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MEASUREMENTS OF $E^+E^- \to D^{(*)}D^{(*)}$ AND $(C\bar{C})(C\bar{C})$ PROCESSES AT BELLE

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The results of the new Belle studies of $e^+e^- \to D^{(*)+}D^{(*)-}$process and double charm production are presented.

1 Measurement of $e^+e^- \to D^{(*)}D^{(*)}$ process

The processes $e^+e^- \to D^{(*)}\overline{D}^{(*)}$, with no extra fragmentation particles in the final state, have not previously been measured for energies $\sqrt{s} \gg 2M_D$. The cross-sections for these processes can be computed once the charmed meson form factors are determined for the appropriate value of momentum transfer, $q^2 \equiv s$. In the HQET approach based on heavy-quark spin symmetry, the form factors can be expressed in terms of a universal form factor, the Isgur-Wise function. With rising q^2 the leading-twist contribution, which violates heavy-quark spin symmetry, also becomes important. A calculation that takes these effects into account [1] predicts that the cross sections for $e^+e^- \to D\overline{D}^*$ and $D^*_L\overline{D}^*_T$ are equal; cross-sections for $D^*_L\overline{D}^*_L$ and $D^*_T\overline{D}^*_T$ are expected to be suppressed by factors ~ 20 and 30 at $\sqrt{s} \simeq 10.6\,\mathrm{GeV}$, and that for $e^+e^- \to D\bar{D}$ by a factor $\sim 10^3$. (Subscripts indicate longitudinal [L] and transverse [T] polarizations of the D^*). The prediction for the scale of the cross-sections $\sigma(e^+e^- \to D^*_L\overline{D}^*_T) \simeq 2.5$ pb is uncertain by a factor ~ 3, because the theoretical formulae contain poorly known parameters, while the prediction of ratios is expected to be more robust [2]. Recently, new calculations in the framework of the constituent quark model have become available [3], which differ from the predictions of [1] in both absolute and relative cross-sections.

In this paper, we present the first measurement of the $e^+e^- \to D^{*+}D^{*-}$ and $e^+e^- \to D^+D^{*-}$[a] cross-sections and polarizations at $\sqrt{s} \simeq 10.6\,\mathrm{GeV}$. We also set an upper limit on the cross-section for $e^+e^- \to D^+D^-$. The analysis is based on $88.9\,\mathrm{fb}^{-1}$ of data at the $\Upsilon(4S)$ resonance and nearby continuum, collected with the Belle detector [4] at the KEKB asymmetric energy e^+e^-collider [5]. We reconstruct D^0 and D^+ mesons in the decay modes $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^+\pi^-$ and $D^+ \to K^-\pi^+\pi^+$. The D^{*+} mesons are reconstructed in the $D^0\pi^+$ decay mode.

The processes $e^+e^- \to D^{(*)+}D^{(*)-}$ can be identified by energy-momentum balance in fully reconstructed events that contain only a pair of charm mesons. But the it results in tiny efficiency. However, because of the simple two-body kinematics, it is sufficient to reconstruct only one of the two charmed mesons in the

[a] charge conjugation is implied

event to identify the processes of interest. We choose the mass of the system recoiling against the reconstructed $D^{(*)+}$ ($M_{\rm recoil}(D^{(*)+})$) as a discriminating variable: $M_{\rm recoil}(D^{(*)+}) = \sqrt{(\sqrt{s} - E_{D^{(*)+}})^2 - \vec{p}^{\,2}_{D^{(*)+}}}$. For the signal process, a peak in the $M_{\rm recoil}$ distribution around the nominal D^- or D^{*-} mass is expected. This method increases the efficiency by a factor of 30–100, compared to full event reconstruction, but suffers from higher background. For the $e^+e^- \to D^+D^{*-}$ and $e^+e^- \to D^{*+}D^{*-}$ processes we find a better compromise between higher statistics and smaller background: the first $D^{(*)+}$ is fully reconstructed, while the recoiling D^{*-} is required to decay into $\overline{D}{}^0\pi^-_{slow}$. The reconstructed π^-_{slow} provides extra information that allows us to reduce the background to a negligible level using the difference between the masses of the systems recoiling against the $D^{(*)+}\pi^-_{slow}$ combination, and against the $D^{(*)+}$ alone, $\Delta M_{\rm recoil} \equiv M_{\rm recoil}(D^{(*)+}) - M_{\rm recoil}(D^{(*)+}\pi^-_{slow})$. The variable $\Delta M_{\rm recoil}$ peaks around the nominal D^{*-}–$\overline{D}{}^0$ mass difference with a resolution of $\sigma_{\Delta M_{\rm recoil}} \sim 1\,{\rm MeV}/c^2$.

The $M_{\rm recoil}(D^{*+})$ and $M_{\rm recoil}(D^+)$ distributions are shown in Figs. 1a and 1b, respectively.

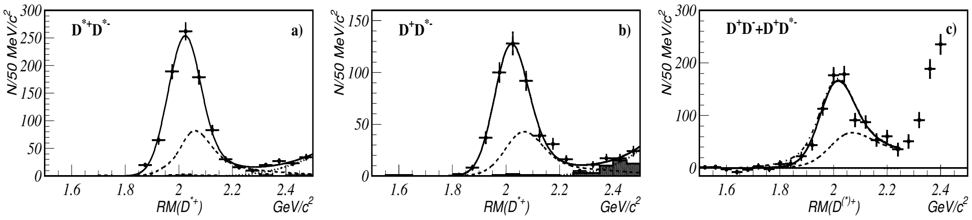

Figure 1. a) $M_{\rm recoil}(D^{*+})$ and b) $M_{\rm recoil}(D^+)$ after applying the $\Delta M_{\rm recoil}$ requirement. Points show the $\Delta M_{\rm recoil}$ signal region; hatched histograms show the $\Delta M_{\rm recoil}$ sideband; solid lines represent the fits described in the text; dotted lines are the expected background contribution. c) $M_{\rm recoil}(D^+)$ after D^+ sideband subtraction without requiring an extra π^-_{slow} in the event.

The backgrounds in the region $M_{\rm recoil} < 2.1\,{\rm GeV}/c^2$ are negligible for both processes, so we consider this interval as the signal region. There are three possible background sources: (I) incorrectly full reconstructed D^{*+} or D^+; (II) π^-_{slow} produced not from D^{*-} decay and thus gives no peak in the $\Delta M_{\rm recoil}$ distribution; (III) $e^+e^- \to D^{(*)+}D^{*-}$, with addition pion

To estimate background (I) numerically, we count the entries in the signal region for the D^{*+} or D^+ mass sidebands. Background (II) is estimated using the $\Delta M_{\rm recoil}$ sideband. The residual background (III) contribution in the signal region is estimated from the fit to the $M_{\rm recoil}(D^{*+})$ distribution. We estimate the total background in the $M_{\rm recoil} < 2.1\,{\rm GeV}/c^2$ interval to be of the order of 1% of the signal for both processes and therefore assume that all events in the interval $M_{\rm recoil} < 2.1\,{\rm GeV}/c^2$ are signal, and include the possible background contribution in the systematic error.

We perform an angular analysis before computing cross-sections. A scatter plot of the helicity angles for the two D^*-mesons from $e^+e^- \to D^{*+}D^{*-}$ ($\cos\phi(D^*_{rec})$

vs. $\cos\phi(D^*_{non-rec})$) for the signal region is shown in Fig. 2a. This two dimensional distribution is fitted by a sum of three functions corresponding to the $D^*_T D^*_T$, $D^*_T D^*_L$ and $D^*_L D^*_L$ final states, obtained from the MC simulation. Figure 2b shows the D^{*-} meson helicity distribution for $e^+e^- \to D^+D^{*-}$. We conclude that in $e^+e^- \to D^{*+}D^{*-}$ and $e^+e^- \to D^+D^{*-}$ production the final states are saturated by $D^*_T D^*_L$ and DD^*_T. After the correction on reconstruction efficiencies we calculate the Born cross-sections for $e^+e^- \to D^{(*)+}D^{*-}$ listed in Table 1.

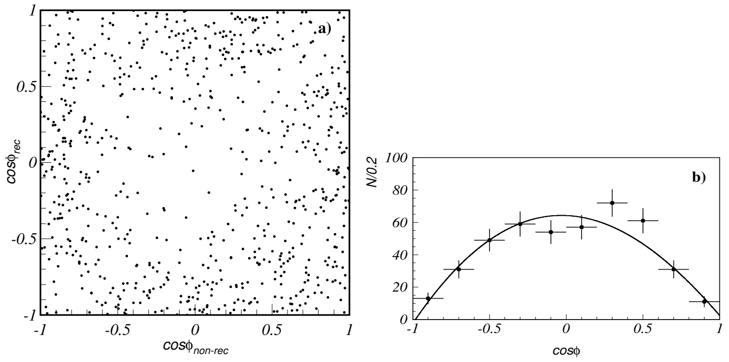

Figure 2. a) A scatter plot of $\cos(\phi_{D^*_{rec}})$ *vs.* $\cos(\phi_{D^*_{non-rec}})$ for $e^+e^- \to D^{*+}D^{*-}$ events. b) D^{*-} meson helicity angle distribution for $e^+e^- \to D^+D^{*-}$ signal candidates. The curve represents the fit described in the text.

Table 1. The Born cross-section results. The first error is statistical and the second one is systematical.

Process	σ_{Born} (pb)	Process	σ_{Born} (pb)
$e^+e^- \to D^{*+}_T D^{*-}_T$	< 0.02 @ 90% CL	$e^+e^- \to D^+ D^{*-}_L$	< 0.006 @ 90% CL
$e^+e^- \to D^{*+}_T D^{*-}_L$	$0.55 \pm 0.03 \pm 0.05$	$e^+e^- \to D^+ D^{*-}_T$	$0.62 \pm 0.03 \pm 0.06$
$e^+e^- \to D^{*+}_L D^{*-}_L$	< 0.02 @ 90% CL	$e^+e^- \to D^+ D^-$	< 0.04 @ 90% CL

We search for the process $e^+e^- \to D^+D^-$ by studying the mass spectrum of the system recoiling against the reconstructed D^+. Without $\Delta M_{\rm recoil}$ requirement the combinatorial non-D^+ background is significant. We use D^+ mass sidebands to extract the $M_{\rm recoil}$ distribution for the combinatorial background. Figure 1c shows the $M_{\rm recoil}(D^+)$ distribution after D^+ mass sideband subtraction. We fit this distribution with the sum of two signal functions corresponding to D^- and D^{*-} peaks and a background function. For the fit we use only the region $M_{\rm recoil} < 2.25\,{\rm GeV}/c^2$, because of a possible contribution of $e^+e^- \to D^{(*)}D^{**}$ at higher $M_{\rm recoil}$.

2 Charmonium production

The mechanism of charmonium production in various processes remains a puzzle after many years. Theoretically, the $e^+e^- \to J/\psi gg$ process was considered to be the leading mechanism with a cross-section as high as 1 pb; the color-octet $e^+e^- \to J/\psi g$ contribution could be also significant. In contrast, none of these processes were observed experimentally sofar, while the process $e^+e^- \to J/\psi c\bar{c}$ was measured by Belle with unexpectedly large cross-section [6]. An updated study of charmonium production with additional $c\bar{c}$ pair using a data sample of $101.8\,\mathrm{fb}^{-1}$ collected at the $\Upsilon(4S)$ resonance and nearby continuum are presented here.

In a previous study a significant peak was observed around the η_c mass in the spectrum of the mass recoiling against the J/ψ. In an attempt to explain the large cross-section [7] at least partially, it is suggested in [8] that processes proceeding via two virtual photons may be important and that the observed $e^+e^- \to J/\psi\,\eta_c$ signal might also include double J/ψ events.

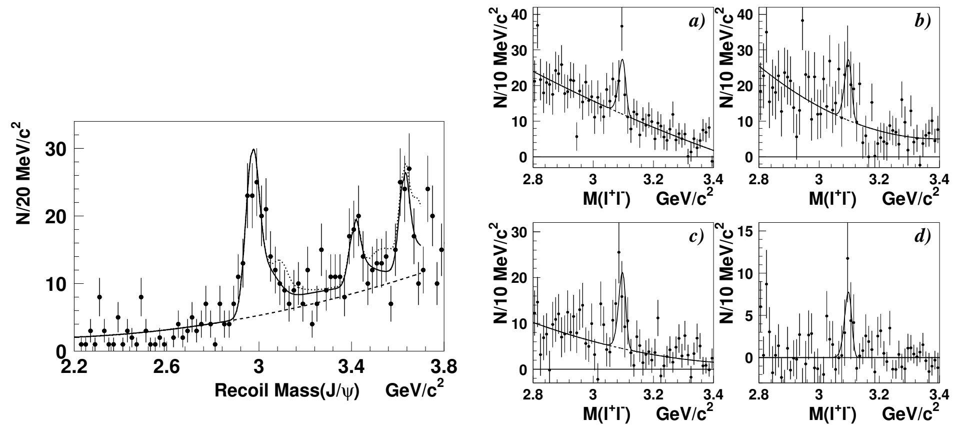

Figure 3. The distribution of recoil mass against the J/ψ (left). Charm meson signals in bins of $\ell^+\ell^-$ mass: a) $D^0 \to K^-\pi^+$; b) $D^0 \to K^-3\pi^\pm$; c) $D^+ \to K^-2\pi^+$; d) $D_s^+ \to K^-K^+\pi^+$. The curves represent the fit described in the text(right).

The spectrum of recoil masses against the J/ψ in the updated data sample is shown in Fig. 3(left): a clear peak is observed around the η_c nominal mass, and a smaller peak is seen around the χ_{c0} nominal mass; the large peak at $\sim 3.63\,\mathrm{GeV}/c^2$ is interpreted as the $\eta_c(2S)$. In this paper we extend our analysis by including all the known charmonium states in the fit to the spectrum of recoil mass against the reconstructed J/ψ. The fit results, listed in Table 2(left), give negative yields for the J/ψ, χ_{c1}, χ_{c2} and $\psi(2S)$. We performed another fit with all these contributions fixed at zero; the result of the latter fit is shown as the solid line in Fig. 3(left). The dotted line in Fig. 3(left) corresponds to the case where the contributions of the J/ψ, χ_{c1}, χ_{c2} and $\psi(2S)$ are set at their 90% confidence level upper limit values. The dashed line is the background function.

Table 2. Summary of the signal yields, charmonium masses and significances for $e^+e^- \to J/\psi, (c\bar{c})_{res}$, cross-sections and upper limits (at 90% CL): $\sigma(e^+e^- \to (c\bar{c})_{res\,1}(c\bar{c})_{res\,2}) \times \mathcal{B}((c\bar{c})_{res\,2} \to \geq 4\,\mathrm{charged})$ (fb).

	N	M [GeV/c^2]	σ	cross-section
η_c	175 ± 23	2.972 ± 0.007	9.9	$46 \pm 6^{+7}_{-9}$
J/ψ	-9 ± 17	fixed	—	< 8
χ_{c0}	61 ± 21	3.409 ± 0.010	2.9	$16 \pm 5 \pm 4$
$\chi_{c1} + \chi_{c2}$	-15 ± 19	fixed	—	< 8
$\eta_c(2S)$	107 ± 24	3.630 ± 0.008	4.4	$25 \pm 6 \pm 6$
$\psi(2S)$	-38 ± 21	fixed	—	< 16

Table 3. Summary of the signal yields and significances for $e^+e^- \to J/\psi D(\Lambda_c)X$.

mode	$D^0 \to K^-\pi^+$	$D^0 \to K^-3\pi^\pm$	$D^+ \to K^-2\pi^+$	$D_s^+ \to K^+K^-\pi^+$	$\Lambda_c \to K^-p\pi^+$
N_{ev}	49.6 ± 13.3	53.0 ± 21.2	56.2 ± 15.4	23.8 ± 9.4	3.0 ± 4.2
σ	3.7	2.5	3.6	2.6	—

In the published Belle paper [6] the $e^+e^- \to J/\psi c\bar{c}$ cross-section was calculated with method relied on the LUND fragmentation model. In the present study we reconstruct as many ground state charm hadrons as possible to reduce the model dependence: $D^0 \to K^-\pi^+(K^-3\pi^\pm)$, $D^+ \to K^-2\pi^+$, $D_s^+ \to K^+K^-\pi^+$ and $\Lambda_c \to pK^-\pi^+$ decay modes are used. To extract the number of charmed hadrons produced conjointly with J/ψ the charmed hadron signals are fitted in bins of dilepton mass. The latter distributions are fitted by a sum of J/ψ signal and second order polynomial functions. Fits are shown in Fig. 3(right) and the results are listed in Table 3. The number of $e^+e^- \to J/\psi\, c\bar{c}$ events is calculated as a sum over the D^0, D^+, D_s^+, Λ_c and $(c\bar{c})_{res}$ yields corrected for the efficiency. Taking into account the total number of reconstructed J/ψ we finally calculate $\frac{\sigma(e^+e^- \to J/\psi\, c\bar{c})}{\sigma(e^+e^- \to J/\psi\, X)} = 0.82 \pm 0.15 \pm 0.14$

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