BLED WORKSHOPS
IN PHYSICS
VOL. 9, NO. 1
p. 78

Proceedings of the Mini-Workshop
Few-Quark States and the Continuum
Bled, Slovenia, September 15-22, 2008

Charm and Charmonium Spectroscopy at Belle

M. Bračko, representing the Belle Collaboration

University of Maribor, Smetanova ulica 17, SI-2000 Maribor, Slovenia
Jožef Stefan Institute, Jamova cesta 39, SI-1000 Ljubljana, Slovenia

Abstract. The Belle experiment at the KEKB asymmetric-energy e^+e^- collider provides an excellent environment not only for B physics, but also for studies in charm and charmonium spectroscopy. Most important Belle achievements in this field include observations of several yet undiscovered particles and measurements of their properties. In this paper we report and briefly discuss most recent of these experimental results.

1 Introduction

The Belle detector [1] at the asymmetric-energy e^+e^- collider KEKB [2] has accumulated about 850 fb^{-1} of data by July 2008. The KEKB collider is called a *B-factory*; it operates with a peak luminosity that exceeds 1.7×10^{34} $\text{cm}^{-2}\text{s}^{-1}$ at the $\Upsilon(4S)$ resonance, slightly above the $B\overline{B}$-production threshold, and the accumulated data set contains a large number of $B\overline{B}$ pairs. Although both B-factories—a similar collider called PEP-II delivers data to the *BABAR* detector—were initially designed for measurements of CP violation in the B-meson system, it was soon clear that excellent detector performance and large amount of experimental data also enable searches for new charm and charmonium states as well as studies of their properties.

2 Excited charmed strange mesons (D_{sJ})

The interest in D_{sJ} mesons received a boost after recent discoveries of two states: $D^*_{s0}(2317)^+$ in $D_s^+\pi^0$ decay mode[1] and $D_{s1}(2460)^+$ in $D_s^{*+}\pi^0$ mode, both observed with continuum $e^+e^- \to c\overline{c}$ events by the *BABAR* [3] and CLEO [4] collaborations, respectively. Belle confirmed the existence of the two states in continuum events [5], but also in $B \to \overline{D}D_{sJ}$ decays [6]. An angular analysis performed in the latter case, favours the $J^P = 0^+$ and 1^+ values for $D^*_{s0}(2317)^+$ and $D_{s1}(2460)^+$, respectively.

Due to the D_s meson in their final state, the states $D^*_{s0}(2317)^+$ and $D_{s1}(2460)^+$ are most naturally interpreted as P-wave excited $c\overline{s}$ states with $j = |\mathbf{L} + \mathbf{S}_{\overline{s}}| = 1/2$, where $|\mathbf{L}| = 1$ is the orbital angular momentum and $\mathbf{S}_{\overline{s}}$ is the spin of the

[1] Charge-conjugated modes are implied, unless explicitly stated otherwise.

light $\bar{s}$-antiquark. Nonetheless, while the masses and widths of previously observed $D_{s1}(2536)^+$ and $D_{s2}(2573)^+$ are in relatively good agreement with potential model predictions, both the masses and widths of $D^*_{s0}(2317)^+$ and $D_{s1}(2460)^+$ states are smaller than expected (see Ref. [7] for a discussion of $c\bar{s}$ models). Additionally, the mass difference between the two newly observed states is much larger that the difference between the masses of $D_{s1}(2536)^+$ and $D_{s2}(2573)^+$. All these properties have led to interpretations of the $D^*_{s0}(2317)^+$ and $D_{s1}(2460)^+$ as four-quark states or at least as states with significant four-quark content. Experimentally, these interpretations could be tested in decays $\overline{B}^0 \to D^+_{sJ}K^-$, where the initial $\overline{B}^0$-meson quark content ($b\bar{d}$) is completely different from the one in the $D^+_{sJ}K^-$ final state ($c\bar{s}s\bar{u}$). However, Belle results [8] were not conclusive about the four-quark content of $D^*_{s0}(2317)^+$ and $D_{s1}(2460)^+$, but at least supported the claim that these two states do not belong to the same spin-doublet.

2.1 Observation of a new state $D_{sJ}(2700)^+$

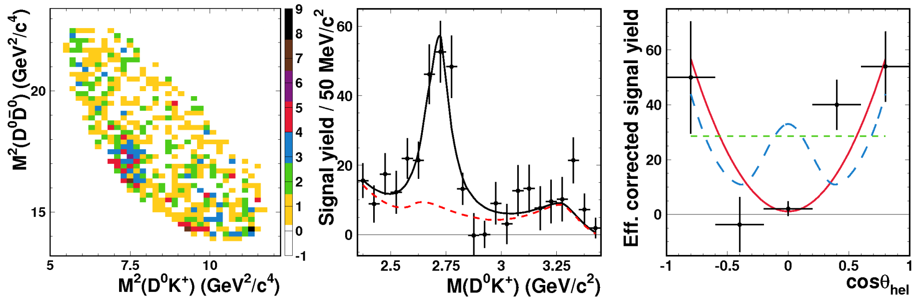

Fig.1. **Left**: Dalitz plot for $B^+ \to \overline{D}^0D^0K^+$ decays. **Centre**: B meson signal yield versus $M(D^0K^+)$ for $M(D^0\overline{D}^0) > 3.85$ GeV/c^2. The solid curve denotes the total fit result, while the dotted curve shows the sum of non-$D_{sJ}(2700)^+$ components—including the $\psi(4160)$ reflection on the right. **Right**: Efficiency corrected $D_{sJ}(2700)^+$ helicity-angle distribution together with predictions for various spin hypotheses: $J = 0$ (dotted line), 1 (solid line) and 2 (dashed line).

In order to obtain further experimental data and help resolve the issues for D_{sJ} states, Belle recently performed an analysis of the $B^+ \to \overline{D}^0D^0K^+$ decays using a data sample containing about $449 \cdot 10^6$ $B\overline{B}$ pairs [9]. A study of the Dalitz plot for the ΔE-M_{bc} signal region[2] (see the left-most plot in Fig. 1) revealed that the decay $B^+ \to \overline{D}^0D^0K^+$ proceeds dominantly via quasi-two-body channels: $B^+ \to \psi(3770)K^+$ and $B^+ \to \overline{D}^0D_{sJ}(2700)^+$. While the observed rate for $\psi(3770)$ production in B meson decays is consistent with our previous observation [10],

[2] The two kinematic variables identify B-meson candidates: $\Delta E \equiv E_B - E_{beam}$ and $M_{bc} \equiv 1/c^2\sqrt{E^2_{beam} - (p_B c)^2}$, where E_B and p_B are the energy and momentum of the B candidate, and E_{beam} is the beam energy, all expressed in the centre-of-mass (CM) frame.

the $D_{sJ}(2700)^+$ is a previously unobserved resonance in the D^0K^+ system (see the central plot in Fig. 1) with a mass of $M = (2708 \pm 9^{+11}_{-10})$ MeV/c^2 and a width of $\Gamma = (108 \pm 23^{+36}_{-31})$ MeV/c^2. The observed decay mode and angular analysis (see the right-most plot in Fig. 1) clearly favour the interpretation of $D_{sJ}(2700)^+$ as a $c\bar{s}$ meson with $J^P = 1^-$. The new meson could be a $c\bar{s}$ radially excited 2^3S_1 state [11] with a mass of $(2710 - 2720)$ MeV/c^2 or the 1^- chiral partner [12] of the $D_{s1}(2536)^+$ meson with a mass of (2721 ± 10) MeV/c^2. Additional measurements are needed for the new meson to distinguish between the two existing interpretations.

2.2 $D_{s1}(2460)^+$ - $D_{s1}(2536)^+$ Mixing

Another interesting result on D_{sJ} mesons comes from the recent study [13] of $D_{s1}(2536)^+$ mesons, produced inclusively in $e^+e^- \to D_{s1}(2536)^+X_{anything}$ reactions. The analysis is based on the e^+e^- continuum data set corresponding to 462 fb^{-1} and uses two decay modes for a $D_{s1}(2536)^+$ reconstruction, namely $D_{s1}(2536)^+ \to D^+\pi^-K^+$ and $D_{s1}(2536)^+ \to D^{*+}K^0_S$. The observed invariant mass $M_{D^+\pi^-K^+}$ and the invariant mass difference $M_{D^0\pi^+K^0_S} - M_{D^0\pi^+}$ for all selected $D^+\pi^-K^+$ and $D^0\pi^+K^0_S$ combinations are shown in Fig. 2. The ratio of branching fractions of the two studied decay modes is found to be: $\mathcal{B}(D_{s1}(2536)^+ \to D^+\pi^-K^+)/\mathcal{B}(D^0\pi^+K^0) = (3.27 \pm 0.18 \pm 0.37)\%$. The decay channel $D_{s1}(2536)^+ \to D^+\pi^-K^+$ is only the second observed three-body decay mode of the $D_{s1}(2536)^+$ meson (after $D_{s1}(2536)^+ \to D_s^+\pi^+\pi^-$) [14].

The large and clean $D_{s1}(2536)^+ \to D^{*+}K^0_S$ sample enables a partial-wave analysis for this decay mode. Heavy Quark Effective Theory (HQET) predicts that for an infinitely heavy c-quark the $D^{*+}K^0_S$ decay of the $|J^P = 1^+; j = 3/2\rangle$ state, $D_{s1}(2536)^+$, should proceed via a pure D-wave [15]. The same decay of its partner $D_{s1}(2460)^+$, the $|1^+; 1/2\rangle$ state, would proceed via a pure S-wave—if this was energetically allowed. Since the heavy quark symmetry is not exact, the two states can mix, and an S-wave component can appear in the decay $D_{s1}(2536)^+ \to D^*K$. Even if mixing is small, the S-wave contribution to the total width can be sizeable, since the D-wave contribution is strongly suppressed by the small energy release in this decay. Using a small polarization of $D_{s1}(2536)^+$ mesons produced in e^+e^- annihilations and performing a simultaneous fit to the three angles in the decay $D_{s1}(2536)^+ \to D^{*+}K^0_S; D^{*+} \to D^0\pi^+$, the measurement shows that the S-wave actually dominates. Its contribution to the total width in the decay $D_{s1}(2536)^+ \to D^{*+}K^0_S$ is $\Gamma_S/\Gamma_{total} = 0.72 \pm 0.05 \pm 0.01$. This result indicates there is a mixing between the two states: $D_{s1}(2536)^+$ and $D_{s1}(2460)^+$.

3 Charmonium and Charmonium-like States

There are several possible mechanisms of the charmonium(-like) particle production at B-factories: production in the B-meson decays, formation of C-even states in $\gamma\gamma$ processes and in e^+e^- annihilation into $J/\psi(c\bar{c})$, and creation of $J^{PC} = 1^{--}$ resonances in e^+e^- annihilation after the photon radiative return. Several of these

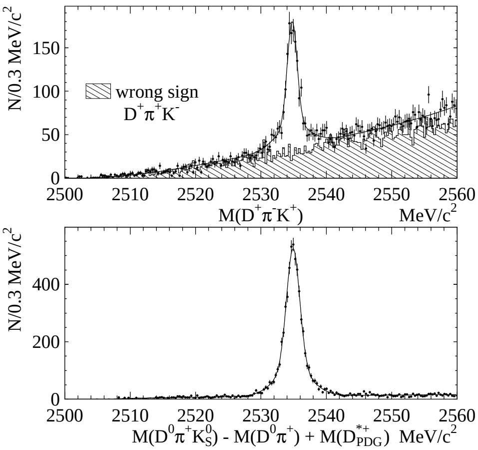

Fig.2. Invariant mass spectra of selected $D^+\pi^-K^+$ (**Top**) and $D^{*+}K^0_S$ (**Bottom**) combinations. The hatched histogram in the top plot shows the spectrum of wrong sign $D^+\pi^+K^-$ combinations. The $M(D^{*+}_{PDG})$ in the bottom denotes the D^{*+} nominal mass from Ref. [14].

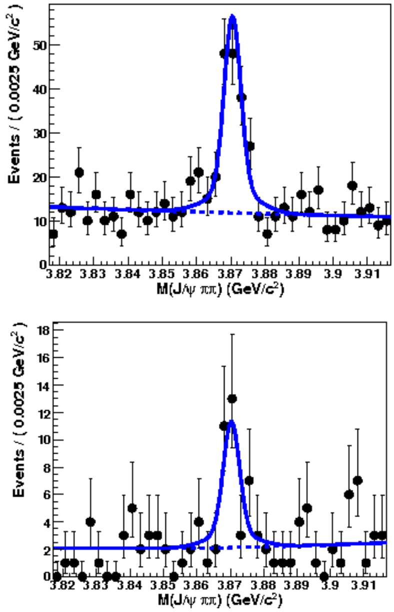

Fig.3. Invariant mass distributions of $J/\psi\pi^+\pi^-$ combinations for $B^+ \to K^+X(3872)$ (**Top**) and $B^0 \to K^0_SX(3872)$ (**Bottom**) decay candidates. The fit results are shown with solid curves.

charmonium(-like) particles have been recently discovered. The naming convention for these new X, Y, Z states indicates the lack of knowledge about their structure and properties at the time of discovery.

3.1 The X(3872) news

In 2003 Belle reported on the $B^+ \to K^+J/\psi\pi^+\pi^-$ analysis [16], where a narrow charmonium-like state X(3872) decaying to $J/\psi\pi^+\pi^-$ was discovered, and soon confirmed by CDF, D0 and *BABAR*[17]. In PDG2006 [14], the world average of the mass is (3871.2 ± 0.5) MeV/c^2 and the upper limit on its width, as measured by Belle, is 2.3 MeV. X(3872) does not appear to be a simple charmonium state and its quantum numbers are not yet determined. The observed $X(3872) \to \gamma J/\psi$ decay [18] (implying $C = +1$) as well as results of angular analyses [19,20] and studies of $J/\psi\pi^+\pi^-$ kinematical properties favour $J^{PC} = 1^{++}$ and 2^{-+} assignments. The latter possibility could have been ruled out by the study of $B \to KD^0\overline{D}^0\pi^0$ decays, where a near-threshold enhancement for the $D^0\overline{D}^0\pi^0$ invariant mass was observed at $(3875.4 \pm 0.7 \pm 1.1)$ MeV/c^2 [21]. However, since the invariant mass of the $D\overline{D}\pi$ peak was about 2σ higher than the world average value for X(3872), this result encouraged speculations about the two similar states, as predicted by a four-quark model of X(3872)[22]. Another interpretation of X(3872), a $D^0\overline{D}^{*0}$

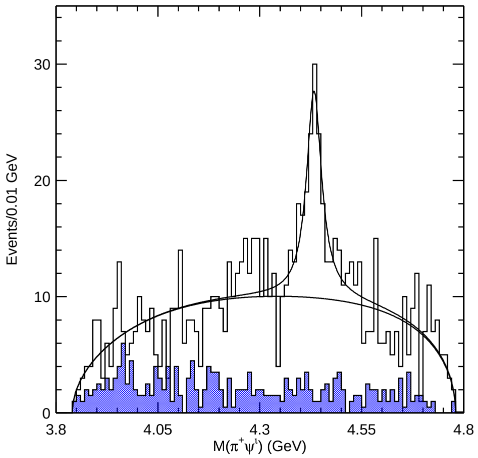

Fig.4. The $\pi^+\psi(2S)$ invariant mass distribution for events in the ΔE-M_{bc} signal region. The shaded histogram shows the scaled contribution from the ΔE sideband, while the solid curves correspond to the fit result.

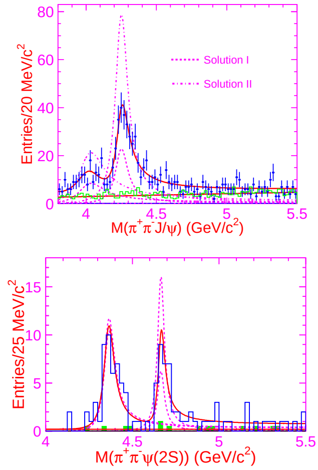

Fig.5. The mass distributions for $\pi^+\pi^- J/\psi$ (**Top**) and $\pi^+\pi^-\psi(2S)$ (**Bottom**) combinations from e^+e^- annihilation with the ISR photon. The curves show the fit and contributions of individual resonances for constructive (Solution I) and destructive (Solution II) interference.

molecule, is strongly motivated by the fact that the $X(3872)$ mass is very close to the $D^0\overline{D}^{*0}$ threshold [23].

Belle recently reported on the updated $X(3872)$ analysis, using the data sample of $657{\cdot}10^6$ $B\overline{B}$ pairs [24]. $X(3872) \to J/\psi\pi^+\pi^-$ decays are reconstructed in both charged and neutral B decays (see Fig. 3), and the observed ratio of the branching fractions, $\mathcal{B}(B^0 \to K^0_S X(3872))/\mathcal{B}(B^+ \to K^+ X(3872)) = 0.82 \pm 0.22 \pm 0.05$, is of the order of unity. Comparison of the neutral and charged B-meson signal can serve as a test for the four-quark hypothesis of $X(3872)$, which predicts the existence of two four-quark states—$c\bar{c}u\bar{u}$ should be produced mainly in charged and $c\bar{c}d\bar{d}$ in neutral B-meson decays—with a mass difference of $\Delta M = (8 \pm 3)$ MeV/c^2 [22]. In contrast to this expectation, no mass difference between the $X(3872)$ candidates in charged and neutral B-meson decay is observed: $\Delta M = (0.18 \pm 0.89 \pm 0.26)$ MeV/c^2. The measurements therefore favour the charm-meson molecular interpretation of $X(3872)$, although the virtual state of two charm mesons is also not excluded [25].

3.2 Charged charmonium-like state: $Z^+(4430)$, ...

Recently a new charged state was observed by the $B \to K\pi^\pm\psi(2S)$ Dalitz analysis, performed on a data sample with $657 \cdot 10^6$ $B\overline{B}$ pairs [26]. Both charged and neutral B decays are used, and the $\psi(2S)$ candidates are reconstructed in four decay modes: e^+e^-, $\mu^+\mu^-$, and $J/\psi\pi^+\pi^-$ with $J/\psi \to e^+e^-$, $\mu^+\mu^-$. After excluding the $K\pi$ Dalitz regions that correspond to $K^*(890)$ and $K^*_2(1430)$

Table 1. Properties of $J^{PC} = 1^{--}$ states (Y resonances) observed by Belle using the ISR technique.

Y state	Decay mode	M (MeV/c^2)	Γ (MeV)
Y(4008)	$J/\psi\pi^+\pi^-$	$4008 \pm 40^{+114}_{-28}$	$226 \pm 44 \pm 87$
Y(4260)	$J/\psi\pi^+\pi^-$	$4247 \pm 12^{+17}_{-32}$	$108 \pm 19 \pm 10$
Y(4360)	$\psi(2S)\pi^+\pi^-$	$4361 \pm 9 \pm 9$	$74 \pm 15 \pm 10$
Y(4660)	$\psi(2S)\pi^+\pi^-$	$4664 \pm 11 \pm 5$	$48 \pm 15 \pm 3$

mesons, a strong enhancement is seen in the $\pi^+\psi(2S)$ invariant mass distribution (Fig. 4). A fit with a Breit-Wigner shape yields a peak mass and width of $(4433 \pm 4 \pm 2)$ MeV/c^2 and $(45^{+18}_{-13}{}^{+30}_{-13})$ MeV, with a 6.5σ statistical significance. The observed resonance called $Z^+(4430)$—if confirmed by other experiments—would be the first charmonium-like meson candidate with non-zero charge, and could be interpreted as a charged molecular or a four-quark state. Systematic studies of $B \to K\pi(c\bar{c})$ decays could reveal other similar neutral and charged partners [22]. During the preparation of this paper, a study was already reported, indicating the existence of a broad doubly peaked structure in the $\pi^+\chi_{c1}$ mass for exclusive $\overline{B}^0 \to K^-\pi^+\chi_{c1}$ decays [27].

3.3 Study of $J^{PC} = 1^{--}$ states using ISR

Initial-state radiation (ISR) has proven to be a powerful tool to search for 1^{--} states at B-factories, since it allows to scan a broad energy range of $\sqrt{s}$ below the initial e^+e^- CM energy, while the high luminosity compensates for the suppression due to the hard-photon emission. With the ISR technique, *BABAR* discovered Y(4260) state above $D^{(*)}\overline{D}^{(*)}$ threshold in the $e^+e^- \to \gamma_{ISR}Y(4260) \to \gamma_{ISR}J/\psi\pi^+\pi^-$ process [28].

Using the same method as *BABAR* on a data sample of 548 fb^{-1}, Belle recently confirmed the Y(4260) state, but also found another resonant structure, called Y(4008) (see the top plot of Fig. 5)[29]. A similar analysis was performed on a 673 fb^{-1} data sample to study the ISR e^+e^- annihilation process resulting in the $\psi(2S)\pi^+\pi^-$ final state [30]. The obtained $\psi(2S)\pi^+\pi^-$ mass distribution, shown in the bottom plot of Fig. 5, reveals two resonant structures, called Y(4360) and Y(4660). While Y(4660) still needs a confirmation, the former resonance, Y(4360), has a mass similar to the wide structure at (4324 ± 24) MeV/c^2, observed previously by *BABAR*[31]. Fit results for Belle measurements are summarized in Table 1. The four Y states observed in $J/\psi\pi^+\pi^-$ and $\psi(2S)\pi^+\pi^-$ decay modes are distinctive, although there is a hint that Y(4260) could also be seen in the $\psi(2S)\pi^+\pi^-$ decay mode [32]. The nature of Y states and their strong couplings to $J/\psi\pi^+\pi^-$ and $\psi(2S)\pi^+\pi^-$ are somewhat puzzling: such heavy charmonium(-like) states should decay mainly to $D^{(*)}\overline{D}^{(*)}$, but it seems that observed Y states do not match the peaks in $e^+e^- \to D^{(*)\pm}D^{(*)\mp}$ cross sections, measured by Belle with ISR at $\sqrt{s} < 5$ GeV [33].

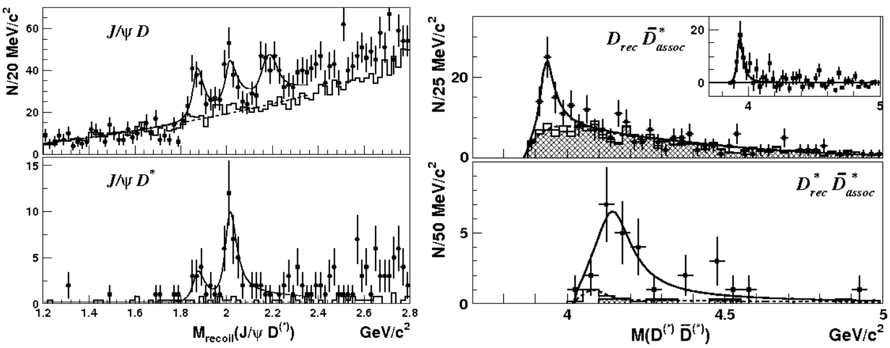

Fig.6. Left: $J/\psi D^{(*)}$ recoil mass distribution, showing peaks at D, D^* and $D^*\pi$ mass. Histograms show the scaled $D^{(*)}$ sidebands; curves indicate the total fit result (solid) and the background component (dashed). **Right**: The $D^{(*)}\overline{D}^{(*)}$ mass distributions for $e^+e^- \to J/\psi D^{(*)}\overline{D}^{(*)}$ events.

3.4 Double $c\overline{c}$ production in e^+e^- annihilation

Belle observed a surprisingly large double charmonium production in a study of the J/ψ and $\psi(2S)(\to J/\psi\pi^+\pi^-)$ recoil mass[3] spectrum for inclusive $e^+e^- \to J/\psi X$ processes [34]. The extracted $e^+e^- \to J/\psi(c\overline{c})$ cross-section was more than five times larger than values from the tree-level QCD calculation and still represents a challenge for theorists. The J/ψ recoil method was further improved

Table 2. Properties of two states observed in double $c\overline{c}$ production. Significance includes systematic uncertainties.

X state	Decay mode	M (MeV/c^2)	Γ (MeV)	Significance (σ)
X(3940)	$D\overline{D}^{(*)}$	$3942^{+7}_{-6} \pm 6$	$37^{+26}_{-15} \pm 8$	5.7
X(4160)	$D^{(*)}\overline{D}^{(*)}$	$4156^{+25}_{-20} \pm 15$	$139^{+111}_{-61} \pm 21$	5.1

and used for studies of $C = +1$ charmonium states above $D\overline{D}$ threshold. A $D^{(*)}$ meson besides the J/ψ is reconstructed, and a constraint $M_{\text{recoil}}(J/\psi D^{(*)}) \sim M(\overline{D}^{(*)}_{\text{PDG}})$ is then applied to select $e^+e^- \to J/\psi D^{(*)}\overline{D}^{(*)}$ events (see the recoil mass distributions in Fig. 6). As a result of this method, two states, X(3940) and X(4160), were identified in the $D\overline{D}^*$ and $D^*\overline{D}^*$ distributions, respectively [35,36]. The fit results for the two peaks, shown in Fig. 6, are summarized in Table 2. Possible interpretation for these states include conventional $\eta_c(3S)$ and $\chi_{c0}(3P)$ charmonia.

[3] E.g. the J/ψ recoil mass, $M_{\text{recoil}}(J/\psi) = 1/c^2\sqrt{(E_{CM} - E^*)^2 - (cp^*)^2}$, is calculated in the CM frame with the total event energy (E_{CM}) and J/ψ energy and momentum (E^* and p^*).

4 Summary and Conclusions

The Belle experiment at the KEKB collider provides an excellent environment for charm and charmonium spectroscopy. As a result, many new particles have already been discovered during the Belle operation, and some of them — like $D_{sJ}(2700)^+$, $X(3872)$, $X(3940)$, $X(4160)$ and $Z^+(4430)$— are mentioned in this report. As new experimental data are still accumulated and many studies are ongoing, more interesting results on charm and charmonium spectroscopy are to be expected from Belle in the near future.

The Belle experimental results have already raised a lot of interest among theoretical physicists. Various interpretations for the nature and properties of newly observed states have been proposed. Some of the answers might be found in the near future, perhaps following also the ideas presented at this workshop.

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