Clebsch-Gordon coefficients. Belle observes a signal of 64 ± 18 events with mass and width

$$\begin{aligned} m_Z &= (3929 \pm 5 \pm 2)\,\text{MeV}/c^2, \\ \Gamma_Z &= (29 \pm 10 \pm 2)\,\text{MeV} . \end{aligned} \quad (20)$$

To determine the spin of this state, they investigate, in the $Z(3940)$ signal region, the angular distribution of one of the Ds with respect to (w.r.t.) the beam axis in the $\gamma\gamma$ CM frame, and find it to be entirely consistent with spin 2, helicity 2, whereas spin 0 is strongly disfavored. Using this spin and helicity assignment, they measure

$$\begin{aligned} &\Gamma^{Z}_{\gamma\gamma} \times \mathcal{B}(Z(3930) \to D\bar{D}) \\ &= (0.18 \pm 0.05 \pm 0.03)\,\text{keV} . \end{aligned} \quad (21)$$

Such a two-photon partial width (assuming a dominant decay to open charm) is in reasonable agreement with the expectation [18] for a conventional charmonium state at this mass. Therefore, the $Z(3940)$ is plausibly identified as a $2\,^3P_2$ $c\bar{c}$ state, the $\chi_{c2}(2P)$.

2.5. Y(4260)

Searching for the $X(3872)$ in ISR events in a data sample of $233\,\text{fb}^{-1}$, BABAR observed a broad structure in the $\pi^+\pi^- J/\psi$ mass spectrum around $4.26\,\text{GeV}/c^2$, the $Y(4260)$ [19]. The ISR production mechanism fixes the QNs of the final state to be $\text{J}^{\text{PC}} = 1^{--}$. Assuming that the observed structure is a single resonance, a B-W fit yields 125 ± 23 signal events corresponding to an electronic width times BF

$$\begin{aligned} &\Gamma^{Y}_{ee} \times \mathcal{B}(Y(4260) \to \pi^+\pi^- J/\psi) \\ &\qquad = (5.5 \pm 1\,^{+0.8}_{-0.7})\,\text{eV} , \end{aligned} \quad (22)$$

a peak cross section [20]

$$\sigma(e^+e^- \to Y(4260)) = (51 \pm 12)\,\text{pb} , \quad (23)$$

and a mass and width

$$\begin{aligned} m_Y &= (4259 \pm 8\,^{+2}_{-6})\,\text{MeV}/c^2, \\ \Gamma_Y &= (88 \pm 23\,^{+6}_{-4})\,\text{MeV} . \end{aligned} \quad (24)$$

Up to very recently, the only other sighting of the $Y(4260)$ came from a BABAR measurement in B decay [2], where a weak ($\sim 3\,\sigma$) signal was observed in

$$\begin{aligned} &\mathcal{B}(B^{\pm} \to K^{\pm}\, Y(4260),\; Y(4260) \to \pi^+\pi^- J/\psi) \\ &\qquad = (2.0 \pm 0.7 \pm 0.2) \times 10^{-5} . \end{aligned} \quad (25)$$

It would be important to repeat this measurement, which used “only” 232M $B\bar{B}$ events, with a larger data sample.

Fortunately, definitive confirmation of the $Y(4260)$ just arrived in the form of a CLEO-c scan [21] of the CM energy region $\sqrt{s} = 3.77 - 4.26\,\text{GeV}$. At the highest scan point, $\sqrt{s} = 4.26\,\text{GeV}$, where they collected $13.2\,\text{pb}^{-1}$ of data, they observe an enhanced cross section for $e^+e^- \to \pi\pi J/\psi$, for charged as well as for neutral pions

$$\sigma(e^+e^- \to \pi^+\pi^- J/\psi) = (58\,^{+12}_{-10} \pm 4)\,\text{nb}\,,$$
$$\sigma(e^+e^- \to \pi^0\pi^0 J/\psi) = (23\,^{+12}_{-8} \pm 1)\,\text{nb}\,. \quad (26)$$

Even though the two measurements are based on only 37 and 8 events, respectively, they are highly significant, thanks to very low backgrounds. Note that the charged-pion measurement compares very favorably with the *BABAR* result in eq. 23. Since the C-parity of the $Y(4260)$ is negative, the QNs of the $\pi\pi$ system are $\text{I}^\text{G}(\text{J}^\text{PC}) = 0^+(0^{++},\ 2^{++})$. Thus, $\pi^+\pi^-$ and $\pi^0\pi^0$ are expected to occur with a (isospin) ratio of 2:1, in agreement with the CLEO measurement in eq. 26. CLEO observes no sign of an enhanced $\pi\pi J/\psi$ decay of the $\psi(4040)$, which is considered to be the $\psi(3S)$ state; this makes the assignment of the $Y(4260)$ as the $\psi(4S)$ state less likely. At this conference, CLEO also showed (preliminary) results from a search for ISR-produced $Y(4260) \to \pi^+\pi^- J/\psi$ using $13.3\,\text{fb}^{-1}$ of CLEO-III data collected on or near the $\Upsilon(4\text{S})$ resonance. They observe a clear $Y(4260)$ signal of 12 events with very little background.

BABAR has searched for the $Y(4260)$ in other ISR-produced final states, *i.e.*, $\pi^+\pi^-\phi$, $p\bar{p}$, and $D\bar{D}$, but observes no signal in any of those. Fig. 3 shows the $\pi^+\pi^-K^+K^-$ invariant mass spectrum from $232\,\text{fb}^{-1}$ of data; no significant structure other than the J/ψ (and maybe a hint of the $\psi(2S)$) is observed, resulting in the (preliminary) upper limit

$$\Gamma^Y_{ee} \times \mathcal{B}(Y(4260) \to \pi^+\pi^-\phi) < 0.4\,\text{eV @ 90\% C.L.} \quad (27)$$

The same dataset has been used to investigate the $p\bar{p}$ final state [20]:

$$\frac{\mathcal{B}(Y(4260) \to p\bar{p})}{\mathcal{B}(Y(4260) \to \pi^+\pi^- J/\psi)} < 0.13 \text{ @ 90\% C.L.} \quad (28)$$

Finally, using $289\,\text{fb}^{-1}$ of data, *BABAR* has measured ISR production of $D\bar{D}$. Fig. 4 shows the $D\bar{D}$ invariant mass spectrum, which shows a significant $\psi(3770)$ signal; it also exhibits several structures previously observed in e^+e^- R-scans which are candidates for $\text{J}^\text{PC} = 1^{--}$ $c\bar{c}$ states, for example $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$. The one place, however, where no structure is apparent in the *BABAR* spectrum is at a $D\bar{D}$ mass of $4260\,\text{MeV}/c^2$. The corresponding (preliminary) upper limit is, unfortunately, not very stringent due to the very low efficiency for reconstructing two D mesons

$$\frac{\mathcal{B}(Y(4260) \to D\bar{D})}{\mathcal{B}(Y(4260) \to \pi^+\pi^- J/\psi)} < 7.6 \text{ @ 95\% C.L.} \quad (29)$$

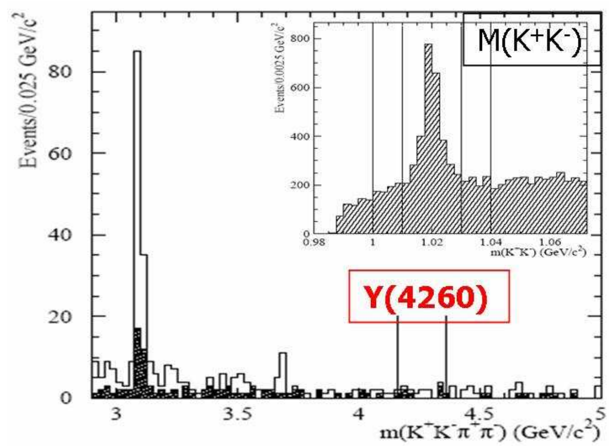

Figure 3: $\pi^+\pi^-K^+K^-$ invariant mass spectrum; ϕ sidebands are shaded. The inset shows the K^+K^- invariant mass, with ϕ signal and sideband regions indicated by the vertical lines.

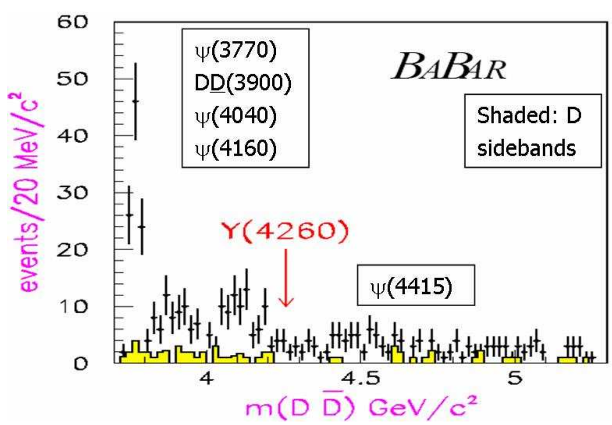

Figure 4: $D\bar{D}$ invariant mass spectrum; D sidebands are shaded yellow.

In summary, the existence of the $Y(4260)$ is now well established, as are its $\text{J}^\text{PC} = 1^{--}$ QNs. However, its nature remains a complete mystery: there is no room for it in the spectrum of 1^{--} charmonium states, and the only final state it has been observed in, $\pi\pi J/\psi$, is a rather unexpected one for a conventional $c\bar{c}$ state of this mass. Exciting unconventional explanations for the $Y(4260)$ have been suggested, *e.g.*, as a $c\bar{c}g$ hybrid state, that will be examined as the data samples increase.

3. Charmed-strange Mesons

The $D^*_{sJ}(2317)$ and $D_{sJ}(2460)$ were first observed by *BABAR* [22] and CLEO [23] in $c\bar{c}$ continuum events, and by Belle [24] in B decay, using data samples of $91\,\text{fb}^{-1}$, $13.5\,\text{fb}^{-1}$, and 124M $B\bar{B}$ events, respectively. The masses of both states are unexpectedly low: below DK and D^*K threshold, respectively. As a consequence, only isospin-violating or electromagnetic decays are kinematically allowed, resulting in very narrow widths for both states. Apart from their low masses, the $D^*_{sJ}(2317)$ and $D_{sJ}(2460)$ decay patterns and angular distributions are consistent with their interpretation as conventional P-wave $c\bar{s}$ mesons with $\mathrm{J^P} = 0^+$ and $\mathrm{J^P} = 1^+$, respectively.

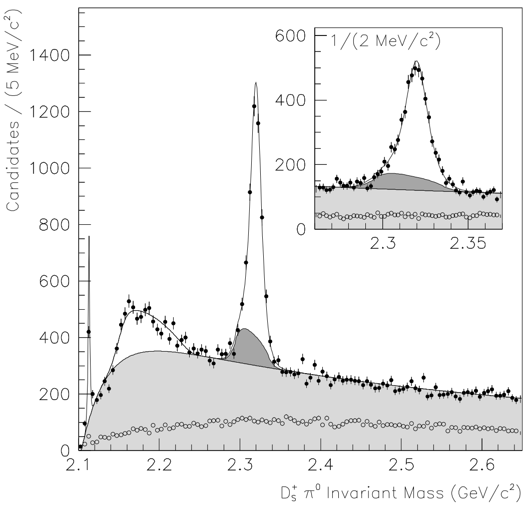

Figure 5: The invariant mass distribution for (solid points) $D_s^+\pi^0$ candidates and (open points) the equivalent using the D_s^+ sidebands. The curve represents the likelihood fit described in the text. Included in this fit is (light shade) a contribution from combinatorial background and (dark shade) the reflection from $D_{sJ}(2460)^+ \to D_s^*(2112)^+\pi^0$ decay. The insert highlights the details near the $D^*_{sJ}(2317)^+$ mass.

BABAR has updated their analysis to use a data sample of $232\,\mathrm{fb}^{-1}$ and performed a comprehensive study [25] of D_{sJ} decays to D_s^+ plus one or two charged pions, neutral pions, or photons; a total of 8 and 9 modes for $D^*_{sJ}(2317)$ and $D_{sJ}(2460)$, respectively, covering all such channels—allowed by spin-parity conservation or not—that are kinematically allowed. The $D^*_{sJ}(2317)^+$ is seen in only one mode: the (allowed) discovery mode $D^*_{sJ}(2317)^+ \to D_s^+\pi^0$; searches in all other modes yield only upper limits. Fig. 5 shows the $D_s^+\pi^0$ invariant mass spectrum. It shows a very large $D^*_{sJ}(2317)^+$ signal ($\mathcal{O}(3000)$ events) plus a $D_s^*(2112)^+$) signal as well as reflections from the $D_s^*(2112)^+$) and the $D_{sJ}(2460)^+$. The latter reflection piles up right underneath the $D^*_{sJ}(2317)^+$ signal, making the extraction of yield and resonance parameters quite difficult. After a detailed study of the shapes of the various contributions to the spectrum, BABAR measures the $D^*_{sJ}(2317)^+$ mass and width

$$m = (2319.6 \pm 0.2 \pm 1.4)\,\mathrm{MeV}/c^2,$$

$$\Gamma < 3.8\,\mathrm{MeV} \text{ @ } 95\%\text{ C.L.} \qquad (30)$$

They have searched for neutral or doubly-charged partners of the $D^*_{sJ}(2317)^+$ in the $D_s^+\pi^-$ and $D_s^+\pi^+$ channel, but find no indication of such states, thus concluding that the $D^*_{sJ}(2317)$ is an isoscalar.

Using 274M $B\bar{B}$ events, Belle has studied [26] the decay angular distributions in $B \to \bar{D}D^*_{sJ}(2317)^+$, $D^*_{sJ}(2317)^+ \to D_s^+\pi^0$, by looking at the angle of the D_s^+ w.r.t. the $D^*_{sJ}(2317)^+$ flight direction in the $D^*_{sJ}(2317)^+$ CM frame, $\theta_{D_s\pi}$; see Fig. 6. They find this angle to have a flat

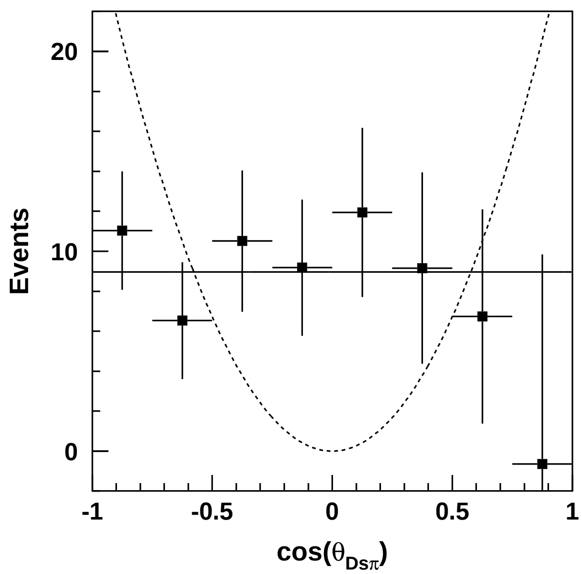

Figure 6: Efficiency corrected angular distribution for $D^*_{sJ}(2317)^+ \to D_s^+\pi^0$. The solid (dashed) line shows the expectation for spin 0 (spin 1).

distribution, consistent with spin 0 and inconsistent with the $dN/d\cos\theta_{D_s\pi} \propto \cos^2\theta_{D_s\pi}$ expectation for spin 1. So from the observed decay mode and angular distribution, one concludes that the $D^*_{sJ}(2317)$ is a $\mathrm{J^P} = 0^+$ particle.

BABAR observes the $D_{sJ}(2460)$ in three channels: $D_{sJ}(2460)^+ \to D_s^*(2112)^+\pi^0$ with $D_s^*(2112)^+ \to D_s^+\gamma$, $D_{sJ}(2460)^+ \to D_s^+\gamma$, and $D_{sJ}(2460)^+ \to D_s^+\pi^+\pi^-$. Fig. 7 shows the $D_s^+\pi^0\gamma$ invariant mass spectrum. It shows a large $D_{sJ}(2460)^+$ signal ($\mathcal{O}(600)$ events) as well as reflections from the $D_s^*(2112)^+$ and the $D^*_{sJ}(2317)^+$. The latter reflection piles up right underneath the $D_{sJ}(2460)^+$ signal, making the extraction of yield, mass, and width quite difficult. Moreover, the resonance parameters can be determined with much better precision in the (all-charged) $D_s^+\pi^+\pi^-$ final state; see below.

Fig. 8 shows the $D_s^+\gamma$ invariant mass spectrum. It shows a large $D_{sJ}(2460)^+$ signal ($\mathcal{O}(900)$ events) as well as reflections from the $D^*_{sJ}(2317)^+$ and the $D_{sJ}(2460)^+$ itself. This time, though, the reflections

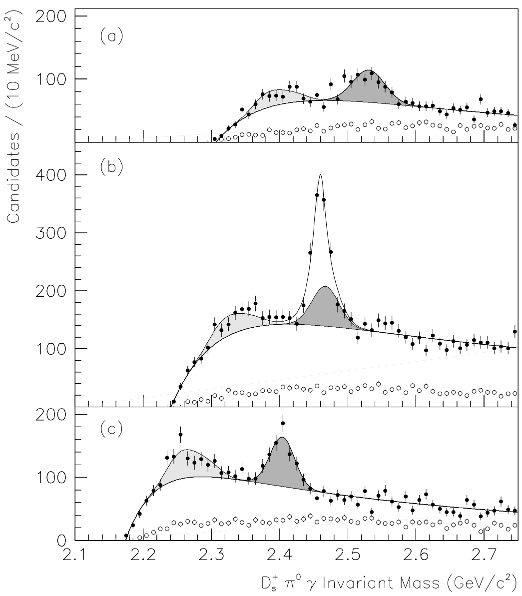

Figure 7: The invariant mass distribution of $D_s^+\pi^0\gamma$ candidates in the (a) upper, (b) signal, and (c) lower $D_s^+\gamma$ mass selection windows for (solid points) the D_s^+ signal and (open points) D_s^+ sideband samples. The dark gray (light gray) region corresponds to the predicted contribution from the $D_{sJ}^*(2317)^+$ ($D_s^*(2112)^+$) reflection.

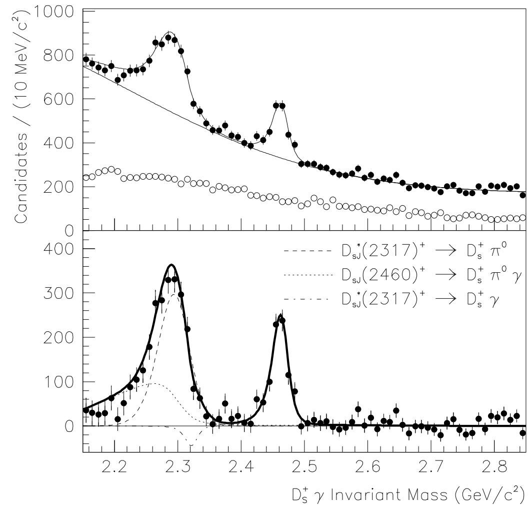

Figure 8: $D_s^+\gamma$ invariant mass distribution. The solid points in the top plot are the mass distribution. The open points are the D_s^+ sidebands, scaled appropriately. The bottom plot shows the same data after subtracting the background curve from the fit. Various contributions to the likelihood fit are also shown.

produce peaks well below the $D_{sJ}(2460)^+$. *BABAR* measures the ratio of BFs

$$\frac{\mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\gamma)}{\mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\pi^0\gamma)} = 0.337 \pm 0.036 \pm 0.038\,. \qquad (31)$$

Note that the existence of this decay mode rules out spin 0 for the $D_{sJ}(2460)$.

Belle has studied [26] the $B \to \bar{D}D_{sJ}(2460)^+$ decay angular distributions for $D_{sJ}(2460)^+ \to D_s^+\gamma$ as well as $D_{sJ}(2460)^+ \to D_s^*(2112)^+\pi^0$ by looking at the angle of the D_s^+ ($D_s^*(2112)^+$) w.r.t. the $D_{sJ}(2460)^+$ flight direction in the $D_{sJ}(2460)^+$ CM frame, $\theta_{D_s\gamma}$ ($\theta_{D_s^*\pi}$). As shown in Fig. 9 for the $D_s^+\gamma$ final state, the distribution is perfectly consistent with the spin-1 expectation, $dN/d\cos\theta_{D_s\gamma} \propto 1-\cos^2\theta_{D_s\gamma}$, and totally inconsistent with the spin-2 expectation, $dN/d\cos\theta_{D_s\gamma} \propto \sin^2\theta_{D_s\gamma}\cos^2\theta_{D_s\gamma}$. Note that the angular distributions in this decay mode cannot distinguish between positive and negative parity; this is a consequence of the (massless) photon missing the helicity-0 state. Having established that the $D_{sJ}(2460)$ is a spin-1 particle, one can use the $D_s^*(2112)^+\pi^0$ final state to establish its parity (with the $D_s^*(2112)$ being a (massive) vector particle with all three helicity components): the $\theta_{D_s^*\pi}$ distribution (see Fig. 10) is consistent with being flat, which is the expectation for a $\mathrm{J^P} = 1^+$ state with pure S-wave between the $D_s^*(2112)^+$ and the π^0 (though the appropriate combination of S- and D-wave could also produce a flat distribution). More importantly, the data is inconsistent with the expectation for $\mathrm{J^P} = 1^-$, which is $dN/d\cos\theta_{D_s^*\pi^0} \propto 1-\cos^2\theta_{D_s^*\pi^0}$. So from the observed decay modes and angular distributions, one concludes that the $D_{sJ}(2460)$ is a spin-1 particle with positive parity.

Fig. 11 shows the $D_s^+\pi^+\pi^-$ invariant mass spectrum. It shows a sizable $D_{sJ}(2460)^+$ signal ($\mathcal{O}(100)$ events) as well as a similar-size $D_{s1}(2536)^+$ signal; there is no indication of the $D_{sJ}^*(2317)^+$. Since this is an all-charged final state, *BABAR* obtains rather precise determinations of the mass and width of both states:

$$\begin{aligned} m &= (2460.2 \pm 0.2 \pm 0.8)\,\mathrm{MeV}/c^2, \\ \Gamma &< 3.5\,\mathrm{MeV}\ @\ 95\%\ \mathrm{C.L.}\,, \end{aligned} \qquad (32)$$

and

$$\begin{aligned} m &= (2534.6 \pm 0.3 \pm 0.7)\,\mathrm{MeV}/c^2, \\ \Gamma &< 2.5\,\mathrm{MeV}\ @\ 95\%\ \mathrm{C.L.} \end{aligned} \qquad (33)$$

They also measure the ratio of BFs

$$\frac{\mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\pi^+\pi^-)}{\mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\pi^0\gamma)} = 0.077 \pm 0.013 \pm 0.008\,. \qquad (34)$$

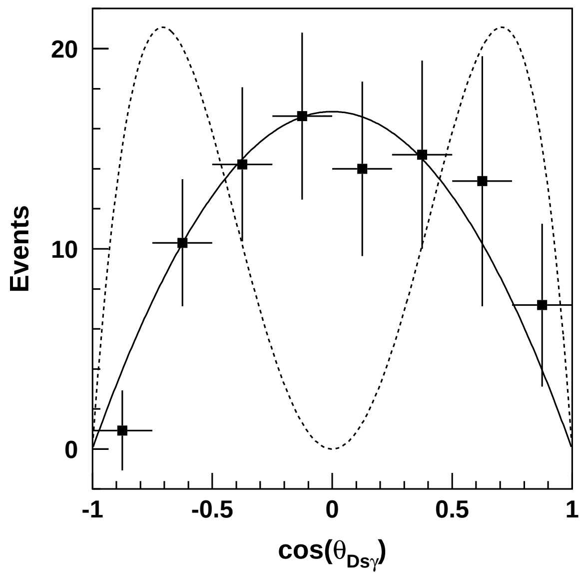

Figure 9: Efficiency corrected angular distribution, $\cos\theta_{D_s\gamma}$, for $D_{sJ}(2460)^+ \to D_s^+\gamma$. The solid (dashed) line shows the expectation for spin 1 (spin 2).

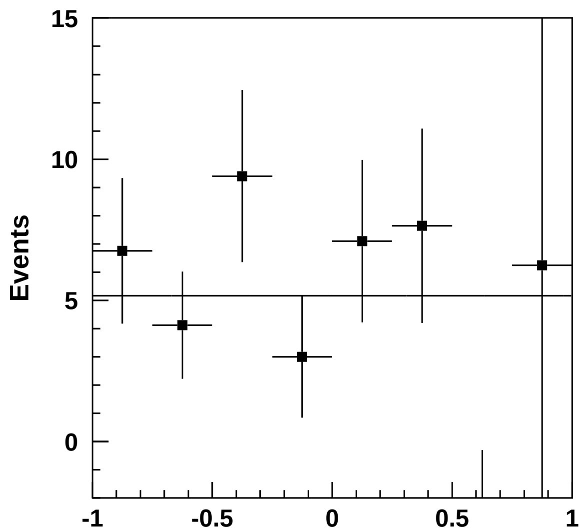

Figure 10: Efficiency corrected angular distribution, $\cos\theta_{D_s^*\pi}$, for $D_{sJ}(2460)^+ \to D_s^*(2112)^+\pi^0$. The solid line shows the expectation for spin 1 and positive parity, for a pure S-wave.

No other $D_{sJ}(2460)$ decay channels are observed. Tab. I gives a summary of the *BABAR* $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$ branching-ratio results.

BABAR has determined [27] for the first time absolute BFs for the $D_{sJ}(2460)$ using a sample of 230M $B\bar{B}$ events, where they fully reconstruct one B meson; from the decay of the other B they re-

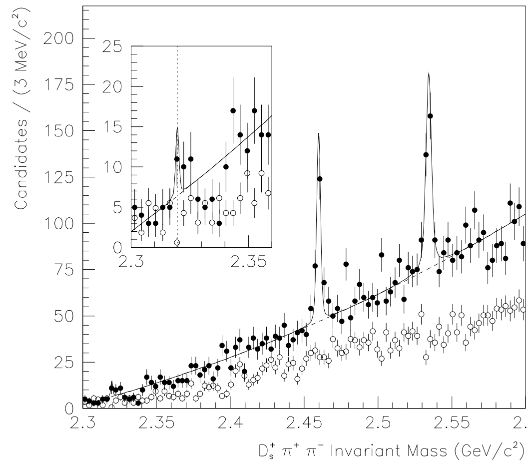

Figure 11: The invariant mass distribution of (solid points) $D_s^+\pi^+\pi^-$ candidates and (open points) the equivalent using the D_s^+ sidebands. The insert focuses on the low mass region. The dotted line in the insert indicates the $D_{sJ}^*(2317)^+$ mass.

construct a charged or neutral D or D^* and examine the mass of the X-system recoiling against it. They observe $D_{sJ}(2460)$ signals in the recoil mass, m_X, an example of which is shown in Fig. 12 for a particular B decay. Combining these re-

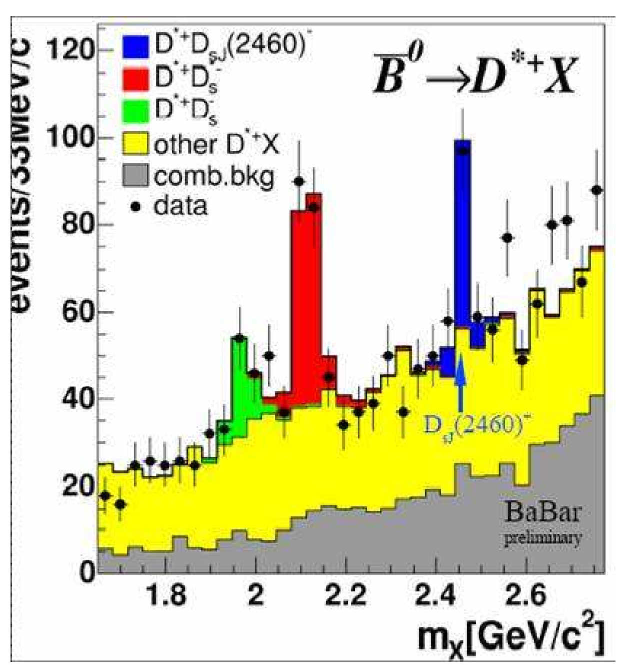

Figure 12: Recoil mass, m_x, in the decay $\bar{B}^0 \to D^{*+}X$ with signal and background overlayed.

sults with previously measured [28] exclusive prod-

Table I A summary of branching-ratio results. The first quoted uncertainty for the central value is statistical and the second is systematic. The limits correspond to 95% CL. A lower limit is quoted for the $D_{sJ}(2460)^+ \to D_s^*(2112)^+\pi^0$ results.

Decay Mode	Central Value	Limit
$\mathcal{B}(D_{sJ}^*(2317)^+ \to X)/\mathcal{B}(D_{sJ}^*(2317)^+ \to D_s^+\pi^0)$		
$D_s^+\gamma$	$-0.02 \pm 0.02 \pm 0.08$	< 0.14
$D_s^+\pi^0\pi^0$	$0.08 \pm 0.06 \pm 0.04$	< 0.25
$D_s^+\gamma\gamma$	$0.06 \pm 0.04 \pm 0.02$	< 0.18
$D_s^*(2112)^+\gamma$	$0.00 \pm 0.03 \pm 0.07$	< 0.16
$D_s^+\pi^+\pi^-$	$0.0023 \pm 0.0013 \pm 0.0002$	< 0.0050
$\mathcal{B}(D_{sJ}(2460)^+ \to X)/\mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\pi^0\gamma)$ [a]		
$D_s^+\pi^0$	$-0.023 \pm 0.032 \pm 0.005$	< 0.042
$D_s^+\gamma$	$0.337 \pm 0.036 \pm 0.038$	—
$D_s^*(2112)^+\pi^0$	$0.97 \pm 0.09 \pm 0.05$	> 0.75
$D_{sJ}^*(2317)^+\gamma$	$0.03 \pm 0.09 \pm 0.05$	< 0.25
$D_s^+\pi^0\pi^0$	$0.13 \pm 0.13 \pm 0.06$	< 0.68
$D_s^+\gamma\gamma$	$0.08 \pm 0.10 \pm 0.04$	< 0.33
$D_s^*(2112)^+\gamma$	$-0.02 \pm 0.08 \pm 0.10$	< 0.24
$D_s^+\pi^+\pi^-$	$0.077 \pm 0.013 \pm 0.008$	—

[a] Denominator includes both $D_s^*(2112)^+\pi^0$ and $D_{sJ}^*(2317)^+\gamma$ channels.

uct BFs $B \to \bar{D}^{(*)}D_{sJ}(2460)^+$, $D_{sJ}(2460)^+ \to D_s^*(2112)^+\pi^0 / D_s^+\gamma$ one obtains absolute BFs

$$\begin{aligned} \mathcal{B}(D_{sJ}(2460)^+ \to D_s^*(2112)^+\pi^0) &= 0.56 \pm 0.13 \pm 0.09\,, \\ \mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\gamma) &= 0.16 \pm 0.04 \pm 0.03\,, \\ \mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\pi^+\pi^-) &= 0.04 \pm 0.01\,. \end{aligned} \quad (35)$$

Thus, the sum of all known $D_{sJ}(2460)$ BFs comes to 0.76 ± 0.17. The error on this is unfortunately large: within $1.5\,\sigma$ we might conclude that all $D_{sJ}(2460)$ decays have been measured or that a large fraction is still missing (although it is totally unclear what sizable channel could be missing from the list that *BABAR* investigated). More data will tell, and more data will eventually enable us to perform the same type of measurement for the $D_{sJ}^*(2317)$.

In summary, *BABAR* has obtained precise measurements of the $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$ masses, widths, and decay modes, including for the first time absolute BFs, and Belle has determined the spin and parity of both states (although it is most unfortunate that the analysis in ref. [26] has never been published). Most experimental data points to an interpretation as conventional P-wave $c\bar{s}$ mesons with $J^P = 0^+$ and $J^P = 1^+$, respectively. Two wrinkles remain in this picture: a lack of understanding why the masses are lower than expected, and the apparent absence (at the current level of sensitivity) of certain radiative decays, *e.g.*, $D_{sJ}^*(2317)^+ / D_{sJ}(2460)^+ \to D_s^*(2112)^+\gamma$. More theoretical work is needed to iron this out.

4. Charmed Baryons

There has been a lot of progress in charmed-baryon spectroscopy in recent years. All nine $J^P = 1/2^+$ ground states ($L = 0$) of singly-charmed baryons in the SU(4) 20'-plet, and all but one of six of the corresponding $J^P = 3/2^+$ 20-plet ground states have been observed. Furthermore, there is a growing number of excited ($L = 1$) states. There are not yet any confirmed sightings of doubly-charmed baryons.

4.1. $\Lambda_c(2940)$

Using 287 fb^{-1} of data, *BABAR* has investigated [29] the D^0p final state in $c\bar{c}$ continuum events. Fig. 13 shows the D^0p invariant mass spectrum. Two prominent structures are immediately visible: one near a D^0p mass of 2880 MeV/c^2 ($\mathcal{O}(3000)$ events), the other near 2940 MeV/c^2 ($\mathcal{O}(2300)$ events). No structure is observed in the D^+p final state, indicating that there is no doubly-charged (isospin) partner for either state. We identify the first structure with the known $\Lambda_c(2880)$, which is observed in this final state for the first time, and measure its mass and width (preliminary)

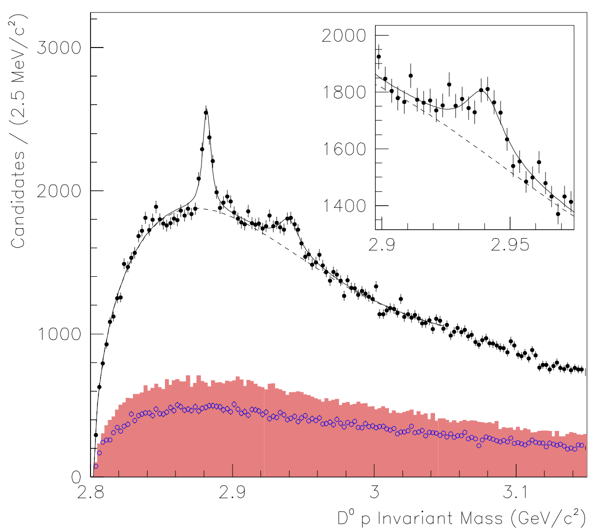

Figure 13: The solid points are the D^0p invariant mass distribution of the final sample. Also shown are (shaded) the contribution from false D^0 candidates estimated from D^0 mass sidebands and (open points) the mass distribution from wrong-sign $\overline{D}^0p$ candidates.

$$\begin{aligned} m &= (2881.9 \pm 0.1 \pm 0.5)\,\mathrm{MeV}/c^2, \\ \Gamma &= (5.8 \pm 1.5 \pm 1.1)\,\mathrm{MeV}\,, \end{aligned} \quad (36)$$

the precision of which is a large improvement over the PDG [8] values. In addition, this analysis determines the state to be an isoscalar.

The second structure we identify as a new charmed baryon, which we label $\Lambda_c(2940)$, with mass and width (preliminary)

$$\begin{aligned} m &= (2939.8 \pm 1.3 \pm 1.0)\,\mathrm{MeV}/c^2, \\ \Gamma &= (17.5 \pm 5.2 \pm 5.9)\,\mathrm{MeV}\,. \end{aligned} \quad (37)$$

The placement of this new state in the SU(4) multiplets (including its spin-parity) is not yet known.

The Belle collaboration has used $462\,\mathrm{fb}^{-1}$ of $c\bar{c}$ continuum data to analyze the $\Lambda_c^+ K^- \pi^+$ final state in search for the doubly-charmed $\Xi_{cc}(3520)^+$, reported [30] by the SELEX collaboration. They find no evidence for this state, but in the process observe two new charmed-strange baryons, $\Xi_{cx}(2980)^+$ and $\Xi_{cx}(3077)^+$, see Fig. 14, where the subscript x denotes

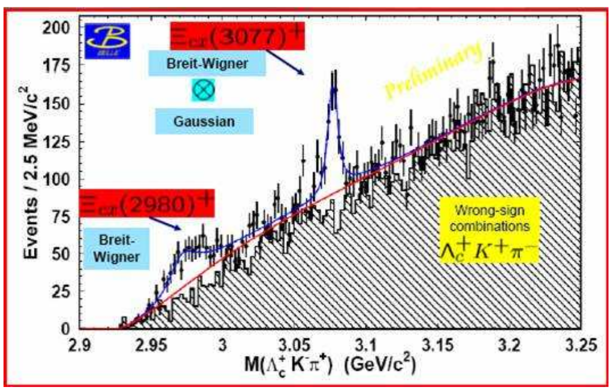

Figure 14: $\Lambda_c^+ K^- \pi^+$ invariant mass spectrum. The shaded area shows (doubly-charged) wrong-sign combinations.

the total angular momentum of the light quark system. Signal yields for the two states are $\mathcal{O}(400)$ and $\mathcal{O}(300)$ events, respectively, and their (preliminary) measured masses and widths are

$$\begin{aligned} m &= (2978.5 \pm 2.1 \pm 2.0)\,\mathrm{MeV}/c^2, \\ \Gamma &= (43.5 \pm 7.5 \pm 7.0)\,\mathrm{MeV}\,, \end{aligned} \quad (38)$$

and

$$\begin{aligned} m &= (3076.7 \pm 0.9 \pm 0.5)\,\mathrm{MeV}/c^2, \\ \Gamma &= (6.2 \pm 1.2 \pm 0.8)\,\mathrm{MeV}\,. \end{aligned} \quad (39)$$

Again, it is not yet known how these states fit into the multiplet scheme.

5. Conclusions

Over the past few years, there has been a lot of progress in the areas of charm and charmonium spectroscopy. *BABAR* and Belle have observed a number of $X/Y/Z$ states in reactions likely to produce $c\bar{c}$ states and have measured many of their properties. The $X(3940)$ and $Z(3930)$ are likely to be conventional charmonium states. The $Y(3940)$ needs confirmation whether it really is a (separate) resonant state. The $X(3872)$ and $Y(4260)$ do not fit into the scheme of conventional charmonium states. They have become good candidates for unconventional explanations, for example, in term of $\bar{D}^0$-D^{*0} molecule and $c\bar{c}g$ hybrid states.

The properties of the $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$ mesons—mass, width, decay modes, and spin-parity—have by now been determined quite precisely. Apart from the unexpectedly low masses and the smallness of certain radiative decays, the properties of both states are consistent with their interpretation as conventional P-wave $c\bar{s}$ mesons with $\mathrm{J^P} = 0^+$ and $\mathrm{J^P} = 1^+$, respectively.

BABAR and Belle keep discovering new charmed baryons, often with signals of hundreds or even thousands of events, but the interpretation of these states in terms of SU(4) multiplets is often uncertain because no spin-parity information is available.

As the B-Factory data samples keep growing, one can expect progress in understanding the nature of all these states to continue, as well as more discoveries of states of conventional and unconventional nature.

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