Search for double charmonium decays of the $P$-wave spin-triplet bottomonium states

C. P. Shen,²⁹ C. Z. Yuan,¹² T. Iijima,³⁰,²⁹ I. Adachi,⁹ H. Aihara,⁵² K. Arinstein,² D. M. Asner,⁴⁰ T. Aushev,¹⁶ A. M. Bakich,⁴⁶ B. Bhuyan,¹⁰ M. Bischofberger,³¹ A. Bozek,³⁵ M. Bräcklo,²⁶,¹⁷ T. E. Browder,⁸ M.-C. Chang,⁴ A. Chen,³² B. G. Cheon,⁶ K. Chilikin,¹⁶ R. Chistov,¹⁶ I.-S. Cho,⁵⁸ K. Cho,²⁰ S.-K. Choi,⁶ Y. Choi,⁴⁵ J. Dalseno,²⁷,⁴⁸ Z. Drášal,³ A. Drutskoy,¹⁶ S. Eidelman,² J. E. Fast,⁴⁰ V. Gaur,⁴⁷ N. Gabyshev,² A. Garmash,² Y. M. Goh,⁷ J. Haba,⁹ T. Hara,⁹ K. Hayasaka,³⁰ H. Hayashii,³¹ Y. Hori,³⁰ Y. Hoshi,⁵⁰ W.-S. Hou,³⁴ H. J. Hyun,²² A. Ishikawa,⁵¹ R. Itoh,⁹ M. Iwabuchi,⁵⁸ T. Iwashita,³¹ T. Julius,²⁸ J. H. Kang,⁵⁸ T. Kawasaki,³⁷ H. J. Kim,²² H. O. Kim,²² J. B. Kim,²¹ K. T. Kim,²¹ M. J. Kim,²² Y. J. Kim,²⁰ B. R. Ko,²¹ S. Kobliž,²⁷ P. Kodyš,³ S. Korpar,²⁶,¹⁷ P. Križan,²⁴,¹⁷ P. Krokovny,² T. Kumita,⁵⁴ Y.-J. Kwon,⁵⁸ J. S. Lange,⁵ S.-H. Lee,²¹ J. Li,⁴⁴ J. Libby,¹¹ C.-L. Lim,⁵⁸ C. Liu,⁴³ Z. Q. Liu,¹² D. Liventsev,¹⁶ R. Louvot,²³ S. McOnie,⁴⁶ K. Miyabayashi,³¹ H. Miyata,³⁷ Y. Miyazaki,²⁹ R. Mizuk,¹⁶ G. B. Mohanty,⁴⁷ A. Moll,²⁷,⁴⁸ T. Mori,²⁹ N. Muramatsu,⁴² R. Mussa,¹⁵ E. Nakano,³⁹ M. Nakao,⁹ H. Nakazawa,³² S. Nishida,⁹ K. Nishimura,⁸ O. Nitoh,⁵⁵ S. Ogawa,⁴⁹ T. Ohshima,²⁹ S. Okuno,¹⁸ S. L. Olsen,⁴⁴,⁸ Y. Onuki,⁵² G. Pakhlova,¹⁶ C. W. Park,⁴⁵ H. K. Park,²² T. K. Pedlar,²⁵ M. Petric,¹⁷ L. E. Piilonen,⁵⁶ A. Poluektov,² M. Ritter,²⁷ M. Röhrken,¹⁹ H. Sahoo,⁸ Y. Sakai,⁹ T. Samuki,⁵¹ Y. Sato,⁵¹ O. Schneider,²³ C. Schwanda,¹³ K. Senyo,⁵⁷ O. Seon,²⁹ M. Shapkin,¹⁴ T.-A. Shibata,⁵³ J.-G. Shiu,³⁴ A. Sibidanov,⁴⁶ F. Simon,²⁷,⁴⁸ J. B. Singh,⁴¹ P. Smerkol,¹⁷ Y.-S. Soln,⁵⁸ E. Solovieva,¹⁶ S. Stanic,³⁸ M. Starić,¹⁷ T. Sumiyoshi,⁵⁴ G. Tatishvili,⁴⁰ Y. Teramoto,³⁹ T. Tsuboyama,³⁹ M. Uchida,⁵³ S. Uehara,⁹ Y. Unno,⁷ S. Uno,⁹ P. Urquiola,¹ G. Varner,⁸ K. E. Varvell,⁴⁶ C. H. Wang,³³ P. Wang,¹² X. L. Wang,¹² M. Watanabe,³⁷ Y. Watanabe,¹⁸ E. Won,²¹ Y. Yamashita,³⁶ Y. Yusa,³⁷ Z. P. Zhang,⁴³ V. Zhilich,² V. Zhulanov,² and A. Zupanc¹⁹

(The Belle Collaboration)

²Budker Institute of Nuclear Physics SB RAS and Novosibirsk State University, Novosibirsk 630090
³Faculty of Mathematics and Physics, Charles University, Prague
⁴Department of Physics, Fu Jen Catholic University, Taipei
⁵Justus-Liebig-Universität Gießen, Gießen
⁶Gyeongsang National University, Chinju
⁷Hanyang University, Seoul
⁸University of Hawaii, Honolulu, Hawaii 96822
⁹High Energy Accelerator Research Organization (KEK), Tsukuba
¹⁰Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
¹¹Indian Institute of High Energy Physics, Madras
¹²Institute of High Energy Physics, Moscow, Russia
¹³Institute of High Energy Physics, Vienna
¹⁴Institute of High Energy Physics, Protvino
¹⁵INFN - Sezione di Torino, Torino
¹⁶Institute for Theoretical and Experimental Physics, Moscow
¹⁷J. Stefan Institute, Ljubljana
¹⁸Kanagawa University, Yokohama
¹⁹Institut für Experimentelle Kernphysik, Karlsruher Institut für Technologie, Karlsruhe
²⁰Korea Institute of Science and Technology Information, Daejeon
²¹Korea University, Seoul
²²Kyungpook National University, Taegu
²³École Polytechnique Fédérale de Lausanne (EPFL), Lausanne
²⁴Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana
²⁵Luther College, Decorah, Iowa 52101
²⁶University of Maribor, Maribor
²⁷Max-Planck-Institut für Physik, München
²⁸University of Melbourne, School of Physics, Victoria 3010
²⁹Graduate School of Science, Nagoya University, Nagoya
³⁰Kobayashi-Maskawa Institute, Nagoya University, Nagoya
³¹Nara Women’s University, Nara
³²National Central University, Chung-li
³³National United University, Miao Li
³⁴Department of Physics, National Taiwan University, Taipei
Using a sample of 158 million $\Upsilon(2S)$ events collected with the Belle detector, we search for the first time for double charmonium decays of the $P$-wave spin-triplet bottomonium states ($\Upsilon(2S) \to \gamma \chi_{bJ}$, $\chi_{bJ} \to J/\psi J/\psi$, $J/\psi\psi'$, $\psi'\psi''$ for $J = 0, 1, 2$). No significant $\chi_{bJ}$ signal is observed in the double charmonium mass spectra, and we obtain the following upper limits, $B(\chi_{bJ} \to J/\psi J/\psi) < 7.1 \times 10^{-5}$, $2.7 \times 10^{-5}$, $4.5 \times 10^{-5}$, $B(\chi_{bJ} \to J/\psi\psi') < 1.2 \times 10^{-4}$, $1.7 \times 10^{-5}$, $4.9 \times 10^{-5}$, $B(\chi_{bJ} \to \psi'\psi'') < 3.1 \times 10^{-5}$, $6.2 \times 10^{-5}$, $1.6 \times 10^{-5}$ for $J = 0, 1, 2$, respectively, at the 90% confidence level. These limits are significantly lower than the central values (with uncertainties of 50% to 70%) predicted using the light cone formalism but are consistent with calculations using the NRQCD factorization approach.

PACS numbers: 13.25.Gv, 13.25.Hw, 14.40.Pq
The detector is described in detail elsewhere [18]. It 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 comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside the coil is instrumented to detect $K_L^0$ mesons and to identify muons (KLM).

For well reconstructed charged tracks, the impact parameters perpendicular to and along the beam direction with respect to the nominal interaction point are required to be less than 0.5 cm and 4 cm, respectively, and the transverse momentum in the laboratory frame is required to be larger than 0.1 GeV/c. We require the number of well reconstructed charged tracks to be greater than three for $\gamma J/\psi J/\psi$, and greater than four for $\gamma J/\psi\psi'$ and $\gamma\psi'\psi'$. For the modes with $\psi'$ in the final states, events with exactly four charged tracks are removed to suppress the significant background from QED processes. For each charged track, information from different detector sub-systems is combined to form a likelihood $L_{\ell}$ for each particle species [26]. A track with $R_{\ell} = \frac{E_{\ell}}{p_{\ell}} < 0.4$ is identified as a pion with an efficiency of about 97% for the momentum range of interest; about 3.5% are misidentified K tracks. For electron identification, the likelihood ratio is defined as $R_{e} = \frac{L_{e}}{L_{\mu}}$, where $L_{\mu}$ and $L_{e}$ are the likelihoods for electron and non-electron, respectively, determined using the ratio of the energy deposit in the ECL to the momentum measured in the SVD and CDC, the shower shape in the ECL, matching between the position of the charged track trajectory and the cluster position in the ECL, the hit information from the ACC and the $dE/dx$ information in the CDC [27]. For muon identification, the likelihood ratio is defined as $R_{\mu} = \frac{L_{\mu}}{L_{e} + L_{\pi} + L_{K}}$, where $L_{\mu}$, $L_{\pi}$, and $L_{K}$ are the likelihoods for muon, pion, and kaon hypotheses, respectively, based on the matching quality and penetration depth of associated hits in the KLM [28].

A neutral cluster is used as a photon candidate if it does not match the extrapolation of any charged track and its energy is greater than 50 MeV. In calculating the recoil mass of $\gamma J/\psi$ or $\gamma\psi'$, all photon candidates except those within 0.05 radians of the electron/positron tracks are included. No $\pi^0$ signal is observed in combining the low energy radiative photon with any of the remaining photon candidates in the event after all the selection criteria are applied.

In order to correct for the effect of bremsstrahlung and 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 $e^+/e^-$ momentum. For the lepton pair used to reconstruct $J/\psi$, both tracks should have $R_{\ell} > 0.95$ in the $e^+/e^-$ mode; or one track should have $R_{\mu} > 0.95$ while the other should satisfy $R_{\mu} > 0.05$ in the $\mu^+\mu^-$ mode. The lepton pair identification efficiency is about 90% for $J/\psi \rightarrow e^+e^-$ and 87% for $J/\psi \rightarrow \mu^+\mu^-$. In order to improve the $J/\psi$ momentum resolution, a mass-constrained fit is then performed for $J/\psi$ signals in all the modes. As different modes have almost the same $J/\psi$ mass resolutions, the $J/\psi$ signal region is defined as $|m_{ee} - m_{J/\psi}| < 0.03$ GeV/$c^2$ ($\approx 2.5\sigma$), where $m_{J/\psi}$ is the nominal mass of $J/\psi$ [24].
The $J/\psi$ mass sidebands are defined as $2.97$ GeV/c$^2 < M_{\ell^+\ell^-} < 3.03$ GeV/c$^2$ or $3.17$ GeV/c$^2 < M_{\ell^+\ell^-} < 3.23$ GeV/c$^2$, and are twice as wide as the signal region. For $\psi' \rightarrow \ell^+\ell^-$, the $\psi'$ signal region is defined as $|M_{\ell^+\ell^-} - m_{\psi'}| < 0.0375$ GeV/c$^2$ ($\approx 2.5\sigma$), where $m_{\psi'}$ is the nominal mass of $\psi'$. The $\psi'$ mass sidebands are defined as $3.535$ GeV/c$^2 < M_{\ell^+\ell^-} < 3.610$ GeV/c$^2$ or $3.760$ GeV/c$^2 < M_{\ell^+\ell^-} < 3.855$ GeV/c$^2$, and are twice as wide as the signal region. For $\psi' \rightarrow \pi^+\pi^-J/\psi$, we require the two pion candidates be positively identified. The $\psi'$ signal region is defined as $|M_{\pi^+\pi^-J/\psi} - m_{\psi'}| < 0.009$ GeV/c$^2$ ($\approx 3\sigma$). Figure 3 shows the mass distributions of the reconstructed $J/\psi \rightarrow \ell^+\ell^-$ (a), $\psi' \rightarrow \pi^+\pi^-J/\psi$ (b) and $\psi' \rightarrow \ell^+\ell^-$ (c) candidates.

Figure 2 shows scatter plots of the photon spectra in the $e^+e^-$ C.M. frame versus (a) $M_{\text{miss}}(\gamma J/\psi)$ with $J/\psi \rightarrow \ell^+\ell^-$ reconstructed, (b) $M_{\text{miss}}(\gamma \psi')$ with $\psi' \rightarrow \pi^+\pi^-J/\psi$ reconstructed, and (c) $M_{\text{miss}}(\gamma \psi')$ with $\psi' \rightarrow \ell^+\ell^-$ reconstructed. No evidence for $J/\psi$ or $\psi'$ signals can be seen in the $\gamma J/\psi$ or $\gamma \psi'$ missing mass distributions.

Figure 2 shows the simulated photon spectra in the $e^+e^-$ C.M. frame from the $\Upsilon(2S) \rightarrow \gamma \chi_{bJ} \rightarrow \gamma J/\psi J/\psi$ MC samples. Breit-Wigner (BW) functions convolved with Novosibirsk functions \cite{29} are used as $\chi_{bJ}$ signal shapes while Chebyshev polynomial functions model the combinatorial backgrounds ($\approx 11$% in $\chi_{bJ}$ signal region). The extended maximum likelihood fits to the photon spectra with all the parameters free are shown in Fig. 3. Based on the fit results, the efficiencies are $(5.75 \pm 0.12)\%$, $(6.25 \pm 0.12)\%$, and $(5.87 \pm 0.12)\%$ for $\Upsilon(2S) \rightarrow \gamma \chi_{bJ} \rightarrow \gamma J/\psi J/\psi$ for $J = 0$, 1 and 2, respectively. Similarly, the sum of the efficiencies from all the modes is found to be $(3.40 \pm 0.06)\%$, $(3.78 \pm 0.06)\%$, and $(3.53 \pm 0.06)\%$ for $\Upsilon(2S) \rightarrow \gamma \chi_{bJ} \rightarrow \gamma J/\psi \psi'$, $(2.06 \pm 0.04)\%$, $(2.15 \pm 0.04)\%$, and $(2.09 \pm 0.04)\%$ for $\Upsilon(2S) \rightarrow \gamma \chi_{bJ} \rightarrow \gamma \psi' \psi'$ for $J = 0$, 1 and 2, respectively.

After all the event selections, no events from the $\Upsilon(2S)$ MC sample with generic decays survive. Other possible backgrounds with $J/\psi/\psi'$ signals from channels such as $e^+e^- \rightarrow J/\psi \chi_{cJ}$, $\psi' \chi_{bJ}$, have very small cross-sections (at the few fb level \cite{30}) and hence are neglected in the analysis.

Figures 4(a), (b) and (c) show the photon spectra from $\Upsilon(2S)$ data for $\chi_{bJ} \rightarrow J/\psi J/\psi$, $J/\psi \psi'$, and $\psi' \psi'$ candidate events, respectively, with all the modes included. Here the shaded histograms show the $J/\psi$ or $\psi'$ mass sidebands normalized to the width of the $J/\psi$ or $\psi'$ signal range and the dashed histograms are the normalized continuum contributions. The continuum background contribution is extrapolated down to the $\Upsilon(2S)$ resonance. For the extrapolation, three factors are applied to account for: the relative luminosities of the two samples, efficiency dependence on the C.M. energy, and cross-section dependence on the C.M. energy. The cross section extrapolation with C.M. energy is assumed to have a $1/s$ dependence.

No clear $\chi_{bJ}$ signals are observed in Fig. 4. For $\chi_{bJ} \rightarrow J/\psi J/\psi$, a unbinned extended maximum likelihood method is applied to the photon spectrum with the MC simulated signal shape smeared with a Gaussian function to take into account a 8.5% difference in photon energy resolution between data and MC samples. The photon energy resolution is measured with $\Upsilon(2S) \rightarrow \gamma \chi_{bJ} \rightarrow \gamma \gamma \Upsilon(1S)$, $\Upsilon(1S) \rightarrow \mu^+\mu^-$ events. For $\chi_{bJ} \rightarrow J/\psi \psi'$ $(\psi'\psi')$ decays, an unbinned extended maximum likelihood simultaneous fit is performed to all the modes mentioned above. The ratios of the $\chi_{bJ}$ yields in different modes are fixed to $\epsilon_i$ (i denotes the i-th mode) with all the intermediate state branching fractions included, and $\epsilon_i$ is the MC-determined efficiency for the i-th mode. The fits are performed with the same method as in the $J/\psi J/\psi$ mode. Figure 4 shows the fit results, where for (b) and (c) the solid curves are the sum of all the fit contributions, and the dashed curves are the sum of the background functions. In all of the modes, the background levels from the fits are a little higher than the estimations from the normalized continuum or the normalized $J/\psi/\psi'$ mass sidebands. It may indicate that there are double-charmonium production together with one photon or more particles in $\Upsilon(2S)$ decays.

The upper limit on the number of signal events at the 90% C.L. ($n^{\text{up}}$) is calculated by solving the equation

$$\int_{0}^{n^{\text{up}}} \frac{C(x)dx}{\epsilon(x)dx} = 0.9,$$

where $x$ is the number of signal events, and $C(x)$ is the likelihood function depending on $x$ from the fit to the data, with $x$ being the number of signal events in the fit. The values of $n^{\text{up}}$ are found to be 21, 13, and 22 for $\chi_{bJ} \rightarrow J/\psi J/\psi$; 20, 5.8, and 17 for $\chi_{bJ} \rightarrow J/\psi \psi'$; and 3.0, 12, and 3.3 for $\chi_{bJ} \rightarrow \psi'\psi'$, for $J = 0$, 1, and 2, respectively, when requiring the signal yields to be non-negative in the fit.

There are several sources of systematic errors for the branching fraction measurement. The uncertainty in the tracking efficiency for tracks with angles and momenta characteristic of signal events is about 0.35% per track, and is additive. The photon reconstruction contributes an additional 3.8% per photon. The uncertainty due to particle identification efficiency is 1.3% for each pion in $\psi'$, $\pi^+\pi^-J/\psi$. According to a measurement of the lepton identification efficiency using a control sample of $\gamma\gamma \rightarrow \ell^+\ell^-$, the MC simulates data within 1.7% for an electron-positron pair and 1.7% for a muon pair. According to MC simulation, the trigger efficiency is greater than 99.5% and we take 0.5% as systematic error due to the trigger simulation uncertainty. Errors on the branching fractions of the intermediate states are taken from the PDG \cite{24}, which are about 12%, 6.0% and 5.0% for $\chi_{b0}$, $\chi_{b1}$ and $\chi_{b2}$ decays. By changing the order of the background polynomial and the range of the fit, the relative difference in the upper limits of the number of signal
The arrows show the required signal mass regions.

FIG. 2: Scatter plots of the photon spectra in the $e^+e^-$ C.M. frame versus (a) $M_{\text{miss}}(J/\psi)$ with $J/\psi \to \ell^+\ell^-$ reconstructed, (b) $M_{\text{miss}}(\gamma\psi')$ with $\psi' \to \pi^+\pi^-J/\psi$ reconstructed, and (c) $M_{\text{miss}}(\gamma\psi')$ with $\psi' \to \ell^+\ell^-$ reconstructed. The dotted lines show the $J/\psi$ or $\psi'$ signal regions ($\approx \pm 3\sigma$).

events is 7.6%-28% depending on the decay mode, which is taken as systematic error due to the uncertainty of fit. For our MC signal samples, $J/\psi$ and $\psi'$ decays are simulated with a generic decay model. The signal efficiencies are determined based on the fitted results. The error on the number of fitted signal events is less than 2.1%, which is taken as the MC statistical error in the efficiency. The masses of $\chi_{bJ}$ have been measured well [24] and the uncertainties on the masses of $\chi_{bJ}$ do not affect the efficiency determination. Comparing several theoretical calculations, the maximum values of $\chi_{b0}$ and $\chi_{b2}$ widths are 2.15 MeV/$c^2$ [31] and 0.33 MeV/$c^2$ [32], respectively. The efficiency differences between these values and the nominal values are taken as systematic errors due to the uncertainty of resonance parameters, which are less than 5.2% and 1.2% for $\chi_{b0}$ and $\chi_{b2}$ decays. Finally, the uncertainty on the total number of $\Upsilon(2S)$ events is 2.3%. Assuming that all of these systematic error sources are independent, and combining them in quadrature, we obtain the total systematic error listed in Table I.

Since there is no evidence for signals in the modes studied, we determine upper limits on the branching fractions of $\chi_{bJ}$ to double charmonia. Table II lists the upper limits $n_{\text{up}}^\Upsilon(2S)$ for the numbers of the signal events, detection efficiencies, systematic errors, and upper limits on the branching fractions of $\chi_{bJ}$ decays. In order to calculate conservative upper limits on these branching fractions, the efficiencies are lowered by a factor of $1 - \sigma_{\text{sys}}$ in the calculation.

To summarize, we find no significant signals in the $\chi_{bJ} \to J/\psi J/\psi$, $J/\psi\psi'$, or $\psi'\psi'$ final states using a sample of 158 million $\Upsilon(2S)$ events. The results obtained on the $\chi_{bJ}$ decay branching fractions are listed in Table II. Our upper limits are much lower than the central values predicted in the LC formalism [13] and pQCD calculation [16], but are consistent with calculations using the NRQCD factorization approach [13, 14].

TABLE I: Summary of the limits on $\chi_{bJ}$ decays into $J/\psi J/\psi$, $J/\psi\psi'$, and $\psi'\psi'$. Here $n_{\text{up}}^\Upsilon(2S)$ is the upper limit on the number of signal events, $\varepsilon$ is the sum of the efficiencies from different modes with $J/\psi$ and $\psi'$ decay branching fractions and trigger efficiency included, $\sigma_{\text{sys}}$ is the total systematic error, and $B_R$ is the upper limit on the branching fraction of $\chi_{bJ}$ decays, where the values of $B(\Upsilon(2S) \to \gamma\chi_{bJ}) = (3.8 \pm 0.4)\%$, $(6.9 \pm 0.4)\%$ and $(7.15 \pm 0.35)\%$ for $J = 0, 1$ and 2 are used [24]. The upper limits are at 90% C.L.

| Channel   | $n_{\text{up}}^\Upsilon(2S)$ | $\varepsilon(\%)$ | $\sigma_{\text{sys}}(\%)$ | $B_R$ |
|-----------|-------------------------------|-------------------|---------------------------|-------|
| $\chi_{b0} \to J/\psi J/\psi$ | 21 | 5.8 | 16 | $7.1 \times 10^{-5}$ |
| $\chi_{b1} \to J/\psi J/\psi$ | 13 | 6.3 | 30 | $2.7 \times 10^{-5}$ |
| $\chi_{b2} \to J/\psi J/\psi$ | 22 | 5.9 | 27 | $4.5 \times 10^{-5}$ |
| $\chi_{b0} \to J/\psi\psi'$ | 20 | 3.4 | 17 | $1.2 \times 10^{-4}$ |
| $\chi_{b1} \to J/\psi\psi'$ | 5.8 | 3.8 | 15 | $1.7 \times 10^{-5}$ |
| $\chi_{b2} \to J/\psi\psi'$ | 17 | 3.5 | 16 | $4.9 \times 10^{-5}$ |
| $\chi_{b0} \to \psi'\psi'$ | 3.0 | 2.1 | 20 | $3.1 \times 10^{-5}$ |
| $\chi_{b1} \to \psi'\psi'$ | 12 | 2.2 | 17 | $6.2 \times 10^{-5}$ |
| $\chi_{b2} \to \psi'\psi'$ | 3.3 | 2.1 | 12 | $1.6 \times 10^{-5}$ |

We thank the KEKB group for excellent operation of the accelerator, the KEK cryogenics group for effi-
FIG. 3: The fits to the photon spectra from the $\Upsilon(2S) \rightarrow \gamma \chi_{bJ} \rightarrow \gamma J/\psi J/\psi$ MC signal samples with one $J/\psi$ reconstructed and the $\gamma J/\psi$ recoil mass within the $J/\psi$ mass region for (a) $\chi_{b0}$, (b) $\chi_{b1}$ and (c) $\chi_{b2}$, respectively. The $\chi_{bJ}$ shapes are described by Breit-Wigners convolved with Novosibirsk functions, while Chebychev polynomial functions are used to describe the background.

FIG. 4: The photon spectra in $\Upsilon(2S)$ data for (a) $\gamma J/\psi J/\psi$, (b) $\gamma J/\psi \psi'$, and (c) $\gamma \psi' \psi'$ final states. The shaded histograms are from normalized $J/\psi / \psi'$ mass sidebands events and dashed histograms are normalized continuum contributions. The fits to the photon spectra are described in the text. The solid curves are the best fits, the dashed curves represent the backgrounds. The arrows show the expected central positions of the $\chi_{bJ}$ states.

We acknowledge support from MEXT, JSPS and Nagoya’s TLPRC (Japan); ARC and DIISR (Australia); NSFC (China); MMSI (Czechia); DST (India); MEST, NRF, NSDC of KISTI, and WCU (Korea); MNiSW (Poland); MES and RFAAE (Russia); ARRS (Slovenia); SNSF (Switzerland); NSC and MOE (Taiwan); and DOE and NSF (USA).

[1] K. Abe et al. (Belle Collaboration), Phys. Rev. Lett. 89, 142001 (2002).
[2] K. Abe et al. (Belle Collaboration), Phys. Rev. D 70, 071102 (2004).
[3] B. Aubert et al. (BaBar Collaboration), Phys. Rev. D 72, 031101 (2005).
[4] E. Braaten and J. Lee, Phys. Rev. D 67, 054007 (2003).
[5] K. Y. Liu, Z. G. He and K. T. Chao, Phys. Lett. B 557, 45 (2003).
[6] K. Y. Liu, Z. G. He and K. T. Chao, Phys. Rev. D 77, 014002 (2008).
[7] G. T. Bodwin, J. Lee and E. Braaten, Phys. Rev. Lett. 90, 162001 (2003).
[8] Y. J. Zhang, Y. J. Gao and K. T. Chao, Phys. Rev. Lett. 96, 092001 (2006).
[9] G. T. Bodwin, J. Lee and C. Yu, Phys. Rev. D 77, 094018 (2008).
[10] Z. G. He, Y. Fan and K. T. Chao, Phys. Rev. D 75, 074011 (2007).
[11] P. Sun, G. Hao and C. F. Qiao, Phys. Lett. B 702, 49 (2011) and references therein.
[12] V. G. Kartvelishvili and A. K. Likhoded, Yad. Fiz. 40, 1273 (1984).
[13] J. Zhang, H. R. Dong and F. Feng, Phys. Rev. D 84, 094031 (2011).
[14] W. L. Sang, R. Rashidin, U. Kim and J. Lee, Phys. Rev. D 84, 074026 (2011).
[15] V. V. Braguta, A. K. Likhoded, and A. V. Luchinsky, Phys. Rev. D 80, 094008 (2009); Phys. Atom. Nucl. 73, 1054 (2010).
[16] V. V. Braguta, A. K. Likhoded, and A. V. Luchinsky, Phys. Rev. D 72, 094018 (2005).
[17] X. L. Wang et al. (Belle Collaboration), Phys. Rev. D
84, 071107(R) (2011).
[18] A. Abashian et al. (Belle Collaboration), Nucl. Instr. and Methods Phys. Res. Sect. A 479, 117 (2002).
[19] S. Kurokawa and E. Kikutani, Nucl. Instr. and Methods Phys. Res. Sect. A 499, 1 (2003), and other papers included in this volume.
[20] D. J. Lange, Nucl. Instrum. Meth. A 462, 152 (2001).
[21] K. W. Edwards et al. (CLEO Collaboration), Phys. Rev. D 59, 032003 (1999).
[22] For $\chi_{bJ}$ decays, MC signal samples are also produced with the helicity amplitude formulae from $\chi_{cJ} \rightarrow VV$ ($V = \omega$ or $\phi$) [23] or from Ref. [13]. The largest difference in the efficiencies is less than 10%. The efficiencies with the phase space mode are lower, which will give conservative upper limits on the production rates.
[23] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 107, 092001 (2011).
[24] K. Nakamura et al. (Particle Data Group), J. Phys. G 37, 075021 (2010) and 2011 partial update for the 2012 edition.
[25] T. Sjostrand, S. Mrenna and P. Skands, JHEP 026, 0605 (2006).
[26] E. Nakano, Nucl. Instr. and Methods Phys. Res. Sect. A 494, 402 (2002).
[27] K. Hanagaki et al., Nucl. Instrum. Meth. A 485, 490 (2002).
[28] A. Abashian et al., Nucl. Instrum. Meth. A 491, 69 (2002).
[29] The Novosibirsk function is defined as $f(x) = \exp[-\frac{1}{2}(\ln^2(1 + \Lambda(x - x_0))/\sigma^2 + \tau^2)]$ with $\Lambda = \sinh(\tau\sqrt{\ln4})/(\sigma\sqrt{\ln4})$. The parameters represent the mean ($x_0$), the width ($\sigma$) and the tail asymmetry ($\tau$).
[30] K. Wang, Y. Q. Ma and K. T. Chao, Phys. Rev. D 84, 034022 (2011).
[31] S. N. Gupta, J. M. Johnson and W. W. Repko, Phys. Rev. D 54, 2075 (1996).
[32] J. T. Laverty, S. F. Radford and W. W. Repko, arXiv:0901.3917.