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Search for charmonium and charmoniumlike states in $\Upsilon(1S)$ radiative decays

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Using a sample of 102×10^6 $\Upsilon(1S)$ events collected with the Belle detector, we report on the first search for charge-parity-even charmonium and charmoniumlike states in $\Upsilon(1S)$ radiative decays. No significant χ_{cJ} or η_c signal is observed and 90% C.L. limits on $\mathcal{B}(\Upsilon(1S) \to \gamma\chi_{c0}) < 6.5 \times 10^{-4}$, $\mathcal{B}(\Upsilon(1S) \to \gamma\chi_{c1}) < 2.3 \times 10^{-5}$, $\mathcal{B}(\Upsilon(1S) \to \gamma\chi_{c2}) < 7.6 \times 10^{-6}$, and $\mathcal{B}(\Upsilon(1S) \to \gamma\eta_c) < 5.7 \times 10^{-5}$ are obtained. The product branching fraction limits $\mathcal{B}(\Upsilon(1S) \to \gamma X(3872))\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) < 1.6 \times 10^{-6}$, $\mathcal{B}(\Upsilon(1S) \to \gamma X(3872))\mathcal{B}(X(3872) \to \pi^+\pi^-\pi^0 J/\psi) < 2.8 \times 10^{-6}$, $\mathcal{B}(\Upsilon(1S) \to \gamma X(3915))$ $\mathcal{B}(X(3915) \to \omega J/\psi) < 3.0 \times 10^{-6}$, and $\mathcal{B}(\Upsilon(1S) \to \gamma Y(4140))\mathcal{B}(Y(4140) \to \phi J/\psi) < 2.2 \times 10^{-6}$ are obtained at the 90% C.L. Furthermore, no evidence is found for excited charmonium states below 4.8 GeV/c^2.

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There is renewed interest in charmonium spectroscopy after the operation of the two B factories. In addition to many conventional charmonium states, a number of states with unusual properties have been discovered, which may include states beyond the quark model, such as quark-gluon hybrids, meson molecules, multiquark states, and so on [1–7]. States with $J^{PC} = 1^{--}$ can be studied using initial state radiation (ISR) in the large $\Upsilon(4S)$ data samples. For the study of charge-parity-even charmonium states, radiative decays of the Υ states below open-bottom threshold are used.

The production rates of the lowest lying P-wave spin-triplet (χ_{cJ}, $J = 0$, 1, or 2) and S-wave spin-singlet (η_c) states in $\Upsilon(1S)$ radiative decays are calculated in Ref. [8], where the former is at the part per million level, and the latter is about 5×10^{-5}. There are no calculations for radiative decays involving excited charmonium states, let alone for charmoniumlike states, such as the $X(3872)$ [1], the $X(3915)$ [9], and the $Y(4140)$ [7].

In this article, we report on a search for the χ_{cJ}, η_c, $X(3872)$, $X(3915)$, and $Y(4140)$ states in $\Upsilon(1S)$ radiative decays. The χ_{cJ} states are reconstructed via their $E1$ transition to the J/ψ. The η_c is reconstructed in the $K_S^0 K^+\pi^-$ + c.c., $\pi^+\pi^- K^+K^-$, $2(K^+K^-)$, $2(\pi^+\pi^-)$, and $3(\pi^+\pi^-)$ final states. To search for the $X(3872)$ and $X(3915)$, we use the $\pi^+\pi^- J/\psi$ and $\pi^+\pi^-\pi^0 J/\psi$ final states, while we reconstruct the $Y(4140)$ in the $\phi J/\psi$ mode. This analysis is based on a 5.7 fb^{-1} data sample collected at the $\Upsilon(1S)$ [102×10^6 $\Upsilon(1S)$ events] and a 1.8 fb^{-1} data sample collected at $\sqrt{s} = 9.43$ GeV (continuum data) with the Belle detector [10] operating at the KEKB asymmetric-energy e^+e^- collider [11].

For each charged track, the impact parameters perpendicular to and along the beam direction with respect to the interaction point are required to be less than 0.5 cm and 4 cm, respectively, and the transverse momentum must exceed 0.1 GeV/c in the laboratory frame. For each charged track, information from different detector subsystems is combined to form a likelihood $\mathcal{L}_i$ for each particle species [12]. Tracks with $\mathcal{R}_K = \frac{\mathcal{L}_K}{\mathcal{L}_K + \mathcal{L}_\pi} > 0.6$ are identified as kaons, and tracks with $\mathcal{R}_K < 0.4$ are identified as pions. With these selections, the kaon (pion) identification efficiency is about 90% (96%), while 5% (6%) of kaons (pions) are misidentified as pions (kaons). For electron identification, the likelihood ratio is defined as $\mathcal{R}_e = \frac{\mathcal{L}_e}{\mathcal{L}_e + \mathcal{L}_x}$, where $\mathcal{L}_e$ and $\mathcal{L}_x$ are the likelihoods for electron and nonelectron hypotheses, respectively. These are determined using the ratio of the energy deposited in the electromagnetic calorimeter (ECL) to the momentum measured in the silicon vertex detector and central drift chamber, the shower shape in the ECL, the matching between the position of the charged track trajectory and the cluster position in the ECL, hit information from the aerogel threshold Cherenkov counters, and dE/dx information in the central drift chamber [13]. For muon identification, the likelihood ratio is defined as $\mathcal{R}_\mu = \frac{\mathcal{L}_\mu}{\mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K}$, where $\mathcal{L}_\mu$, $\mathcal{L}_\pi$, and $\mathcal{L}_K$ are the likelihoods for muon, pion, and kaon hypotheses, respectively. These are based on track matching quality and penetration depth of associated hits in the iron flux-return (KLM) [14].

We reconstruct J/ψ mesons from e^+e^- or $\mu^+\mu^-$ candidates. In order to reduce the effect of bremsstrahlung or final-state radiation, photons detected in the ECL within 0.05 radians of the original e^+ or e^- direction are included in the calculation of the $e^+e^-(\gamma)$ invariant mass. For electrons from $J/\psi \to e^+e^-$, one track should have $\mathcal{R}_e > 0.95$ and the other $\mathcal{R}_e > 0.05$; for muons from $J/\psi \to \mu^+\mu^-$, at least one track should have $\mathcal{R}_\mu > 0.95$

(in the χ_{cJ} analysis, the other track should have associated hits in the KLM detector that agree with the extrapolated trajectory of a charged track provided by the drift chamber). The lepton identification efficiency is about 90% for $J/\psi \to e^+e^-$ and 87% for $J/\psi \to \mu^+\mu^-$. In order to improve the J/ψ momentum resolution, a mass fit to the reconstructed J/ψ candidates is then performed for all the channels with J/ψ signals.

A neutral cluster is considered to be a photon candidate if its ECL shower does not match the extrapolation of any charged track and the energy deposition is greater than 40 MeV. The photon candidate with the maximum energy in the e^+e^- center-of-mass frame is taken to be the $\Upsilon(1S)$ radiative decay photon, and its energy is required to be greater than 3.5 GeV, which corresponds to a 4.8 GeV/c^2 mass particle produced in $\Upsilon(1S)$ radiative decays.

To study the $\gamma\chi_{cJ}$ mode, we reconstruct χ_{cJ} via its decay into $\gamma J/\psi$. The deposited energy of χ_{cJ}'s photon is required to be greater than 150 MeV, and the total number of photons in the event is required to be exactly two, in order to suppress multiphoton backgrounds. The higher energy photon is denoted as γ_h and the lower energy one is denoted as γ_l. The angle between the two photons should be larger than 18° to remove the background from split-off fake photons. To remove the ISR background $e^+e^- \to \gamma_{\rm ISR}\psi(2S) \to \gamma_{\rm ISR}\gamma\chi_{cJ}$, where a photon is missed, we require the square of the missing mass of γ_l and lepton pair to be within -0.5 GeV$^2/c^4$ and 0.5 GeV$^2/c^4$ since this background has at least two missing photons [the $\gamma_{\rm ISR}$ photon(s) and one photon from the $\psi(2S)$ decay] and the missing mass tends to be large. Bhabha and dimuon background events with final-state radiative photons are further suppressed by removing events where a photon is detected within a 18° cone around each charged track direction.

A clear J/ψ signal is observed in the $\mu^+\mu^-$ mode, while no significant J/ψ signal is observed in the e^+e^- mode due to residual radiative Bhabha background. The J/ψ signal region is defined as $|m_{\ell^+\ell^-} - m_{J/\psi}| <$ 30 MeV/c^2 ($\approx 2.5\sigma$), and the J/ψ mass sidebands are defined as 2.959 GeV/$c^2 < m_{\ell^+\ell^-} <$ 3.019 GeV/c^2 or 3.175 GeV/$c^2 < m_{\ell^+\ell^-} <$ 3.235 GeV/c^2, where the latter is twice as wide as the signal region.

Figure 1 shows the $\gamma_l J/\psi$ invariant mass distribution after the above selections are applied to the $\Upsilon(1S)$ data sample for the combined e^+e^- and $\mu^+\mu^-$ modes, together with the background estimated from the normalized J/ψ mass sidebands. Apart from possible weak χ_{c0} and χ_{c1} signals, the J/ψ sideband events represent well the signal region, indicating that the production of any of the χ_{cJ} states is not significant. There are no structures at higher masses, where we would expect excited χ_{cJ} states.

A fit to the signal region is performed with Breit-Wigner functions for the resonances convolved with Gaussian resolution functions and a second-order polynomial background term. This fit yields $5.9^{+3.9}_{-3.1}$, $8.5^{+3.8}_{-3.1}$, and $0.6^{+2.1}_{-1.4}$ events for the χ_{c0}, χ_{c1}, and χ_{c2}, respectively. Here the width of the Gaussian resolution function is fixed as 7.0 MeV/c^2, its Monte Carlo (MC) determined value. Bayesian upper limits on the number of events at the 90% C.L. by integrating the likelihood distribution (as a function of the yield) are found to be 11.5, 13.8, and 2.4 for the χ_{c0}, χ_{c1}, and χ_{c2}, respectively.

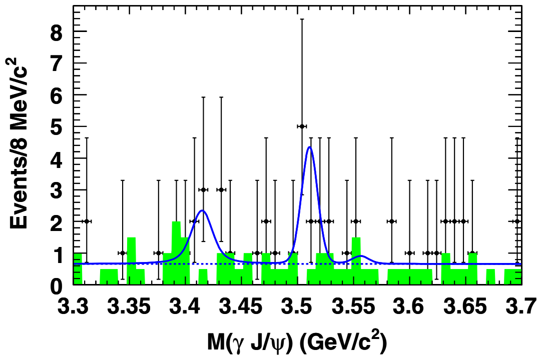

FIG. 1 (color online). The $\gamma_l J/\psi$ invariant mass distribution in the $\Upsilon(1S)$ data sample. Hints of χ_{c0} and χ_{c1} signals are seen, although no obvious χ_{c2} signal is observed. The solid curve is the best fit, the dashed curve is the background, and the shaded histogram is from the normalized J/ψ mass sidebands.

To study the $\gamma\eta_c$ mode, we reconstruct the η_c mass from the invariant masses of $K_S^0K^+\pi^-$ + c.c., $\pi^+\pi^-K^+K^-$, $2(K^+K^-)$, $2(\pi^+\pi^-)$, and $3(\pi^+\pi^-)$. Well-measured charged tracks are selected and the numbers of charged tracks are six for the $3(\pi^+\pi^-)$ final state and four for the other final states. All the charged tracks are required to be identified as kaons or pions. The recoil mass squared of the charged particles in each η_c decay mode is required to be within -1 GeV$^2/c^4$ and 1 GeV$^2/c^4$. For K_S^0 candidates decaying into $\pi^+\pi^-$ in the $K_S^0K^+\pi^-$ + c.c. mode, we require that the invariant mass of the $\pi^+\pi^-$ pair lie within 30 MeV/c^2 of the K_S^0 nominal mass and that the K_S^0 candidate must have a displaced vertex and flight direction consistent with a K_S^0 originating from the IP; the same selection method is used in Ref. [15]. There are events with leptons misidentified as pions in the $\pi^+\pi^-K^+K^-$ and $2(\pi^+\pi^-)$ modes, and they are removed by requiring $\mathcal{R}_e < 0.9$ and $\mathcal{R}_\mu < 0.9$ for the pion candidates.

Figure 2 shows the combined mass distribution for the five η_c decay modes after the selection described above. The peak in hadronic mass at the J/ψ mass, as seen in Fig. 2, can be attributed to the ISR process, $e^+e^- \to \gamma_{\rm ISR}J/\psi$, while the accumulation of events within the η_c mass region is small. The shaded histogram in Fig. 2 is the same distribution for the continuum data, normalized according to the ratio of the luminosities on and off the $\Upsilon(1S)$ peak. From Fig. 2, we can see that the J/ψ signal in $\Upsilon(1S)$ data is well reproduced by the normalized continuum data,

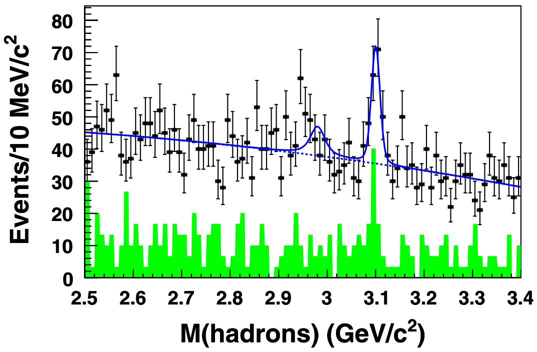

FIG. 2 (color online). The mass distribution for a sum of the five η_c decay modes. The solid line is a sum of the corresponding functions obtained from a simultaneous fit to all the η_c decay modes, and the dashed line is a sum of the background functions from the fit. The shaded histogram is a sum of the normalized continuum events, where the J/ψ signal is produced via ISR.

demonstrating its ISR origin. It is also evident that $\Upsilon(1S)$ radiative decays to light hadrons are substantial, as indicated by the difference between the number of nonresonant events in the two data sets.

We perform a simultaneous fit to all the η_c decay modes, where the η_c mass and width are taken from the PDG [16], and the ratio of the yields in all the channels is fixed to $\mathcal{B}_i\epsilon_i$, where each $\mathcal{B}_i$ is the η_c decay branching fraction for the ith mode reported by the PDG [16], and ϵ_i is the MC determined efficiency for this mode. In the fit, we take a Breit-Wigner function convolved with a Gaussian resolution function (its resolution is fixed to 7.9 MeV$/c^2$ from MC simulation) as the η_c signal shape, another Gaussian function as the J/ψ signal shape, and a second-order polynomial as the background shape. The fitted results are shown in Fig. 2, where the solid line is the sum of the best fit functions in the simultaneous fit, and the dashed line is the sum of the background functions. The fit yields 46 ± 22 η_c signal events, with a statistical significance of 2.2σ. An upper limit on the number of the η_c signal events is estimated to be 72 at the 90% C.L. From the fit, we obtain 89 ± 20 and 54 ± 16 J/ψ signal events in $\Upsilon(1S)$ and normalized continuum data samples, respectively, with a mass of 3099.9 ± 2.1 MeV$/c^2$, which is consistent with PDG value.

The selection criteria for $\Upsilon(1S) \to \gamma X(3872)$, $X(3872) \to \pi^+\pi^- J/\psi$ are similar to those used for ISR $\pi^+\pi^- J/\psi$ events in $\Upsilon(4S)$ data [3]. We require that one J/ψ candidate be reconstructed, that two well identified π's have an invariant mass greater than 0.35 GeV$/c^2$, and that the recoil mass squared of the $\pi^+\pi^- J/\psi$ be between -1 GeV$^2/c^4$ and 1 GeV$^2/c^4$. To suppress ISR $\pi^+\pi^- J/\psi$ background, we require that the polar angle of the radiative photon satisfy $|\cos\theta| < 0.9$ in the e^+e^- center-of-mass system. Except for a few remaining ISR produced $\psi(2S)$ signal events, only a small number of events appear above the $\psi(2S)$ peak in the $\pi^+\pi^- J/\psi$ invariant mass distribution, as shown in Fig. 3(a). Within the $X(3872)$ signal region, there is one event with a mass of 3.870 GeV$/c^2$. However, there are no events in the J/ψ mass sidebands from 3.6 to 4.8 GeV$/c^2$. We estimate the statistical significance of the $X(3872)$ signal to be 2.3σ if the background distribution is flat above 3.7 GeV$/c^2$. Assuming that the number of signal events follows a Poisson distribution with a uniform prior probability density function and there is no background, the upper limit on the number of the $X(3872)$ signal events is 3.9 [16].

We validate our analysis by measuring the $\psi(2S)$ ISR production cross section as observed in the $\pi^+\pi^- J/\psi$ mode. By relaxing the photon polar angle requirement, we observe 383 $\psi(2S)$ signal events and a cross section of $e^+e^- \to \gamma_{\rm ISR}\psi(2S)$ is measured to be $(20.2 \pm 1.1(\text{stat}))$ pb, in agreement with a theoretical calculation of 18.5 pb using PDG [16] values for the $\psi(2S)$ resonance parameters as input.

To study the $\gamma\pi^+\pi^-\pi^0 J/\psi$ mode, we require the invariant mass of a pair of photons to be within 10 MeV$/c^2$ around the nominal π^0 mass (the mass resolution is about 4 MeV$/c^2$) to select π^0 candidates. The other event selection criteria are similar to those in the $X(3872) \to \pi^+\pi^- J/\psi$ mode, except that we do not require the $\pi^+\pi^-$ invariant mass to be greater than 0.35 GeV$/c^2$, which is used to remove the γ conversion background events in the $\pi^+\pi^- J/\psi$ mode.

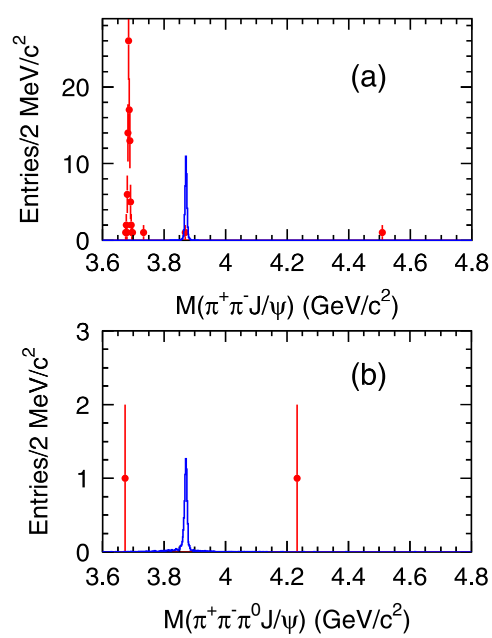

FIG. 3 (color online). (a) Distribution of the $\pi^+\pi^- J/\psi$ invariant mass for $\Upsilon(1S) \to \gamma\pi^+\pi^- J/\psi$ candidates. (b) Distribution of the $\pi^+\pi^-\pi^0 J/\psi$ invariant mass for $\Upsilon(1S) \to \gamma\pi^+\pi^-\pi^0 J/\psi$ candidates. Points with error bars are data, and open histograms are the MC expectation for the $X(3872)$ signal (not normalized). The peak at 3.686 GeV$/c^2$ in (a) is due to $\psi(2S)$ production via ISR.

Figure 3(b) shows the $\pi^+\pi^-\pi^0 J/\psi$ invariant mass distribution, where the open histogram is the MC expectation for the $X(3872)$ signal shape plotted with an arbitrary normalization. We observe two events in the $\pi^+\pi^-\pi^0 J/\psi$ mass spectrum between 3.6 GeV$/c^2$ and 4.8 GeV$/c^2$ in the $\Upsilon(1S)$ data. For these two events, the $\pi^+\pi^-\pi^0 J/\psi$ masses are 3.67 GeV$/c^2$ and 4.23 GeV$/c^2$, and the corresponding $\pi^+\pi^-\pi^0$ masses are 0.54 GeV$/c^2$ and 1.04 GeV$/c^2$, respectively. The event at 3.67 GeV$/c^2$ is likely to be from $e^+e^- \to \gamma_{\rm ISR}\eta J/\psi \to \gamma_{\rm ISR}\pi^+\pi^-\pi^0\ell^+\ell^-$, since 0.9 events are expected from MC simulation. No event is observed within the $X(3872)$ or $X(3915)$ mass region. An upper limit on the number of $X(3872)$ or $X(3915)$ signal events is 2.3 at the 90% C.L. [16].

We also search for the $Y(4140)$ in its decays into $\phi J/\psi$, with $\phi \to K^+K^-$ and $J/\psi \to \ell^+\ell^-$. The selection criteria are very similar to the analysis of $X(3872) \to \pi^+\pi^- J/\psi$ above. Here two kaons are required to be positively identified and one J/ψ candidate is reconstructed. No clear J/ψ or ϕ signal can be seen after the initial event selection. We define the J/ψ signal region as $|m_{\ell^+\ell^-} - m_{J/\psi}| < 30$ MeV$/c^2$, and the ϕ signal region as 1.01 GeV$/c^2 < m_{K^+K^-} <$ 1.03 GeV$/c^2$, according to MC simulation. After applying all of the above event selection criteria, there are no candidate events in the $\phi J/\psi$ invariant mass region between 4 GeV$/c^2$ and 4.8 GeV$/c^2$. An upper limit on the number of $Y(4140)$ signal events is 2.3 at the 90% C.L. [16].

There are several sources of systematic error in determining limits on the branching fractions. A particle identification efficiency uncertainty between 2.4% and 3.7% is assigned depending on the final-state particles. An uncertainty in the tracking efficiency for tracks with angles and momenta characteristic of signal events is about 1% per track, and is additive. Photon reconstruction contributes an additional 2% per photon. Errors on the branching fractions of the intermediate states are taken from the PDG [16]. For the η_c decays, the biggest difference in the efficiency by using a phase space distribution and including possible intermediate resonance states is 2.1%. The difference in overall efficiency for a flat radiative photon angular distribution and a $1 \pm \cos^2\theta$ distribution is less than 3.0%. Therefore, we quote an additional error of 5% for all the states studied due to limited knowledge of their decay dynamics. According to MC simulation, the trigger efficiency is rather high, with an uncertainty that is smaller than 1%. The uncertainty due to the missing mass squared requirement is 1.0% for the channels with only one photon and 4.7% for channels with more than one photon. Uncertainties on the χ_{cJ} and η_c signal event yields are estimated to be 1.6% and 15%, respectively, by changing the order of the background polynomial, the range of the fit, and the values of the masses and widths of the resonances. In the $\Upsilon(1S) \to \gamma\chi_{cJ}$ mode, the uncertainty that is associated with the requirement on the number of photons is 2% after applying a correction factor of 0.96 to the MC efficiency, which is determined from a study of a very pure $\Upsilon(1S) \to \mu^+\mu^-$ event sample. In the $\eta_c \to K_S^0 K^+\pi^-$ + c.c. mode, the uncertainty in the K_S efficiency is determined by comparing yields for a sample of high momentum $K_S \to \pi^+\pi^-$ decays before and after applying the K_S candidate selection criteria; the efficiency difference between data and MC simulation is less than 4.9% [17]. Finally, the uncertainty on the total number of $\Upsilon(1S)$ events is 2.2%. Assuming that all of these systematic error sources are independent, we add them in quadrature to obtain total systematic errors as shown in Table I. In order to calculate conservative upper limits on these branching fractions, the efficiencies have been lowered by a factor of $1 - \sigma_{\rm sys}$.

TABLE I. Summary of the limits on $\Upsilon(1S)$ radiative decays to charmonium and charmoniumlike states R. $N_{\rm sig}^{\rm UP}$ is the upper limit on the number of signal events, ε is the efficiency, $\sigma_{\rm sys}$ is the total systematic error, and $\mathcal{B}(\Upsilon(1S) \to \gamma R)^{\rm UP}$ ($\mathcal{B}_R$) is the upper limit at the 90% C.L. on the decay branching fraction in the charmonium state case, and on the product branching fraction in the charmoniumlike state case.

State (R)	$N_{\rm sig}^{\rm UP}$	ε (%)	$\sigma_{\rm sys}$ (%)	$\mathcal{B}_R(10^{-5})$
χ_{c0}	11.5	15.1	11	65
χ_{c1}	13.8	17.0	11	2.3
χ_{c2}	2.4	15.8	11	0.76
η_c	72	25.1	23	5.7
$X(3872) \to \pi^+\pi^- J/\psi$	3.9	23.2	7.6	0.16
$X(3872) \to \pi^+\pi^-\pi^0 J/\psi$	2.3	7.6	9.7	0.28
$X(3915) \to \omega J/\psi$	2.3	8.1	9.7	0.30
$Y(4140) \to \phi J/\psi$	2.3	19.4	7.7	0.22

In summary, Table I lists the final results for the upper limits on the branching fractions of all the states studied, together with the upper limits on the numbers of signal events and their detection efficiencies. The results obtained on the χ_{cJ} and η_c production rates are not in contradiction with the calculations in Ref. [8]. No $X(3872)$, $X(3915)$, or $Y(4140)$ signals are observed, and the production rates of the $\pi^+\pi^- J/\psi$, $\pi^+\pi^-\pi^0 J/\psi$, $\omega J/\psi$, or $\phi J/\psi$ modes are found to be less than a few times 10^{-6} at the 90% C.L. Furthermore, we find no evidence for excited charmonium states below 4.8 GeV$/c^2$.

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