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

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The BESII Collaboration observed a resonance, the $X(1835) \rightarrow \pi^+\pi^-\eta'$, in the radiative decay $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$, 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 $1836.5^{+3.0}_{-2.1}(\text{stat.})^{+5.6}_{-2.0}(\text{syst.})$ MeV/$c^2$ and $190^{+9}_{-7}(\text{stat.})^{+38}_{-30}(\text{syst.})$ MeV, respectively, with a product branching fraction of $\mathcal{B}(J/\psi \rightarrow \gamma X) \cdot \mathcal{B}(X \rightarrow \pi^+\pi^-\eta') = [2.87 \pm 0.09(\text{stat.})^{+0.49}_{-0.52}(\text{syst.})] \times 10^{-4}$[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 $\eta'$ [4,5]; a $p\bar{p}$ bound state [6,7]; a glueball candidate [4,12]; or a $\eta_c$-glueball mixture [13]. C-even glueballs can be studied in the process $e^+e^- \rightarrow \gamma^* \rightarrow H + G_J$ [14], where $H$ denotes a $c\bar{c}$ quark pair or charmonium state and $G_J$ is a glueball, as shown in Fig. 1. In this paper, we report the search for $X(1835)$ in the process $e^+e^- \rightarrow J/\psi X(1835)$ 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 (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) 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 detect $K^0_L$ mesons and to identify muons (KLM). 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 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 min-
In order 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 $\theta$ is the angle between the $J/\psi$ 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 $e^+e^- \rightarrow J/\psi X(1835)(\gamma)$ signal events, where the $J/\psi$ decays to $e^+e^-$ or $\mu^+\mu^-$ and the $X(1835)$ decays to $\eta'\pi^+\pi^-$, followed by $\eta' \rightarrow \eta \pi^+\pi^-$ and $\eta \rightarrow \gamma\gamma$.

The $J/\psi$ 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 $J/\psi$ 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 $\mu$m. The $J/\psi$ signal region is defined by the mass window $|M_{t^+-t^-} - M_{J/\psi}| < 30$ MeV/$c^2$ ($\sim 2.5\sigma$), common for both dimuon and dielectron channels. We also define a sideband region as 70 MeV/$c^2 < |M_{t^+-t^-} - M_{J/\psi}| < 190$ MeV/$c^2$, which is used to estimate the contribution from the dilepton combinatorial background under the $J/\psi$ peak. A mass-constrained fit to the reconstructed $J/\psi$ candidates is then performed to improve their momentum resolution. The mass of the system recoiling against a reconstructed $J/\psi$ is determined from:

$$M_{\text{recoil}} = \sqrt{(E_{CM} - E_{J/\psi})^2 - p_{J/\psi}^2},$$

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 $J/\psi$ 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 $J/\psi e^+e^- \rightarrow \gamma\gamma$ is large. According to a study reported in Ref. [18], these backgrounds contribute mainly to $N_{ch} = 3$ and $N_{ch} = 4$ events (where $N_{ch}$ is the number of charged tracks in an event). We suppress these backgrounds by requiring $N_{ch} > 4$. The mass distributions for $J/\psi$ candidates in the region $0 < M_{\text{recoil}} < 3$ GeV/$c^2$ after the selection are shown in Fig. 2.

The $M_{\text{recoil}}$ distributions are shown in Fig. 3. The remaining backgrounds are mainly from two sources. One is the combinatorial dilepton events in the $J/\psi$ mass window that are estimated from the $J/\psi$ sideband data, as shown in Fig. 3. The other background is the non-prompt $J/\psi$ decay products from excited charmonium states (such as $\psi', \chi_{cJ}$). This is found to contribute negligibly to the $J/\psi$ signal. To understand the background from $\psi' \rightarrow \pi^+\pi^- J/\psi$ decays, we reconstruct such events by combining the detected $J/\psi$ mesons with any pair of oppositely charged pion tracks and find fewer than five events in the region $M_{\text{recoil}} < 3$ GeV/$c^2$ at 95% C.L.

$J/\psi$ mesons from $B$ decay are kinematically forbidden to produce a recoil mass below 3 GeV/$c^2$.

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

We search for an $X(1835)$ signal using an unbinned maximum likelihood fit to the $M_{\text{recoil}}$ distributions shown in Fig. 3 in the region $0.8 < M_{\text{recoil}} < 2.8$ 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 $J/\psi \rightarrow \mu^+\mu^-$ and $J/\psi \rightarrow e^+e^-$ to be consistent with the ratio of $\varepsilon_1$ and $B_1$, where $\varepsilon_1$ and $B_1$ are the efficiency and branching fraction for the two channels, respectively. The $\varepsilon_1$ 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]:

$$\sigma_{\text{Born}} = \sigma_{\text{measured}}(\text{non–ISR}) / \xi_{\text{Born}},$$

where $\sigma_{\text{measured}}(\text{non–ISR})$ is the cross section when the energy of a radiative photon is less than 10 MeV. The
the QED calculation [22], below the cut-off energy to the Born cross section. From the QED calculation, \( \xi_{\text{Born}} \) is determined to be 0.629 for \( E_{\text{rad},\gamma} = 10 \text{ MeV} \). The final Born cross section is then estimated as

\[
\sigma_{\text{Born}} = \frac{R_c f_{\text{non_isr}}}{\xi_{\text{Born}}} \times \frac{N_{\text{fit}}}{\mathcal{L}_{\text{int}} \varepsilon_{\text{sum}} B_{\text{sum}}},
\]

where \( N_{\text{fit}} \) is the sum of the fitted event yields in the \( \mu^+\mu^- \) and \( e^+e^- \) modes, the factor \( R_c \) 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 \( E_{\text{rad},\gamma} = 10 \text{ MeV} \), this part of the soft ISR process accounts for approximately 65% of the total. Here, \( \mathcal{L}_{\text{int}} \) is the integrated luminosity, \( \varepsilon_{\text{sum}} \) is the total detection efficiency and \( B_{\text{sum}} \) is the total branching fraction of \( J/\psi \rightarrow \mu^+\mu^- \) 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 \( \sigma_{\text{Born}} \) is calculated by replacing \( N_{\text{fit}} \) with the upper limit on the signal yield at 90% C.L. in Eq. [3]. We integrate the likelihood function starting at \( N_{\text{event}} = 0 \); 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 \( J/\psi \) decay modes is \( N_{\text{event}} = 46.7 \) at 90% C.L.

Systematic uncertainties listed in Table II are dominated by the following sources. The form-factor dependence on \( Q^2 \) affects the shape of the ISR tail. We replace the \( 1/Q^2 \) dependence with \( 1/Q^4 \) and find the results change by 5%; this is taken as the corresponding systematic uncertainty. We change the minimum remaining system energy (after ISR) from 8 GeV to 9 GeV to estimate the systematic uncertainty from MC simulation. 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 \( M_{\text{recoil}} \) on \( J/\psi \) sideband data); fitting \( M_{\text{recoil}} \) including the signal region (1.7 GeV/c^2–2.2 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 \( \sin \theta \) distributions to compare and estimate the systematic uncertainty associated with different possible polarizations of the \( J/\psi \). The width of the \( X(1835) \) remeasured by BESIII is \( \Gamma = 190^{+38}_{-36} \) (stat.) +38 (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 \( J/\psi \) reconstruction. The luminosity and branching ratio uncertainties are negligible.

The systematic uncertainties caused by the \( J/\psi \) polarization for the two decay modes \( J/\psi \rightarrow \mu^+\mu^- \) and \( J/\psi \rightarrow e^+e^- \) are correlated, which will expand or shrink the likelihood functions in the same way. Other sources of systematic uncertainties for the two \( J/\psi \) decay modes are uncorrelated. In the combination of the two \( J/\psi \) decay modes, some systematic uncertainties cancel. However, in the upper limit calculation, we use just the system-
atic uncertainty for $J/\psi \rightarrow e^+e^-$, 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 $J/\psi$ reconstruction independently of the decay modes of $X(1835)$. The MC simulation $e^+e^- \rightarrow J/\psi X(1835)$, where $X(1835)$ decays to $\eta' \pi^+\pi^-$ with $\eta' \rightarrow \pi^0\pi^0\pi^-$, is a mode with fewest charged tracks that satisfies $N_{ch} > 4$ and thus has the lowest efficiency. 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 $\sigma$ 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 $J/\psi$ recoil mass distribution from the assumed process $e^+e^- \rightarrow J/\psi X(1835)$. No significant evidence for $X(1835)$ production in this process is found. An upper limit is set to be: $\sigma_{\text{Born}}(e^+e^- \rightarrow J/\psi X(1835)) \cdot B(X(1835) \rightarrow 3 \text{ charged tracks}) < 1.3 \text{ fb at 90\% C.L}$, including systematic uncertainties. This upper limit is three orders of magnitude smaller than the cross section for prompt production of the $J/\psi$ meson [18]. No evidence is found to support the hypothesis of the $X(1835)$ as a glueball produced in association with a $J/\psi$ in the Belle experiment.

We thank the KEKB group for the excellent operation of the accelerator; the KEK cryogenics group for the efficient operation of the solenoid; and the KEK computer group, the National Institute of Informatics, and the PNNL/EMSL computing group for valuable computing and SINET4 network support. We acknowledge support from the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan, the Japan Society for the Promotion of Science (JSPS), and the Tau-Lepton Physics Research Center of Nagoya University; the Australian Research Council and the Australian Department of Industry, Innovation, Science and Research; Austrian Science Fund under Grant No. P 22742-N16; the National Natural Science Foundation of China under contract No. 10575109, 10775142, 10825524, 10875115, 10935008 and 11175187; the Ministry of Education, Youth and Sports of the Czech Republic under contract No. MSM0021620859; the Carl Zeiss Foundation, the Deutsche Forschungsgemeinschaft and the VolkswagenStiftung; the Department of Science and Technology of India; The WCU program of the Ministry Education Science and Technology, National Research Foundation of Korea Grant No. 2011-0029457, 2012-0008143, 2012R1A1A2008330, 2013R1A1A3007772, BRL program under NRF Grant No. KRF-2011-0020333, KRF-2011-0021196, BK21 Plus program, and GSDC of the Korea Institute of Science and Technology Information; the Polish Ministry of Science and Higher Education and the National Science Center; the Ministry of Education and Science of the Russian Federation and the Russian Federal Agency for Atomic Energy; the Slovenian Research Agency; the Basque Foundation for Science (IERBASQUE) and the UPV/EHU under program UFI 11/55; the Swiss National Science Foundation; the National Science Council and the Ministry of Education of Taiwan; and the U.S. Department of Energy and the National Science Foundation. This work is supported by a Grant-in-Aid from MEXT for Science Research in a Priority Area (“New Development of Flavor Physics”), and from JSPS for Creative Scientific Research (“Evolution of Tau-lepton Physics”).

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