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Search for the process $e^+e^- \to J/\psi X(1835)$ at $\sqrt{s} \approx 10.6$ GeV

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We report the results of a search for the $X(1835)$ state in the process $e^+e^- \to J/\psi X(1835)$ using a data sample of 672 fb^{-1} collected with the Belle detector at and near the $\Upsilon(4S)$ resonance at the KEKB asymmetric-energy e^+e^- collider. No significant evidence is found for this process, and an upper limit is set on its cross section times the branching fraction: $\sigma_{\text{Born}}(e^+e^- \to J/\psi X(1835)) \cdot \mathcal{B}(X(1835) \to \geq 3\,\text{charged tracks}) < 1.3$ fb at 90% confidence level.

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The BESII Collaboration observed a resonance, the $X(1835) \to \pi^+\pi^-\eta'$, in the radiative decay $J/\psi \to \gamma\pi^+\pi^-\eta'$, with a 7.7σ statistical significance [1]. Recently, the structure has been confirmed by BESIII in the same process with a statistical significance greater than 20σ [2]. From a fit with a Breit-Wigner function, the mass and width are determined to be $1836.5 \pm 3.0(\text{ stat.})^{+5.6}_{-2.1}(\text{ syst.})$ MeV$/c^2$ and $190 \pm 9(\text{ stat.})^{+38}_{-36}(\text{syst.})$ MeV, respectively, with a product branching fraction of $\mathcal{B}(J/\psi \to \gamma X) \cdot \mathcal{B}(X \to \pi^+\pi^-\eta') = [2.87 \pm 0.09(\text{stat.})^{+0.49}_{-0.52}(\text{syst.})] \times 10^{-4}$ [2]. The Belle Collaboration also searched for the $X(1835)$ in two-photon collisions, but no strong evidence was found [3]. Many theoretical models have been proposed to interpret its underlying structure. Some consider the $X(1835)$ as a radial excitation of the η' [4,5]; a $p\bar{p}$ bound state [6–8]; a glueball candidate [9–12]; or a η_c-glueball mixture [13]. C-even glueballs can be studied in the process $e^+e^- \to \gamma^* \to H\mathcal{G}_J$ [14], where H denotes a $c\bar{c}$ quark pair or charmonium state and $\mathcal{G}_J$ is a glueball, as shown in Fig. 1. In this paper, we search for $X(1835)$ in the process $e^+e^- \to J/\psi X(1835)$ at $\sqrt{s} \approx 10.6$ GeV.

This analysis uses a 604 fb^{-1} data sample collected with the Belle detector [15] at the $\Upsilon(4S)$ resonance and 68 fb^{-1} 60 MeV below it at the KEKB asymmetric-energy e^+e^- collider [16]. The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector, a 50-layer central drift chamber, an array of aerogel threshold Cherenkov counters, a barrel-like arrangement of time-of-flight scintillation counters, and an electromagnetic calorimeter comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5T magnetic field. An iron flux return located outside of the coil is instrumented to identify K_L and muons. Two different inner detector configurations were used: a 2.0 cm radius beam pipe and a 3-layer silicon vertex detector for the first 155 fb^{-1} data, and a 1.5 cm radius

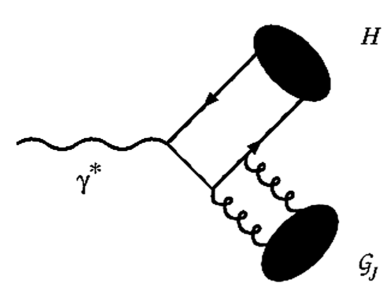

FIG. 1. Possible Feynman diagram for $\gamma^* \to H + \mathcal{G}_J$ [14].

beam pipe with a 4-layer vertex detector for the remaining data sample.

A Monte Carlo (MC) simulation based on the BABAYAGA event generator [17], in which the initial state radiation (ISR) correction is taken into account, is used to estimate the selection efficiency. We assume the minimum remaining system energy (after initial state radiation) to be 8 GeV. To incorporate the $X(1835)\ J/\psi$ reaction into BABAYAGA, the two-body final state is assumed to be distributed according to $1+\cos^2\theta$ in the e^+e^- center-of-mass (CM) system, where θ is the angle between the J/ψ and e^- beam direction in the CM system. The mass of $X(1835)$ is generated according to a Breit-Wigner function, with the reported mass of 1836 MeV/c^2 and width of 190 MeV. The efficiency is calculated using $e^+e^- \to J/\psi X(1835)(\gamma)$ signal events, where the J/ψ decays to e^+e^- or $\mu^+\mu^-$ and the $X(1835)$ decays to $\eta'\pi^+\pi^-$, followed by $\eta' \to \eta\pi^+\pi^-$ and $\eta \to \gamma\gamma$.

The J/ψ reconstruction procedure is similar to that described in Ref. [18]. Oppositely charged tracks that are both identified either as muons or electrons are combined as a J/ψ candidate. To correct for final state radiation and bremsstrahlung, photons within 50 mrad of the $e^\pm$ are included in the e^+e^- invariant mass calculation. The lepton identification efficiencies are 96% and 98% for $\mu^\pm$ and $e^\pm$, respectively. The two lepton candidate tracks are required to have a common vertex, with a distance to the IP in the $r\phi$ plane (transverse to the beam direction) smaller than 100 μm. The J/ψ signal region is defined by the mass window $|M_{l^+l^-} - M_{J/\psi}| < 30$ MeV/c^2 ($\sim 2.5\sigma$), common for both dimuon and dielectron channels. We also define a sideband region as 70 MeV/$c^2 < |M_{l^+l^-} - M_{J/\psi}| < 190$ MeV/c^2, which is used to estimate the contribution from the dilepton combinatorial background under the J/ψ peak. A mass-constrained fit to the reconstructed J/ψ candidates is then performed to improve their momentum resolution. The mass of the system recoiling against a reconstructed J/ψ is determined from

$$M_{\mathrm{recoil}} = \sqrt{(E_{\mathrm{CM}} - E^*_{J/\psi})^2 - p^{*2}_{J/\psi}}, \qquad (1)$$

where E_{CM} is the CM energy of e^+e^- collisions, and $E^*_{J/\psi}$ and $p^*_{J/\psi}$ are the energy and momentum of the J/ψ candidate in the CM system, respectively.

The background due to initial state radiation with a hard photon [radiative return to $J/\psi(\psi(2S))$] [19] and the QED process $J/\psi e^+e^-$[20] is large. According to a study reported in Ref. [18], these backgrounds contribute mainly to $N_{\mathrm{ch}} = 3$ and $N_{\mathrm{ch}} = 4$ events (where N_{ch} is the number of charged tracks in an event). We suppress these backgrounds by requiring $N_{\mathrm{ch}} > 4$. The mass distributions for J/ψ candidates in the region $0 < M_{\mathrm{recoil}} < 3$ GeV/c^2 after the selection are shown in Fig. 2.

The M_{recoil} distributions are shown in Fig. 3. The remaining backgrounds are mainly from two sources.

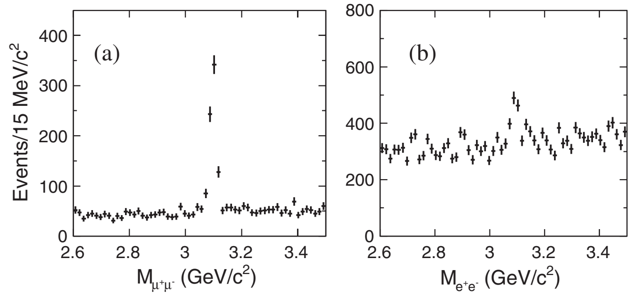

FIG. 2. Mass distribution for the J/ψ candidates reconstructed from $\mu^+\mu^-$(a) and e^+e^-(b) in the region $0 < M_{\mathrm{recoil}} < 3$ GeV/c^2.

One is the combinatorial dilepton events in the J/ψ mass window that are estimated from the J/ψ sideband data, as shown in Fig. 3. The other background is the nonprompt J/ψ decay products from excited charmonium states (such as ψ', χ_{cJ}). This is found to contribute negligibly to the J/ψ signal. To understand this kind of background from $\psi' \to \pi^+\pi^- J/\psi$ decays, we reconstruct such events by combining the detected J/ψ mesons with any pair of

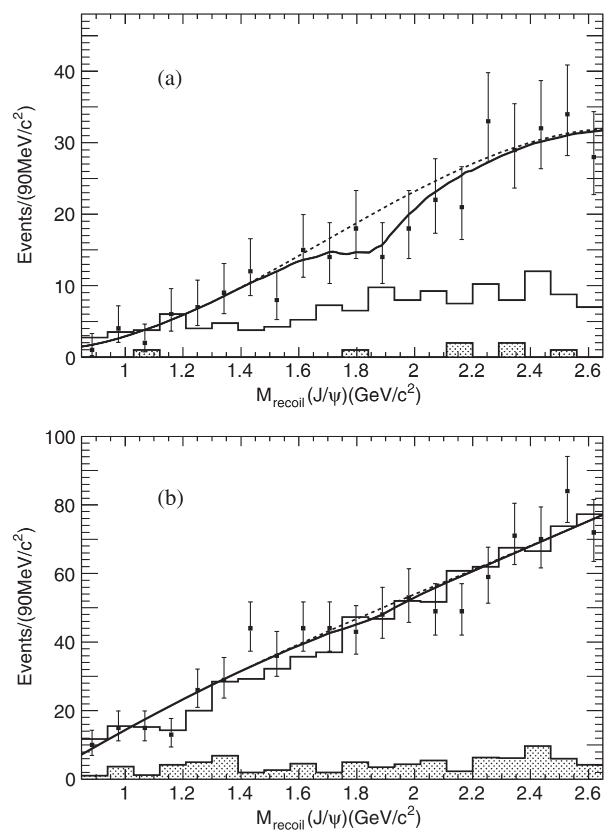

FIG. 3. Distribution of the recoil mass against the J/ψ reconstructed from $\mu^+\mu^-$(a) and e^+e^-(b). The points are data, the solid histograms represent the backgrounds from the J/ψ sideband, and the hatched histograms represent the charmed- plus uds-quark backgrounds. The solid lines are results of the fits in the recoil mass region and the dashed lines are the total background.

oppositely charged pion tracks and find fewer than five events in the region $M_{\mathrm{recoil}} < 3\ \mathrm{GeV}/c^2$ at 95% C.L. J/ψ mesons from B decay are kinematically forbidden to produce a recoil mass below $3\ \mathrm{GeV}/c^2$.

In order to understand the J/ψ peaking background from $e^+e^- \to J/\psi+$ hadrons, we analyze a sample of continuum MC events at the $\Upsilon(4S)$ generated with EvtGen [21], which contains charmed- plus uds-quark backgrounds. After the selection criteria are applied, the surviving background is less than the combinatorial lepton pair background, as shown in Fig. 3. Annihilation of two virtual photons in the process $e^+e^- \to \gamma^*\gamma^* \to J/\psi\gamma^* \to J/\psi f\bar{f}$ may contribute significantly to the background in the M_{recoil} mass region, where $f\bar{f}$ denotes a pair of light quarks hadronizing into multihadrons. This type of background is suppressed by the $N_{\mathrm{ch}} > 4$ cut.

We search for an $X(1835)$ signal using an unbinned maximum likelihood fit to the M_{recoil} distributions shown in Fig. 3, in the region $0.85\ \mathrm{GeV}/c^2 < M_{\mathrm{recoil}} < 2.65\ \mathrm{GeV}/c^2$. The signal shape is fixed to the MC simulation using the mass and width from the BESIII measurement [2]. The background is represented by a third-order Chebychev function. A simultaneous fit is performed for the $\mu^+\mu^-$ and e^+e^- channels, which constrains the expected signal from $J/\psi \to \mu^+\mu^-$ and $J/\psi \to e^+e^-$ to be consistent with the ratio of ε_i and $\mathcal{B}_i$, where ε_i and $\mathcal{B}_i$ are the efficiency and branching fraction for the two channels, respectively. The ε_i values are obtained from MC simulation including ISR. The results of the fit are shown in Table I and Fig. 3.

The Born cross section is determined by the following formula derived from the second-order calculation of the perturbation theory [22]:

$$\sigma_{\mathrm{Born}} = \sigma_{\mathrm{measured}}(\text{non-ISR})/\xi_{\mathrm{Born}}, \tag{2}$$

where $\sigma_{\mathrm{measured}}(\text{non-ISR})$ is the cross section when the energy of a radiative photon is less than 10 MeV. The value of this cutoff energy $E_{\mathrm{rad.}\gamma}$ is arbitrary; the final result is independent of this choice. The factor ξ_{Born} relates the measured cross section with radiative photons below the cutoff energy to the Born cross section. From the QED calculation [22], ξ_{Born} is determined to be 0.629 for $E_{\mathrm{rad.}\gamma} = 10$ MeV. The final Born cross section is then estimated as

$$\sigma_{\mathrm{Born}} = \frac{R_\varepsilon f_{\text{non-ISR}}}{\xi_{\mathrm{Born}}} \times \frac{N_{\mathrm{fit}}}{\mathcal{L}_{\mathrm{int}}\varepsilon_{\mathrm{sum}}\mathcal{B}_{\mathrm{sum}}}, \tag{3}$$

TABLE I. Fit results for the M_{recoil} region 0.85–2.65 GeV/c^2.

Mode	N_{signal}	$N_{\mathrm{background}}$
$J/\psi \to \mu^+\mu^-$	-20.0 ± 20.0	346.0 ± 18.4
$J/\psi \to e^+e^-$	-7.5 ± 7.6	880.5 ± 31.3

where N_{fit} is the sum of the fitted event yields in the $\mu^+\mu^-$ and e^+e^- modes, the factor R_ε is the ratio of the full and non-ISR reconstruction efficiencies and $f_{\text{non-ISR}}$ is the fraction of non-ISR events depending on the final states that are incorporated using the signal MC sample. For $E_{\mathrm{rad.}\gamma} = 10$ MeV, this part of the soft ISR process accounts for approximately 65% of the total. Here, $\mathcal{L}_{\mathrm{int}}$ is the integrated luminosity, $\varepsilon_{\mathrm{sum}}$ is the total detection efficiency and $\mathcal{B}_{\mathrm{sum}}$ is the total branching fraction of $J/\psi \to \mu^+\mu^-$ and e^+e^- decays.

Since the fit does not return any significant signal in the $X(1835)$ mass region, we set an upper limit on its production rate. The upper limit of σ_{Born} is calculated by replacing N_{fit} with the upper limit on the signal yield at 90% C.L. in Eq. (1). We integrate the likelihood function starting at $N_{\mathrm{event}} = 0$; the upper limit is set when the integral reaches 90% of the total area. The total upper limit of $X(1835)$ events in the two J/ψ decay modes is $N_{\mathrm{event}} = 46.7$ at 90% C.L.

Systematic uncertainties listed in Table II are dominated by the following sources. In MC simulation of ISR process, the corresponding systematic uncertainty is estimated by replacing the $1/Q^2$ dependence of the form factor with $1/Q^4$ and changing the minimum remaining system energy (after ISR) from 8 GeV to 9 GeV. The uncertainty from the background estimation is evaluated by the variations in the result arising from changes in the fitting range and background shape (the latter being obtained from fitting M_{recoil} on J/ψ sideband data); fitting M_{recoil} including the signal region ($1.7\ \mathrm{GeV}/c^2$–$2.2\ \mathrm{GeV}/c^2$); and floating the background parameters. The quantum numbers J^{PC} of the $X(1835)$ reported by BES are 0^{-+}, corresponding to a $(1 + \cos^2\theta)$ polar angular distribution. We generate events with flat and $\sin^2\theta$ distributions to compare and estimate the systematic uncertainty associated with different possible polarizations of the J/ψ. The width of the $X(1835)$ remeasured by BESIII is $\Gamma = 190 \pm 9\,(\mathrm{stat.})^{+38}_{-36}(\mathrm{syst.})$ MeV [2]; the systematic uncertainty caused by different widths is taken into account.

Other systematic uncertainties come from MC statistics (3%), track reconstruction efficiency (1% per track) and lepton identification uncertainty (1.5% per lepton) in J/ψ

TABLE II. Contributions to the systematic uncertainties.

	Syst. uncertainties (%)	
Source	$\mu^+\mu^-$	e^+e^-
ISR	5	5
Background estimation	9	13
J/ψ polarization	8	10
$X(1835)$ width	16	16
Track reconstruction	5	5
Lepton identification	3	3
MC statistics	3	3
Sum in quadrature	22	24

reconstruction. The luminosity and branching ratio uncertainties are negligible.

The systematic uncertainties caused by the J/ψ polarization for the two decay modes $J/\psi \to \mu^+\mu^-$ and $J/\psi \to e^+e^-$ are correlated, which will expand or shrink the likelihood functions in the same way. Other sources of systematic uncertainties for the two J/ψ decay modes are uncorrelated. In the combination of the two J/ψ decay modes, the total systematic uncertainty would be smaller than the one of single e^+e^- decay mode. However, in the upper limit calculation, we use just the systematic uncertainty for $J/\psi \to e^+e^-$, which gives the most conservative result.

Since the recoil mass method is used in the analysis, the efficiency of the $X(1835)$ selection always coincides with the efficiency of J/ψ reconstruction. The MC simulation $e^+e^- \to J/\psi X(1835)$, where $X(1835)$ decays to $\eta'\pi^+\pi^-$ with $\eta' \to \eta\pi^+\pi^-$, $\eta \to \gamma\gamma$, is one of modes with fewest charged tracks that satisfies $N_{\rm ch} > 4$. Using this efficiency in the upper limit calculation also gives a less restrictive upper limit.

After taking into account the systematic uncertainty, the upper limit on $\sigma_{\rm Born}$ is 1.3 fb.

In summary, using a 672 fb^{-1} data sample collected with the Belle detector, we search for the $X(1835)$ state by analyzing the J/ψ recoil mass distribution from the assumed process $e^+e^- \to J/\psi X(1835)$. No significant evidence for $X(1835)$ production in this process is found. An upper limit is set to be $\sigma_{\rm Born}(e^+e^- \to J/\psi X(1835)) \cdot \mathcal{B}(X(1835) \to \geq 3 \text{ charged tracks}) < 1.3$ fb at 90% C.L, including systematic uncertainties. This upper limit is 3 orders of magnitude smaller than the cross section for prompt production of the J/ψ meson [18]. No evidence is found to support the hypothesis of the $X(1835)$ as a glueball produced in association with a J/ψ in the Belle experiment.

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