Charm cross-section and charmonium(like) states in $e^+e^-$ annihilation with Belle

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We report BELLE measurements of the exclusive cross sections for the processes $e^+e^- \rightarrow D^{(*)\pm}D^{*\mp}$, $e^+e^- \rightarrow D\bar{D}$, $e^+e^- \rightarrow D^0D^-\pi^+$, the first observation of $\psi(4415) \rightarrow D\bar{D}_2(2460)$ decay and new state, $Y(4660)$, using ISR. In addition, another cluster of events at around 4.05 GeV/$c$ is reported.

1. Introduction

Exclusive $e^+e^-$ hadronic cross sections to final states with charm meson pairs are of special interest since they provide information on the spectrum of $J^{PC} = 1^{--}$ charmonium states above the open-charm threshold. Parameters of these states obtained from fits to the inclusive cross section [1] are poorly understood theoretically [2].

Initial-state radiation (ISR) is proved to be a powerful tool for measurement of the $e^+e^-$ exclusive hadronic cross sections at $\sqrt{s}$ smaller than the initial $e^+e^-$ center-of-mass energy (E.c.m.) at $B$-factories. ISR allows to obtain cross sections in a broad energy range while the high luminosity of the $B$-factories compensates for the suppression of the ISR. T o disentangle the contributions from different final states and to suppress combinatorial backgrounds, we use the slow pion system. The square of the recoil mass is defined as:

$$M^2_{\text{rec}}(D\bar{D}) = (E_{\text{c.m.}} - E_{D\bar{D}})^2 - p_{D\bar{D}}^2,$$

where $E_{D\bar{D}}$ and $p_{D\bar{D}}$ are the c.m. energy and momentum of the $D\bar{D}$ combination, respectively.

To select $e^+e^- \rightarrow D^{(*)\pm}D^{*\mp}\gamma_{\text{ISR}}$ signal events we use the partial reconstruction method that achieves high efficiency by requiring full reconstruction of only one of the $D^{(*)\pm}$ mesons, the $\gamma_{\text{ISR}}$, and the slow $\pi_{\text{slow}}$ from the other $D^{*\mp}$ [10]. In this case the spectrum of masses recoiling against the $D^{(*)\pm}\gamma_{\text{ISR}}$ system peaks at the $D^{*\mp}$ mass. Here $E_{D^{(*)\pm}}$ and $p_{D^{(*)\pm}}$ are the c.m. energy and momentum, respectively, of the $D^{(*)\pm}\gamma_{\text{ISR}}$ combination. This peak is expected to be wide and asymmetric due to the photon energy resolution function and higher-order corrections to ISR.

2. Recoil mass technique

There are two ways of ISR event reconstruction: partial or full.

In the full reconstruction method we select $e^+e^- \rightarrow D\bar{D}\gamma_{\text{ISR}}$ signal events by reconstructing both the $D$ and $\bar{D}$ mesons. In general, the $\gamma_{\text{ISR}}$ is not required to be detected; its presence in the event is inferred from a peak at zero in the spectrum of the recoil mass against the $D\bar{D}$ system. The square of the recoil mass is defined as:

$$M^2_{\text{rec}}(D\bar{D}) = (E_{\text{c.m.}} - E_{D\bar{D}})^2 - p_{D\bar{D}}^2,$$

where $E_{D\bar{D}}$ and $p_{D\bar{D}}$ are the c.m. energy and momentum of the $D\bar{D}$ combination, respectively.

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To disentangle the contributions from different final states and to suppress combinatorial backgrounds, we use the slow pion from the unreconstructed $D^{*\mp}$. The difference between the mass recoiling against $D^{(*)\pm}\gamma_{\text{ISR}}$ and
$D^{(*)+}\pi^-_{\text{slow}}\gamma_{\text{ISR}}$ (recoil mass difference):

$$\Delta M_{\text{rec}} = M_{\text{rec}}(D^{(*)+}\gamma_{\text{ISR}}) - M_{\text{rec}}(D^{(*)+}\pi^-_{\text{slow}}\gamma_{\text{ISR}}),$$

has a narrow distribution around the nominal $m_{D_{s-}} - m_{\pi^0}$ value, since the uncertainty in $\gamma_{\text{ISR}}$ momentum partially cancels out.

3. Observation of the significant enhancement at 4.05 GeV.

We identify $e^+e^- \to J/\psi\pi^+\pi^-\gamma_{\text{ISR}}$ process by peak in the distribution on the recoil mass against the $J/\psi\pi^+\pi^-$ combination; $J/\psi$ is reconstructed in $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$ modes.

Fig. a) shows the $\pi^+\pi^- J/\psi$ invariant mass distribution in the region of 3.8–5.5 GeV/$c^2$. There is a clear enhancement at 4.25 GeV/$c^2$ similar to that observed by the BaBar Collaboration [11]. In addition, there is a clustering of events around 4.05 GeV/$c^2$ that is significantly above the background level.

An unbinned maximum likelihood fit is applied to the $\pi^+\pi^- J/\psi$ mass spectrum in Fig. a). Since there are two clusters of events in the mass distribution, we fit it with two coherent Breit-Wigner (BW) resonance functions assuming there is no continuum production of $e^+e^- \to \pi^+\pi^- J/\psi$. There are two solutions with equally good fit quality. The masses ($(4008 \pm 40^{+114}_{-28})$ MeV/$c^2$ and $(4247 \pm 12^{+17}_{-32})$ MeV/$c^2$ for the first and second states, respectively) and widths ($(226 \pm 44 \pm 87)$ MeV/$c^2$ and $(108 \pm 19 \pm 10)$ MeV/$c^2$) of the resonances are the same for both solutions; the partial widths to $e^+e^-$ and the relative phase between them are different. The interference is constructive for one solution and destructive for the other. The statistical significance of the structure around 4.05 GeV/$c^2$ is estimated to be 7.4$\sigma$ and is greater than 5$\sigma$ in all of the fitting scenarios that are considered.

4. First observation of $Y(4660)$ state.

Similar analysis is done for the $\pi^+\pi^-\psi(2S)\gamma_{\text{ISR}}$ final state.

Fig. b) shows the $\pi^+\pi^-\psi(2S)$ invariant mass for selected $\psi(2S)$ events, together with background estimated from the scaled $\psi(2S)$ mass sidebands. Two distinct peaks are evident, one at 4.36 GeV/$c^2$ and another at 4.66 GeV/$c^2$.

An unbinned maximum likelihood fit that includes two coherent $P$-wave Breit-Wigner (BW) functions and a constant, incoherent background is applied to the $\pi^+\pi^-\psi(2S)$ mass spectrum in Fig. b). The fit results in two solutions with equally good fit quality, masses ($(4361 \pm 9 \pm 9)$ MeV/$c^2$ for the first state, $(4361 \pm 9 \pm 9)$ MeV/$c^2$ for the second state) and widths ($(74 \pm 15 \pm 10)$ MeV/$c^2$ and $(48 \pm 15 \pm 3)$ MeV/$c^2$). The interference is constructive for one solution and destructive for the other. A statistical significance of 5.8$\sigma$ is obtained for the peak around 4.66 GeV/$c^2$. 

Figure 1. Fit to the a): $\pi^+\pi^- J/\psi$ b): $\pi^+\pi^-\psi(2S)$ mass spectrum with two coherent resonances. The curves show the best fit and the contribution from each component. The dashed curves are for solution I, and the dotted curves for solution II.
5. Measurement of the near-threshold $e^+e^- \rightarrow D^{(*)\pm}D^{\ast\mp}$ cross section

For the measurement of the exclusive cross section we determine the $D^{(*)\pm}D^{\ast\mp}$ mass. The $e^+e^- \rightarrow D^{(*)\pm}D^{\ast\mp}$ cross sections are extracted from the $D^{(*)\pm}D^{\ast\mp}$ mass distributions after background subtraction using the relation described in [6]. The resulting exclusive $e^+e^- \rightarrow D^{(*)\pm}D^{\ast\mp}$ cross sections are shown in Fig. 2. The shape of the $e^+e^- \rightarrow D^{(*)\pm}D^{\ast\mp}$ cross section is complicated with several local maxima and minima. Aside from a prominent excess near the $\psi(4040)$, the $e^+e^- \rightarrow D^{\ast\pm}D^{\ast\mp}$ cross section is relatively featureless. The measured cross sections are compatible [12] within errors with the $D^{(*)\pm}D^{\ast\mp}$ exclusive cross section in the energy region up to 4.260 GeV measured by CLEO-c [13].

6. Measurement of the near-threshold $e^+e^- \rightarrow D\overline{D}$ cross section

The $e^+e^- \rightarrow D^0\overline{D}^0$ and $e^+e^- \rightarrow D^+D^-$ exclusive cross sections, measured with full event reconstruction method are shown in Fig. 3. Belle results, shown with the red points, are compared to the BaBar data (blue points). The observed $e^+e^- \rightarrow D\overline{D}$ exclusive cross sections are consistent with recent BaBar measurements [14] and are in qualitative agreement with the coupled-channel model predictions of Ref. [15]. This includes a peak at 3.9 GeV/$c^2$ that is seen both in Belle and BaBar mass spectra.

7. Observation of $\psi(4415) \rightarrow D\overline{D}^0_2(2460)$ decay

We use the full reconstruction method described above to select $e^+e^- \rightarrow D^0\overline{D}^0\pi^+\pi^-\gamma_{ISR}$ signal candidates. The $e^+e^- \rightarrow D^0\overline{D}^0\pi^+$ cross section extracted from the background-subtracted $D^0\overline{D}^0\pi^+$ mass distribution demonstrates a prominent peak in a region of $\psi(4415)$ resonance. To study the resonant structure in
ψ(4415) decays, we select $D^0 D^- \pi^+$ combinations from a $\pm 100 \text{MeV}/c^2$ mass window around the nominal $\psi(4415)$ mass $[16]$. We perform a separate study of $e^+e^- \to D\bar{D}^*_{2}(2460)$ and $e^+e^- \to D(D\pi)_{\text{non} \Delta D^*_{2}(2460)}$. The $M_{D^0 D^- \pi^+}$ spectrum for the $\Delta D^*_{2}(2460)$ signal region is shown in Fig. 4(a). A clear peak corresponding to $\psi(4415) \to \Delta D^*_{2}(2460)$ decay is evident near the $\Delta D^*_{2}(2460)$ threshold. We perform a likelihood fit to $M_{D^0 D^- \pi^+}$ distribution with the $\Delta D^*_{2}(2460)$ signal parametrized by an $s$-wave RBW function. The significance for the signal is obtained to be $\sim 10\sigma$. The obtained peak mass $m_{\psi(4415)} = (4.411 \pm 0.007{\text{(stat.)}}) \text{GeV}/c^2$ and total width $\Gamma_{\text{tot}} = (77 \pm 20{\text{(stat.)}}) \text{MeV}/c^2$ are in good agreement with the PDG $[16]$ values, the recent BES results $[1]$ and predictions of Ref. $[2]$.

8. Conclusions

In summary, we presented the first observation of the new charmonium-like state, $Y(4660)$, significant enhancement near 4.05 GeV/c$^2$, the first measurement of the exclusive cross sections for the processes $e^+e^- \to D^{(*)}\bar{D}^+\pi^-$, $e^+e^- \to \Delta \bar{D}^*$, $e^+e^- \to D^0 D^- \pi^+$ and the first observation of $\psi(4415) \to \Delta D^*_{2}(2460)$ decay. The obtained ISR results are in a good agreement with the recent CLEO-c and BaBar measurements of the exclusive cross sections.

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