Observation of Double $c\bar{c}$ Production in e^+e^- Annihilation at $\sqrt{s} \approx 10.6$ GeV

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We report the observation of prompt J/ψ via double $c\bar{c}$ production from the e^+e^- continuum. In this process one $c\bar{c}$ pair fragments into a J/ψ meson while the remaining pair either produces a charmonium state or fragments into open charm. Both cases have been experimentally observed. We find cross sections of $\sigma[e^+e^- \to J/\psi\eta_c(\gamma)] \times \mathcal{B}(\eta_c \to \geq 4 \text{ charged}) = (0.033^{+0.007}_{-0.006} \pm 0.009)$ pb and $\sigma(e^+e^- \to J/\psi D^{*+}X) = (0.53^{+0.19}_{-0.15} \pm 0.14)$ pb and infer $\sigma(e^+e^- \to J/\psi c\bar{c})/\sigma(e^+e^- \to J/\psi X) = 0.59^{+0.15}_{-0.13} \pm 0.12$. These results are obtained from a 46.2 fb^{-1} data sample collected near the $\Upsilon(4S)$ resonance, with the Belle detector at the KEKB collider.

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Prompt charmonium production in e^+e^- annihilation provides an opportunity to study both perturbative and nonperturbative effects in QCD. In a previous Letter [1] we presented cross-section measurements for prompt J/ψ and $\psi(2S)$ production, and studies of their kinematic properties, which were compared to predictions of the effective field theory (NRQCD) [2–5] model. The BaBar Collaboration has also published results on prompt J/ψ production [6]. NRQCD predicts that prompt J/ψ production at $\sqrt{s} \approx 10.6$ GeV is dominated by $e^+e^- \to J/\psi gg$, with additional contributions from $J/\psi g$, $J/\psi c\bar{c}$, and other processes. The color-octet $J/\psi g$ signal predicted in Refs. [4,5] is not observed [1]. The results in Refs. [1,6] do not constrain the contributions from $J/\psi gg$ and $J/\psi c\bar{c}$.

In this Letter, we present the results of a search for $J/\psi c\bar{c}$ production, where the additional $c\bar{c}$ pair fragments into either charmonium or charmed hadrons. According to recent theoretical calculations the $J/\psi c\bar{c}$ cross section is as small as 0.07 pb [3,5,7].

This analysis is based on 41.8 fb^{-1} of data at the $\Upsilon(4S)$ and 4.4 fb^{-1} at an energy 60 MeV below the resonance, collected with the Belle detector at the KEKB asymmetric energy storage rings [8]. Belle is a large solid-angle magnetic spectrometer [9]. Charged particles are reconstructed in a 50-layer central drift chamber (CDC). Kaon/pion separation is based on dE/dx measurements in the CDC, time of flight measurements, and the response of aerogel Čerenkov counters (ACC). Electron identification is based on a combination of dE/dx measurements, the ACC response, and information about the shape, energy deposit, and position of the associated shower in the electromagnetic calorimeter (ECL). Muon identification is provided by 14 layers of 4.7 cm thick iron plates interleaved with resistive plate counters. Photons are reconstructed in the ECL as showers with an energy larger than 20 MeV that are not associated with charged tracks.

We use hadronic events separated from QED, $\tau\tau$, two-photon, and beam-gas interaction backgrounds by the selection criteria described in Ref. [1]. Charged pion and kaon candidates are well reconstructed tracks that have been positively identified. K_S candidates are reconstructed by combining $\pi^+\pi^-$ pairs with an invariant mass within 10 MeV/c^2 of the nominal K_S mass. We require the distance between the pion tracks at the K_S vertex to be less than 1 cm, the transverse flight distance from the interaction point to be greater than 0.5 cm, and the angle between the K_S momentum direction and decay path to be smaller than 0.1 rad. Photons of energy greater than 50 MeV are combined to form $\pi^0 \to \gamma\gamma$ candidates if their invariant mass lies within 10 MeV/c^2 of the nominal π^0 mass. Such $\gamma\gamma$ pairs are fitted with a π^0 mass constraint to improve the momentum resolution.

The $J/\psi \to \ell^+\ell^-$ reconstruction procedure is identical to that presented in Ref. [1]. Two positively identified lepton candidates are required to form a common vertex that is less than 500 μm from the interaction point in the plane perpendicular to the beam axis. For $J/\psi \to e^+e^-$, the invariant mass calculation includes the four-momentum of photons detected within 50 mrad of the $e^\pm$ directions, as a partial correction for final state radiation and bremsstrahlung energy loss. J/ψ mesons from $B\overline{B}$ events are removed by requiring the momentum of the meson in the e^+e^- center of mass (CM) system, $p^*_{J/\psi}$, to be greater than 2.0 GeV/c. QED processes are suppressed by requiring the total charged multiplicity ($N_{\rm ch}$) to be greater than 4. Some $e^+e^- \to \psi(2S)\gamma$ events survive the $N_{\rm ch} > 4$ cut due to beam background or fake tracks, etc.: we further suppress this process by rejecting events with a photon of CM energy $E^* > 3.5$ GeV.

The $J/\psi \to \ell^+\ell^-$ signal region is defined by the mass window $|M_{\ell^+\ell^-} - M_{J/\psi}| < 30$ MeV/c^2 ($\approx 2.5\sigma$). The sideband region $100 < |M_{\ell^+\ell^-} - M_{J/\psi}| < 400$ MeV/c^2 is used to estimate the contribution from the dilepton combinatorial background under the J/ψ peak.

Distributions of the mass of the system recoiling against the J/ψ candidate—the "recoil mass"—after this selection are shown in Fig. 1(a), for both signal and sideband regions. The recoil mass is defined as $M_{\rm recoil} = [(\sqrt{s} - E^*_{J/\psi})^2 - p^{*\,2}_{J/\psi}]^{1/2}$. A clear threshold near $2\,m_c$ can be seen. To avoid model dependence, we do not perform an acceptance correction. As examples, the Monte Carlo (MC) efficiencies for both $e^+e^- \to J/\psi q\bar{q}$ ($q = u, d, s$) and $J/\psi c\bar{c}$ events are shown in the inset: the variation with $M_{\rm recoil}$ is smooth. For recoil masses smaller than 2.8 GeV/c^2, no significant J/ψ signal is observed in the dilepton mass distribution: a fit finds 16.4 ± 7.8 events in this region.

The region $2m_c \lesssim M_{\rm recoil} < 2m_D$ is studied in more detail in order to search for production of J/ψ together with an additional charmonium state. We apply a mass constrained fit to the J/ψ candidates before determining $p^*_{J/\psi}$. Monte Carlo simulation predicts that this improves the $M_{\rm recoil}$ resolution from 49 to 27 MeV/c^2 at $M_{\rm recoil} \sim 3.0$ GeV/c^2. The resulting recoil mass spectrum in the data is presented in Fig. 1(b): a clear peak is observed around 3.0 GeV/c^2. Since $e^+e^- \to \gamma^* \to J/\psi J/\psi$ is forbidden by charge conjugation symmetry, we interpret this peak as evidence for the process $e^+e^- \to J/\psi\eta_c$. Additional peaks at recoil masses consistent with the χ_{c0} and $\eta_c(2S)$ mass [10] are also seen.

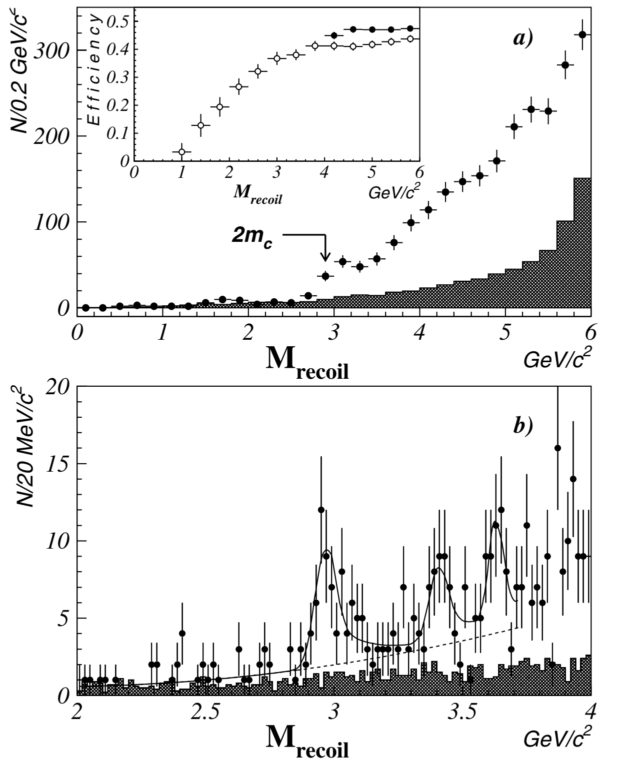

FIG. 1. (a) The recoil mass distribution for the J/ψ signal region (points) and scaled sidebands (hatched histogram). The inset shows the MC reconstruction efficiency for $e^+e^- \to J/\psi q\bar{q}$ [$q = u, d, s$ (open circles)] and $e^+e^- \to J/\psi c\bar{c}$ events (closed circles). (b) The recoil mass distribution after refitting the J/ψ candidate with a mass constraint for the J/ψ signal region (points) and scaled sidebands (hatched histogram). The curve represents the fit described in the text.

To reproduce the η_c shape in the recoil mass spectrum we generate $e^+e^- \to \gamma^*(\gamma) \to J/\psi\eta_c(\gamma)$ Monte Carlo events, with the width of the η_c Breit-Wigner function fixed to its nominal value [11]. We assume p-wave $J/\psi\eta_c$ production, as required by parity conservation, and phase space suppression of $\gamma^* \to J/\psi\eta_c$ as the virtual γ^* energy varies due to initial state radiation (ISR). This effect produces a high-mass tail in $M_{\rm recoil}$. Similar MC samples are used to derive the line shapes for the χ_{c0} and $\eta_c(2S)$: the $\eta_c(2S)$ line shape is narrower than that of the η_c, due to the larger mass of the state and its presumed smaller intrinsic width; the χ_{c0} line shape assumes s-wave production. The effect of varying the energy dependence of the cross section in the ISR calculation is included in the systematic error.

We fit the recoil mass spectrum below the open charm threshold ($M_{\rm recoil} < 3.73$ GeV/c^2) with the charmonium line shapes fixed, the masses left as free parameters, and a quadratic function to describe the background. We find an η_c yield $N_{\eta_c} = 67^{+13}_{-12}$ at a mass $M = (2.962 \pm 0.013)$ GeV/c^2, with a χ_{c0} yield $N_{\chi_{c0}} = 39^{+14}_{-13}$ at $M_{\chi_{c0}} = (3.403 \pm 0.014)$ GeV/c^2, and an $\eta_c(2S)$ yield $N_{\eta_c(2S)} = 42^{+15}_{-13}$ at $M_{\eta_c(2S)} = (3.622 \pm 0.012)$ GeV/c^2.

We assess the significance of each signal i using $\sigma_i \equiv \sqrt{-2\ln(\mathcal{L}_0^i/\mathcal{L}_{\max})}$, where $\mathcal{L}_{\max}$ is the maximum likelihood returned by the fit, and $\mathcal{L}_0^i$ is the likelihood with the yield of the state i [$i = \eta_c, \chi_{c0}, \eta_c(2S)$] set to zero. We find $\sigma_{\eta_c} = 6.7$, $\sigma_{\chi_{c0}} = 3.3$, and $\sigma_{\eta_c(2S)} = 3.4$. As the significance of the χ_{c0} and $\eta_c(2S)$ peaks is low, we perform an additional fit using only the η_c shape and the quadratic background: this finds $N_{\eta_c} = 56^{+13}_{-12}$ with $\sigma_{\eta_c} = 5.9$. We use this result, together with the results of fits after varying the charmonium intrinsic widths [11] and the choice of background shape, to estimate the systematic error on the η_c yield due to the fitting procedure.

To determine the $e^+e^- \to J/\psi\eta_c(\gamma)$ cross section we correct the signal yield for the MC reconstruction efficiency. Because of the requirement $N_{\rm ch} > 4$, the recoil system must contain at least three charged tracks: this removes η_c decays into zero or two charged tracks plus neutrals. As η_c branching fractions are poorly known, we express our result in terms of the product $\sigma[e^+e^- \to J/\psi\eta_c(\gamma)] \times \mathcal{B}(\eta_c \to \geq 4 \text{ charged})$, which we find to be $(0.033^{+0.007}_{-0.006} \pm 0.009)$ pb. Here and elsewhere, the uncertainty quoted second is the systematic error. The various sources of systematic error are listed in Table I.

To study the $J/\psi c\bar{c}$ mechanism in the region $M_{\rm recoil} \geq 2m_D$, we search for fully reconstructed D^{*+} and D^0 decays [12] in events with a J/ψ meson. For the study of $J/\psi D^{*+}$ associated production we reconstruct $D^{*+} \to D^0\pi^+$ using five D^0 decay modes: $K^-\pi^+$, K^-K^+, $K^-\pi^-\pi^+\pi^+$, $K_S\pi^+\pi^-$, and $K^-\pi^+\pi^0$. We select D^0 candidates in a ± 10 MeV/c^2 mass window for the charged modes and a ± 20 MeV/c^2 window for $K^-\pi^+\pi^0$ (approximately 2σ in each case). To improve the $M_{D^0\pi^+}$ resolution D^0 candidates are refitted to the nominal D^0 mass.

Although $B \to J/\psi X$ decays are rejected by the selection, semileptonic B decays contribute to the background under the J/ψ peak and lead to a large D^{*+} signal. To remove the remaining $B\bar{B}$ background we require that either the D^{*+} or one of the leptons from the J/ψ candidate have a momentum above the kinematic limit for B decays: $p^*_{D^{*+}} > 2.6$ GeV/c or $p^*_{\ell^\pm} > 2.6$ GeV/c. Choosing the $D^0\pi^+$ combination with the best D^0 mass yields at most one $J/\psi D^{*+}$ candidate per event.

The scatter plot of the dilepton mass versus the $D^0\pi^+$ mass, and the $D^0\pi^+$ mass projection, are shown in Figs. 2(a) and 2(b). We perform a fit to the $D^0\pi^+$ mass distribution in the J/ψ signal window, with a Gaussian for the D^{*+} signal and a threshold function $A\sqrt{M_{D^0\pi^+} - M_{\rm thres}}$ for the background. The J/ψ sideband is fit simultaneously and used to estimate the combinatorial $(\ell^+\ell^-)D^{*+}$ contribution to the D^{*+} yield in the signal region. We find $N_{D^{*+}} = 10.5^{+3.6}_{-3.0}$, with a combinatorial contribution of 0.4 ± 0.3: the signal yield is $10.1^{+3.6}_{-3.0}$, with significance 5.3. As a cross-check we fit the dilepton mass distribution for $2.008 < M_{D^0\pi^+} < 2.012$ GeV/c^2, finding $N_{J/\psi} = 9.6^{+3.6}_{-2.9}$. The J/ψ signal shape is fixed from MC simulation, and we include a linear background function.

For the study of $J/\psi D^0$ associated production we use only the cleanest D^0 decay modes $D^0 \to K^-\pi^+$ and K^-K^+. As in the $J/\psi D^{*+}$ study, we remove $B\bar{B}$ events by requiring $p^*_{D^0} > 2.6$ GeV/c or $p^*_{\ell^\pm} > 2.6$ GeV/c.

A plot of dilepton versus $K^-\pi^+(K^-K^+)$ masses and the projection onto the $K^-\pi^+(K^-K^+)$ mass axis are shown in Figs. 2(c) and 2(d). A simultaneous fit to the $K^-\pi^+(K^-K^+)$ mass distribution in the J/ψ signal window and the sideband finds $N_{D^0} = 15.9^{+5.4}_{-4.7}$ in the signal region, with a combinatorial $(\ell^+\ell^-)D^0$ contribution of 1.0 ± 0.8. The signal yield is $14.9^{+5.4}_{-4.8}$, with significance 3.7. We use a Gaussian signal shape and a linear background function in the fit. As a cross-check, we also fit the

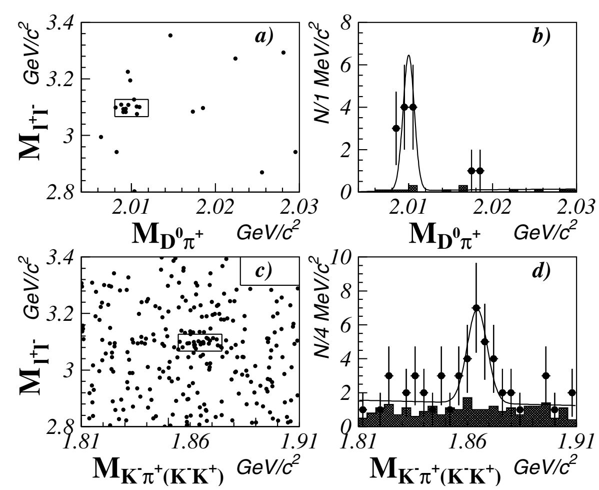

FIG. 2. Results of a search for associated production of J/ψ and charm mesons: (a) the scatter plot $M(l^+l^-)$ vs $M(D^0\pi^+)$; (b) projection onto the $M(D^0\pi^+)$ axis; (c) the scatter plot $M(l^+l^-)$ vs $M[K^-\pi^+(K^+K^-)]$; (d) projection onto the $M[K^-\pi^+(K^+K^-)]$ axis. Points with error bars show the J/ψ signal region and the hatched histograms show the scaled sidebands. The boxes in the scatter plots represent the signal regions defined as $|M_{\ell^+\ell^-} - M_{J/\psi}| < 30$ MeV/c^2, $|M_{D^0\pi^+} - M_{D^{*+}}| < 2$ MeV/c^2, $|M_{K^-\pi^+(K^+K^-)} - M_{D^0}| < 10$ MeV/c^2. The curves represent the fit described in the text.

TABLE I. Sources of systematic error for $\sigma(e^+e^- \to J/\psi\eta_c)$.

Source	Systematic error (%)
ISR correction	±19
Fitting procedure	±16
J/ψ polarization	±11
Track reconstruction	±5
Lepton identification	±4
Total	±28

dilepton mass spectrum for D^0 signal and sideband regions, obtaining $N_{J/\psi} = 17.7^{+5.3}_{-4.6}$ and $N_{J/\psi} = 4.3 \pm 0.8$, respectively, where the sideband number is the result of the fit scaled to the expected contribution under the D^0 peak. We therefore find a signal yield of $13.4^{+5.4}_{-4.7}$ by this method; the small difference from the nominal yield is included in the systematic error. For all fits the signal shapes are fixed from the Monte Carlo simulation.

To study our reconstruction efficiency for J/ψ mesons produced together with a charmed meson, we generate $e^+e^- \to J/\psi c\bar{c}$ MC events using a simple model adapted from the QQ event generator [13]. Since the efficiency for both particle reconstruction and selection criteria strongly depend on the kinematics, we correct the kinematic characteristics of the MC events to match those of the data using a large sample of continuum J/ψ events. In particular, the distributions of the recoil mass, the J/ψ production and helicity angles, and the angle between the $c\bar{c}$ thrust axis and boost are adjusted to match the data. These quantities almost fully describe the kinematics of $e^+e^- \to J/\psi c\bar{c}$. The fragmentation function of $c\bar{c}$ into charmed mesons in each bin of $Q^2_{c\bar{c}} \equiv M^2_{\rm recoil}$ is the only characteristic that has an effect on the efficiency that cannot be determined from the data. We vary this function over a wide range, taking the difference in the efficiency into account as a systematic error.

The efficiency is first calculated for $p^*_{J/\psi} > 2.0$ GeV/c and then extrapolated to the full momentum interval, taking into account the cross sections for inclusive continuum production obtained in Ref. [1] for both $p^*_{J/\psi} > 2.0$ and $p^*_{J/\psi} < 2.0$ GeV/c data. The overall efficiencies for $J/\psi D^{*+}$ and $J/\psi D^0$ are calculated to be $\epsilon_{J/\psi D^{*+}} = (4.1 \pm 1.0) \times 10^{-4}$ and $\epsilon_{J/\psi D^0} = (3.7 \pm 0.8) \times 10^{-4}$, respectively. Using these values, we find cross sections $\sigma(e^+e^- \to J/\psi D^{*+}X) = (0.53^{+0.19}_{-0.15} \pm 0.14)$ pb and $\sigma(e^+e^- \to J/\psi D^0 X) = (0.87^{+0.32}_{-0.28} \pm 0.20)$ pb. Contributions to the systematic error are summarized in Table II.

According to the Lund model, $c\bar{c}$ fragmentation produces charmed mesons at the rate of 0.53 per event for D^{*+}, and 1.18 per event for D^0, where both numbers include feed-down from higher states (in particular, $D^{*+} \to D^0\pi^+$) [14]. Assuming that these rates apply to $c\bar{c}$ fragmentation in $e^+e^- \to J/\psi c\bar{c}$, we calculate $\sigma(e^+e^- \to J/\psi c\bar{c})$ and find $(1.01^{+0.36}_{-0.30} \pm 0.26)$ pb and $(0.74^{+0.28}_{-0.24} \pm 0.19)$ pb based on our D^{*+} and D^0 measurements, respectively. No systematic error is included for our use of the Lund fragmentation rates. These results are slightly correlated, as two events are common to both samples. Taking this into account, we average the results and obtain $(0.87^{+0.21}_{-0.19} \pm 0.17)$ pb. In Ref. [1] we found the inclusive prompt J/ψ cross section to be $\sigma(e^+e^- \to J/\psi X) = (1.47 \pm 0.10 \pm 0.11)$ pb, based on a 32.7 fb^{-1} dataset. We therefore infer that a large fraction of prompt J/ψ events, $\sigma(e^+e^- \to J/\psi c\bar{c})/\sigma(e^+e^- \to J/\psi X) = 0.59^{+0.15}_{-0.13} \pm 0.12$, is due to the $e^+e^- \to J/\psi c\bar{c}$ process.

TABLE II. Systematic error contributions for $\sigma(e^+e^- \to J/\psi DX)$. Numbers in parentheses show contributions to the error on the ratio $\sigma(e^+e^- \to J/\psi c\bar{c})/\sigma(e^+e^- \to J/\psi X)$.

	Systematic error (%)			
	$J/\psi D^0$		$J/\psi D^{*+}$	
MC kinematics correction	± 11	(± 8)	± 10	(± 8)
$c\bar{c}$ fragmentation function	± 8	(± 8)	± 15	(± 15)
Fitting procedure	± 10	(± 10)	± 5	(± 5)
Efficiency of $p^*_{J/\psi}$ cut	± 11	(0)	± 11	(0)
Track reconstruction	± 8	(± 4)	± 12	(± 8)
Lepton and K identification	± 6	(± 3)	± 6	(± 3)
Total	23	(16)	26	(20)

Contributions to the systematic error on this ratio are shown in Table II by the numbers in parentheses.

This $J/\psi c\bar{c}$ cross section is an order of magnitude larger than predicted in Refs. [3,5,7] and contradicts the NRQCD expectation that the $J/\psi c\bar{c}$ fraction is small [3,5]. We note that our result is dependent on the fragmentation model assumed for the $c\bar{c}$ system. In the future, more comprehensive measurements including associated $J/\psi D^+$, $J/\psi D_s^+$, and $J/\psi \Lambda_c^+$ production could significantly reduce this model dependence.

In summary, we have observed both a charmonium state and charmed mesons accompanying prompt J/ψ production in e^+e^- annihilation. We measure $\sigma[e^+e^- \to J/\psi \eta_c(\gamma)] \times \mathcal{B}(\eta_c \to \ \geq 4 \text{ charged}) = (0.033^{+00.007}_{-0.006} \pm 0.009)$ pb and $\sigma(e^+e^- \to J/\psi D^{*+}X) = (0.53\,^{+0.19}_{-0.15} \pm 0.14)$ pb and estimate $\sigma(e^+e^- \to J/\psi c\bar{c})/\sigma(e^+e^- \to J/\psi X) = 0.59^{+0.15}_{-0.13} \pm 0.12$. Our results favor $e^+e^- \to J/\psi c\bar{c}$ as the leading mechanism for prompt J/ψ production at $\sqrt{s} \approx 10.6$ GeV.

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