Production of New Charmoniumlike States in $e^+e^- \to J/\psi D^{(*)}\bar{D}^{(*)}$ at $\sqrt{s} \approx 10.6$ GeV

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0031-9007/08/100(20)/202001(5)

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(Received 5 October 2007; published 19 May 2008)

We report a study of the processes $e^+e^- \to J/\psi D^{(*)}\bar{D}^{(*)}$. In $J/\psi D^*\bar{D}^*$ we observe a significant enhancement in the $D^*\bar{D}^*$ invariant mass spectrum, which we interpret as a new charmoniumlike state and denote $X(4160)$. The $X(4160)$ parameters are $M = (4156^{+25}_{-20} \pm 15)\ \mathrm{MeV}/c^2$ and $\Gamma = (139^{+111}_{-61} \pm 21)\ \mathrm{MeV}$. We also report a new measurement of the $X(3940)$ mass and width: $M = (3942^{+7}_{-6} \pm 6)\ \mathrm{MeV}/c^2$ and $\Gamma = (37^{+26}_{-15} \pm 8)\ \mathrm{MeV}$. The analysis is based on a 693 fb^{-1} data sample recorded near the $\Upsilon(4S)$ resonance by the Belle detector at the KEKB asymmetric-energy collider.

DOI: 10.1103/PhysRevLett.100.202001 PACS numbers: 13.66.Bc, 12.38.Bx, 14.40.Gx

Double charmonium production in e^+e^- annihilation, first observed by Belle in 2002 [1], can be used to search for new charmonium states with charge conjugation $C = +1$, recoiling against known and easily reconstructed $C = -1$ charmonium mesons such as the J/ψ or $\psi(2S)$. Studies of various double charmonium final states [2,3] have demonstrated that there is no significant suppression of the production of radially excited states: the cross sections for $J/\psi\eta_c$, $\psi(2S)\eta_c$, $J/\psi\eta_c(2S)$, and $\psi(2S)\eta_c(2S)$ are comparable. These studies also show that scalar and pseudoscalar charmonia are produced copiously recoiling against a J/ψ or $\psi(2S)$. A new charmoniumlike state, the $X(3940)$, has previously been observed in the spectrum recoiling against J/ψ, and reconstructed in the $D^*\bar{D}$ [4] final state [5]. Recently, there have been a number of reported new charmonium or charmoniumlike states above the $D\bar{D}$ threshold [6] with properties that are quite different from those expected in the quark model. These experimental results have renewed interest in the spectroscopy, decay and production of charmonia [7].

In this Letter we report the observation of a new charmoniumlike state in the process $e^+e^- \to J/\psi D^{(*)}\bar{D}^{(*)}$ and the measurement of its parameters. We also present a new measurement of the $X(3940)$ resonance parameters. The integrated luminosity used for this analysis is 693 fb^{-1} collected with the Belle detector [8] near the $\Upsilon(4S)$ resonance at the KEKB asymmetric-energy e^+e^- collider [9].

This study is performed using event selection and J/ψ reconstruction procedures identical to those used in Refs. [1,5]. We reconstruct D^0 mesons using five decay modes: $K^-\pi^+$, K^-K^+, $K^-\pi^-\pi^+\pi^+$, $K^0_S\pi^+\pi^-$ and $K^-\pi^+\pi^0$. Candidate D^+ mesons are reconstructed using $K^-\pi^+\pi^+$, $K^-K^+\pi^+$ and $K^0_S\pi^+$ decay modes. A $\pm 15\ \mathrm{MeV}/c^2$ mass window is used for all modes except $D^0 \to K^-\pi^+\pi^0$ ($\pm 20\ \mathrm{MeV}/c^2$) ($\approx 2.5\sigma$ in each case). To improve their momentum resolution, D candidates are refitted to their nominal masses. To study the contribution of combinatorial background under the D peak, we use D sidebands selected from a mass window 4 times as large. For the study of the process $e^+e^- \to J/\psi D^*\bar{D}^*$ we use only the cleanest channel, $D^{*+} \to D^0\pi^+$. D^{*+} candidates from the signal window, selected in the interval $\pm 3\ \mathrm{MeV}/c^2$ of the D^{*+} mass ($\approx 3\sigma$), are refitted to the D^{*+} mass. The D^{*+} sideband region is defined by $[2.016, 2.028]\ \mathrm{GeV}/c^2$. Only one $J/\psi D$ or one $J/\psi D^{*+}$ combination per event is accepted; the combination with the best sum of χ^2 of the mass fits for J/ψ and $D^{(*)}$ candidates is selected. In the $D^{(*)}$ sidebands a single candidate per event is selected as well. The sideband is divided into windows of the same width as the signal one, and the candidate with the smallest difference in mass from the center of its window is chosen.

The method for reconstructing the processes $e^+e^- \to J/\psi D^{(*)}\bar{D}^{(*)}$ is described in [5]. In addition to the reconstructed J/ψ, only one of the $D^{(*)}$'s is fully reconstructed (referred to below as $D^{(*)}_{\mathrm{rec}}$: $D_{\mathrm{rec}} = D^0$ or D^+, $D^*_{\mathrm{rec}} = D^{*+}$), and the other unreconstructed $\bar{D}^{(*)}$ (referred to as associated $D \equiv \bar{D}^{(*)}_{\mathrm{assoc}}$) in the event is observed as a peak in the spectra of masses recoiling against the reconstructed combination $J/\psi D^{(*)}_{\mathrm{rec}}$. The recoil mass against the particle or combination of particles is defined as $M_{\mathrm{recoil}}(X) = \sqrt{(E_{\mathrm{CM}} - E^*_X)^2 - p^{*2}_X}$, where E^*_X and p^*_X are the center-of-mass (c.m.) energy and momentum of the (combination of) particle(s). The $M_{\mathrm{recoil}}(J/\psi D^{(*)}_{\mathrm{rec}})$ peak around the D and

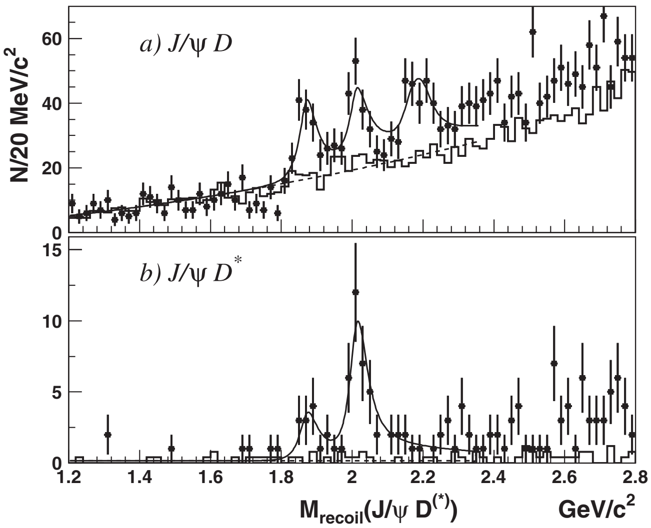

FIG. 1. Distributions of $M_{\rm recoil}(J/\psi D^{(*)}_{\rm rec})$ in the data. Histograms show the scaled $D^{(*)}$ sidebands; curves show the fit results (solid) and the background component (dashed).

D^* masses with a resolution $\sim 30\ {\rm MeV}/c^2$ is used to identify the studied process. As the resolution is smaller than $M_{D^*} - M_D$, the method allows the contributions from the processes $e^+e^- \to J/\psi D\bar{D}$, $D^*\bar{D}$ and $D^*\bar{D}^*$ to be disentangled. The $M_{\rm recoil}(J/\psi D_{\rm rec})$ and $M_{\rm recoil}(J/\psi D^*_{\rm rec})$ spectra in the data are shown in Fig. 1 as points with error bars for the signal $D^{(*)}_{\rm rec}$ windows; histograms show the scaled $D^{(*)}_{\rm rec}$ sideband distributions. The signals for the processes $e^+e^- \to J/\psi D\bar{D}$, $D^*\bar{D}$ and $D^*\bar{D}^*$ are evident in Fig. 1(a) at the D and D^* nominal masses and at a mass $\sim 2.2\ {\rm GeV}/c^2$, respectively. The latter peak is shifted and widened due to a missing pion or photon from D^* decays. The processes $e^+e^- \to J/\psi D^*\bar{D}$ and $D^*\bar{D}^*$ are also clearly seen in Fig. 1(b) as distinct peaks around the D and D^* masses. We use sidebands to describe the combinatorial background contribution through simultaneous likelihood fits to the $D^{(*)}_{\rm rec}$ signal and sideband spectra. The signal shapes are fixed from the Monte Carlo (MC) simulation. The background distribution is parameterized by a second-order polynomial function (linear function in case of $D^*_{\rm rec}$). Only the region below $2.35\ {\rm GeV}/c^2$ is used because of a possible contribution from $e^+e^- \to J/\psi D\bar{D}^{**}$. The signal yields (including the tail due to initial state radiation [ISR]) and statistical significances are listed in Table I.

We perform a study of these observed processes and search for new charmonium states $X_{c\bar{c}}$ that can be produced

TABLE I. Yields (and significances) from the fits to the $M_{\rm recoil}(J/\psi D_{\rm rec})$ and $M_{\rm recoil}(J/\psi D^*_{\rm rec})$ spectra.

$e^+e^- \to$	$J/\psi D\bar{D}$	$J/\psi D^*\bar{D}$	$J/\psi D^*\bar{D}^*$
$J/\psi D_{\rm rec}$	$162 \pm 25(7.6\sigma)$	$159 \pm 28(6.5\sigma)$	$173 \pm 32(5.6\sigma)$
$J/\psi D^*_{\rm rec}$	-	$19.0^{+6.3}_{-5.3}(5.8\sigma)$	$47.2^{+8.5}_{-7.8}(8.4\sigma)$

via $e^+e^- \to J/\psi X_{c\bar{c}}$ followed by the decay $X_{c\bar{c}} \to D^{(*)}\bar{D}^{(*)}$. Tagging the process $e^+e^- \to J/\psi D^{(*)}\bar{D}^{(*)}$ by the requirement $|M_{\rm recoil}(J/\psi D^{(*)}_{\rm rec}) - M_{D^{(*)}}| < 70\ {\rm MeV}/c^2$ we thus divide each of selected $J/\psi D$ or $J/\psi D^{*+}$ combinations into two nonoverlapping samples, each comprising $\sim 50\%$ of the signal events. The ISR tail causes an inefficiency for the tagging requirement as well as cross talk between different final states: the contribution of the process $e^+e^- \to J/\psi D\bar{D}(D^*\bar{D})$ to the sample tagged as $e^+e^- \to J/\psi D^*\bar{D}(D^*\bar{D}^*)$ is $\sim 10\%$, the reverse cross talk is only $\sim 1.5\%$ and neglected. In our study we constrain $M_{\rm recoil}(J/\psi D^{(*)}_{\rm rec})$ to the $\bar{D}^{(*)}_{\rm assoc}$ nominal mass. This improves the resolution on $M_{\rm recoil}(J/\psi)$, which corresponds to the invariant mass of the produced $D^{(*)}$ meson pair, by a factor of 3–10 with respect to the unconstrained value ($\sim 30\ {\rm MeV}/c^2$). The $M(D^{(*)}\bar{D}^{(*)})$ resolution varies from $2\ {\rm MeV}/c^2$ at threshold to $8\ {\rm MeV}/c^2$ at $M(D^{(*)}\bar{D}^{(*)}) = 5.0\ {\rm GeV}/c^2$ for all the processes except $e^+e^- \to J/\psi D^*\bar{D}$ with $D_{\rm rec}\bar{D}^*_{\rm assoc}$. In the latter case the resolution is worse because of the $D_{\rm rec}$ from the D^* decay [$\sim 10\ {\rm MeV}/c^2$ at $M(D^*\bar{D}) \sim 3.94\ {\rm GeV}/c^2$].

In the data the spectra of $M(D^{(*)}\bar{D}^{(*)})$ are shown in Figs. 2(a)–2(d) for $D_{\rm rec}\bar{D}_{\rm assoc}$, $D_{\rm rec}\bar{D}^*_{\rm assoc}$, $D^*_{\rm rec}\bar{D}_{\rm assoc}$, $D^*_{\rm rec}\bar{D}^*_{\rm assoc}$ cases, respectively. Points with error bars correspond to the $D^{(*)}_{\rm rec}$ signal windows; hatched histograms show the scaled $D^{(*)}_{\rm rec}$ sideband distributions. Excesses from the signal $D_{\rm rec}$ window over the sideband distributions are seen around the threshold in all figures. The reflections ($D\bar{D} \to D^*\bar{D}$ and $D^*\bar{D} \to D^*\bar{D}^*$) estimated using the MC simulation are shown with open histograms. Simulated $e^+e^- \to J/\psi D^{(*)}\bar{D}^{(*)}$ MC events are generated with $M(D^{(*)}\bar{D}^{(*)})$ spectra tuned to the data.

We perform simultaneous likelihood fits to $D^{(*)}_{\rm rec}$ signal and sideband distributions to fix the combinatorial background shapes. The accuracy of description of combinatorial backgrounds by $D^{(*)}_{\rm rec}$ sidebands is validated with the MC simulation and with the data, where the $M(D^{(*)}\bar{D}^{(*)})$ spectra in the different sideband intervals are found to be in good agreement with each other. The combinatorial backgrounds are parameterized by $A\sqrt{M - M_{\rm thr}}e^{-BM}$, where A and B are free parameters, except for the case $D_{\rm rec}\bar{D}_{\rm assoc}$, where this shape is found to describe poorly the behavior of the background. In the latter case we parameterize the background by a relativistic Breit-Wigner (BW) function with a free mass, width and amplitude. The signal functions are a sum of a relativistic s-wave BW function and a threshold function ($\sqrt{M - M_{\rm thr}}$) to account for possible nonresonant production. The signal functions are convolved with the resolution functions and multiplied by the efficiency function obtained from the MC simulation. The reflections are taken into account in the fit.

The fitted parameters of the BW functions and significances of the resonance contributions are listed in Table II. We assess the significance of each signal from the change

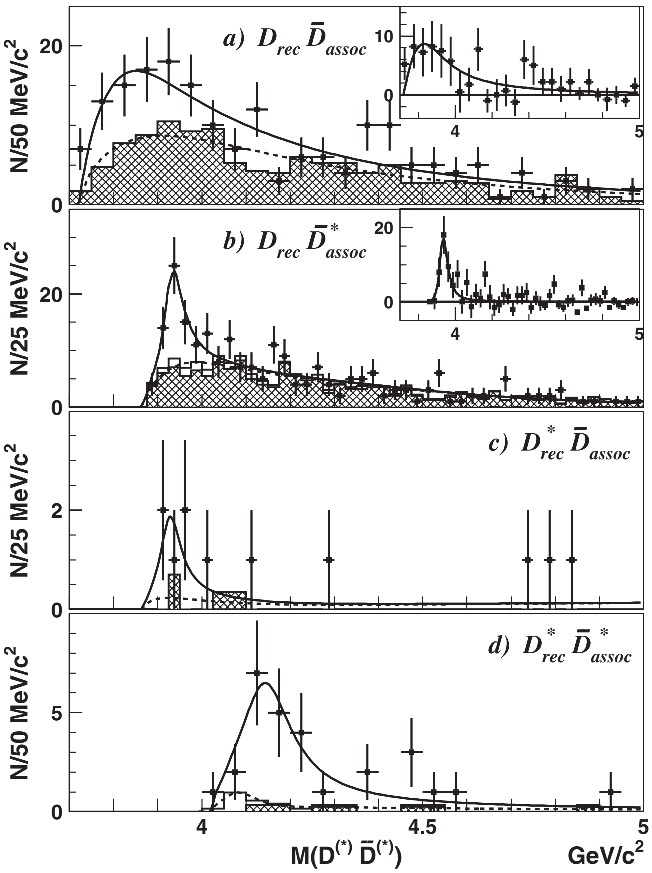

FIG. 2. The $M(D^{(*)}_{\rm rec}\bar{D}^{(*)}_{\rm assoc})$ spectra for events tagged and constrained as (a) $e^+e^- \to J/\psi D\bar{D}$, (b),(c) $e^+e^- \to J/\psi D^*\bar{D}$ and (d) $e^+e^- \to J/\psi D^*\bar{D}^*$ in the data. The solid lines represent the fit results; the dashed lines are background functions.

in the likelihood value when the signal and its three associated degrees of freedom are removed from the fit. The nonresonant contributions are consistent with zero within 1σ in all fits, except for the case $D^*_{\rm rec}\bar{D}_{\rm assoc}$ (1.6σ from zero). The fit results are shown in Fig. 2 as the solid curves; the dashed curves are the background functions. The insets in Figs. 2(a) and 2(b) show the background subtracted spectra with the signal functions superimposed.

A fit to the $M(D\bar{D})$ distribution finds a broad resonance near the threshold, which is tentatively denoted as $X(3880)$, with a statistical significance of only 3.8σ. However, the fit is not stable under variation of background parameterization as well as variation of the bin width. The fit with two resonances better describes the spectrum and is more stable, but the significance of the second resonance is lower than 3σ. We conclude that the observed threshold enhancement is not consistent with nonresonant $e^+e^- \to J/\psi D\bar{D}$ production, but with the present statistics the resonant structure in this process cannot be reliably determined. The significance of the $X(3940)$ signal found by the fit to the $M(D_{\rm rec}\bar{D}^*_{\rm assoc})$ spectrum is 6.0σ. The fitted width of $X(3940)$ is slightly higher than that obtained in our previous analysis [5]. The mass of the state is in good agreement with the previously reported mass; the signal yield scales in proportion to luminosity. The $X(3940)$ signal is also seen in the $M(D^*_{\rm rec}\bar{D}_{\rm assoc})$ spectrum with a significance of 2.8σ, with parameters in good agreement with those from the $M(D_{\rm rec}\bar{D}^*_{\rm assoc})$ fit. As this sample is a small subsample of the $D_{\rm rec}\bar{D}^*_{\rm assoc}$ case, we use the latter fit only as a cross check. The $M(D^*\bar{D}^*)$ spectrum has a clear broad enhancement near threshold, which is seen above the small combinatorial background and the $X(3940)$ reflection. We interpret the observed enhancement, which has a statistical significance of 5.5σ, as a new resonance and denote it as $X(4160)$. Contamination of this peak due to the process $e^+e^- \to \gamma^*\gamma^* \to J/\psi\psi(4160)$ is found to be negligible. Because of the requirement that both the J/ψ and a D^{*+} be reconstructed, the efficiency falls to zero for $|\cos(\theta^*)| \gtrsim 0.8$, where θ^* is the J/ψ production angle in the c.m. frame. Any contribution from annihilation via two virtual photons is strongly concentrated in this region and thus suppressed. Based on the predicted $e^+e^- \to J/\psi\psi(2S)$ cross section [10], and the ratio of dielectron widths of the $\psi(2S)$ and $\psi(4160)$ [11], we expect only 0.5 ± 0.3 events due to the $e^+e^- \to J/\psi\psi(4160)$ process in our final sample. Theoretical predictions for two-virtual-photon processes appear reliable: $e^+e^- \to \rho^0\rho^0$ and $\phi\rho^0$ cross sections [12] are consistent with expected values, and $J/\psi J/\psi$ and $J/\psi\psi(2S)$ signals are not seen [2], again consistent with the predicted cross sections [10]. The present data sample does not allow us to exclude the possibility that the $X(4160)$ is the result of more than one state.

The Born cross sections for the processes $e^+e^- \to J/\psi X(3940)$ $[X(4160)]$ multiplied by $\mathcal{B}_{D^{(*)}\bar{D}^*} \equiv \mathcal{B}(X \to D^{(*)}\bar{D}^*)$ are calculated from the fitted $X(3940)$ and $X(4160)$ yields with the procedure used in the previous analysis [2]:

$$\sigma(e^+e^- \to J/\psi X(3940))\mathcal{B}_{D^*\bar{D}} = (13.9^{+6.4}_{-4.1} \pm 2.2)\ \text{fb},$$
$$\sigma(e^+e^- \to J/\psi X(4160))\mathcal{B}_{D^*\bar{D}^*} = (24.2^{+12.8}_{-8.3} \pm 5.0)\ \text{fb}. \quad (1)$$

From the fits to the Figs. 2(a) and 2(b) distributions including an $X(4160)$ term, we find the following upper limits:

TABLE II. Summary of the signal yields, masses [MeV/c^2], widths [MeV] and significances for $e^+e^- \to J/\psi(D^{(*)}\bar{D}^{(*)})_{\rm res}$.

State	$N_{\rm events}$	M	Γ	$\mathcal{N}_\sigma$
$X(3880)(D_{\rm rec}\bar{D}_{\rm assoc})$	63^{+31}_{-25}	3878 ± 48	347^{+316}_{-143}	3.8
$X(3940)(D_{\rm rec}\bar{D}^*_{\rm assoc})$	52^{+24}_{-16}	3942^{+7}_{-6}	37^{+26}_{-15}	6.0
$X(3940)(D^*_{\rm rec}\bar{D}^*_{\rm assoc})$	$5.2^{+3.4}_{-2.7}$	3934^{+23}_{-17}	57^{+62}_{-34}	2.8
$X(4160)(D^*_{\rm rec}\bar{D}^*_{\rm assoc})$	$23.8^{+12.3}_{-8.0}$	4156^{+25}_{-20}	139^{+111}_{-61}	5.5

TABLE III. Summary of the systematic errors in the masses (M in MeV/c^2), widths (Γ in MeV) and production cross sections (σ in %) for $X(3940)$ [$X(4160)$] resonances.

	$X(3940)$			$X(4160)$		
Source	M	Γ	σ	M	Γ	σ
Fitting procedure	±4	±6	±5	±12	±18	±2
Selection	±4	±5	±4	±8	±11	±5
Momentum scale	±3	⋯	⋯	±3	⋯	⋯
Angular distributions	⋯	⋯	±12	⋯	⋯	±16
Reconstruction	⋯	⋯	±6	⋯	⋯	±8
Identification	⋯	⋯	±4	⋯	⋯	±4
$\mathcal{B}(D^{(*)})$	⋯	⋯	±3	⋯	⋯	±4
Total	±6	±8	±16	±15	±21	±20

$$\mathcal{B}_{D\bar{D}}(X(4160))/\mathcal{B}_{D^*\bar{D}^*}(X(4160)) < 0.09 \quad \text{at} \quad 90\%\text{C.L.},$$
$$\mathcal{B}_{D^*\bar{D}}(X(4160))/\mathcal{B}_{D^*\bar{D}^*}(X(4160)) < 0.22 \quad \text{at} \quad 90\%\text{C.L.} \tag{2}$$

The systematic errors of the parameters and production cross sections for $X(3940)$ and $X(4160)$ resonances are summarized in Table III. To estimate the fitting systematics we study the difference in $X(3940)$ [$X(4160)$] parameters returned by the fit to the Figs. 2(b) and 2(d) distributions under variation of the signal and background parameterizations, the fit ranges and the histogram bins as well as the resolution functions. We also vary the definitions of the signal and sideband regions to check the stability of the resonance parameters. Another uncertainty in the mass determination due to possible momentum scale bias was estimated in the previous paper [5] to be <3 MeV/c^2. The systematic error for the cross section calculation is dominated by the uncertainty in the J/ψ production and polarization angular distributions. In the MC calculation both angular distributions are assumed to be flat and extreme cases ($1 \pm \cos^2\theta$) are considered to estimate the systematic uncertainty in this assumption. In the case of the $X(4160)$ another source of the systematic uncertainty is the D^{*+} polarization, which is taken into account by varying the D^{*+} helicity angle distribution. Other contributions come from the uncertainty in the track and π^0 reconstruction efficiencies, lepton and kaon identification, and in the absolute $\mathcal{B}(D^{(*)})$.

In summary, we have observed the processes $e^+e^- \to J/\psi D\bar{D}$ ($D^*\bar{D}$, $D^*\bar{D}^*$) and found significant near-threshold enhancements in the $M(D^{(*)}\bar{D}^{(*)})$ spectra in each of these processes. We report the observation of the clear enhancement with a significance of 5.1σ, including systematic uncertainties, in the invariant mass distribution of $D^*\bar{D}^*$ combinations in the process $e^+e^- \to J/\psi D^*\bar{D}^*$, which we interpret as a new charmoniumlike state, the $X(4160)$. The $X(4160)$ parameters are $M = (4156^{+25}_{-20} \pm 15)$ MeV/c^2 and $\Gamma = (139^{+111}_{-61} \pm 21)$ MeV. Although the masses and widths of the $X(4160)$ and $\psi(4160)$ are not inconsistent, the contribution of the latter state to the observed peak is found to be negligibly small. We have confirmed our observation of the charmoniumlike state, $X(3940) \to D\bar{D}^*$, produced in the process $e^+e^- \to J/\psi X(3940)$ with a significance of 5.7σ, including systematics. The $X(3940)$ mass and width are $M = (3942^{+7}_{-6} \pm 6)$ MeV/c^2 and $\Gamma = (37^{+26}_{-15} \pm 8)$ MeV. These measurements are consistent with our published results and supersede them. We find that the inclusive peak in the $M_{\rm recoil}(J/\psi)$ spectrum near 3940 MeV/c^2 may consist of several states; thus, our previous measurement of $X(3940)$ branching fractions may be not reliable [5].

We thank the KEKB group for excellent operation of the accelerator, the KEK cryogenics group for efficient solenoid operations, and the KEK computer group and the NII for valuable computing and Super-SINET network support. We acknowledge support from MEXT and JSPS (Japan); ARC and DEST (Australia); NSFC and KIP of CAS (China); DST (India); MOEHRD, KOSEF and KRF (Korea); KBN (Poland); MES and RFAAE (Russia); ARRS (Slovenia); SNSF (Switzerland); NSC and MOE (Taiwan); and DOE (USA).

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