Observation of a charmonium-like enhancement in the $\gamma\gamma \rightarrow \omega J/\psi$ process

S. Uehara, T. Aushev, A. M. Bakich, K. Belous, V. Bhardwaj, M. Bischofberger, M. Bračko, T. E. Browder, P. Chang, A. Chen, P. Chen, B. G. Cheon, C.-C. Chiang, I.-S. Cho, S.-K. Choi, Y. Choi, J. Dalseno, A. Drutskoy, S. Eidelman, D. Epifanov, M. Feindt, N. Gabyshev, H. Ha, J. Haba, K. Hayasaka, H. Hayashii, Y. Hoshi, W.-S. Hou, Y. B. Hsiung, H. J. Hyun, K. Inami, R. Itoh, M. Iwabuchi, M. Iwasaki, Y. Iwasaki, N. J. Joshi, J. H. Kang, T. Kasahara, C. Kiesling, H. J. Kim, Y. I. Kim, Y. J. Kim, B. R. Ko, P. Kodyš, S. Korpar, P. Krokovny, T. Kumita, A. Kuzmin, Y.-J. Kwon, S.-H. Kyeong, J. S. Lange, M. J. Lee, S.-H. Lee, J. Li, C. Liu, Y. Liu, D. Liventsev, R. Louvot, A. Matyja, S. McOnie, K. Miyabayashi, H. Miyata, Y. Miyazaki, R. Mizuk, R. Mussa, E. Nakano, M. Nakazawa, Z. Natkaniec, S. Nishida, O. Nitoh, S. Ogawa, T. Oshihama, S. Okuno, S. L. Olsen, P. Pakhlov, G. Pakhlova, C. W. Park, H. Park, H. K. Park, R. Pestotnik, M. Petrić, E. Pilon, M. Röhrken, S. Ryu, H. Sahoo, Y. Sakai, O. Schneider, C. Schwanda, M. E. Sevior, M. Shapkin, C. P. Shen, J.-G. Shiu, B. Shwartz, J. B. Singh, P. Smerkol, E. Solovieva, M. Starič, Y. Teramoto, K. Trabelsi, Y. Unno, S. Uno, P. Urquijo, G. Varner, K. Vervink, C. H. Wang, P. Wang, Y. Watanabe, R. Wedd, E. Won, B. D. Yabsley, Y. Yamashita, C. Z. Yuan, C. C. Zhang, T. Zivko, O. Zyukova, (The Belle Collaboration)
We report the results of a search for a charmonium-like state produced in the process $\gamma\gamma \rightarrow \omega J/\psi$ in the 3.9–4.2 GeV/$c^2$ mass region. We observe a significant enhancement, which is well-described by a resonant shape with mass $M = (3915 \pm 3 \pm 2)$ MeV/$c^2$ and total width $\Gamma = (17 \pm 10 \pm 3)$ MeV. This enhancement may be related to one or more of the three charmonium-like states so far reported in the 3.90–3.95 GeV/$c^2$ mass region.

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Many new charmonium-like states have been discovered by the B-factory experiments, typically via a prominent hadronic decay to a known charmonium state, such as $J/\psi$, $\psi(2S)$ or $\chi_c1$. Some have attracted particular interest because of their net electric charge [1]. Three of the new (neutral) states were discovered by Belle in the 3.90–3.95 GeV/$c^2$ mass region. The $X(3940)$ was found in the $e^+e^- \rightarrow J/\psi X$ double charmonium production process, with a prominent decay to the $D\bar{D}$ final state [2]. The $Y(3940)$ was observed in the $B$ decay process $B^- \rightarrow Y(3940)K^-$ with $Y(3940) \rightarrow \omega J/\psi$ [3, 4], and is a candidate for an exotic state, such as a hybrid meson ($cc\bar{c}\bar{c}$), or a $D\bar{D}$ bound state [5]. The $Z(3930)$ was found in the $\gamma\gamma \rightarrow D\bar{D}$ process [6], and is usually identified with the $\chi_{c2}(2P)$. These three states appear in different production and decay processes, and are usually considered to be distinct particles, however there is no decisive evidence for this. The interpretation of these states has been discussed by many authors: see, e.g., Ref. [3].

It is important to search for a signature of the $Y(3940)$ or any other resonant state contributing to two-photon production of $\omega J/\psi$. This final state is the lightest combination of two vector mesons with definite $C$-even and $I = 0$ quantum numbers that can be produced in two-photon processes via a hidden-charm state. In this paper we present measurements of the $\gamma\gamma \rightarrow \omega J/\psi$ process in the 3.9–4.2 GeV/$c^2$ mass region, in which we observe a resonant enhancement. The signal is from the two-photon process $e^+e^- \rightarrow e^+e^-\omega J/\psi$ in the “zero-tag” mode, where neither the final-state electron nor positron recoiling from photon emission are detected.

We use experimental data recorded with the Belle detector [5] at the KEKB $e^+e^-$ asymmetric-energy (3.5 on 8 GeV) collider [6], corresponding to an integrated luminosity of 694 fb$^{-1}$. The data are accumulated mainly on the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58$ GeV) and 60 MeV below it. A small fraction of data from different beam energies near 10.36 GeV (the $\Upsilon(3S)$ mass) and 10.87 GeV (the $\Upsilon(5S)$ mass) is also included in the sample.

A comprehensive description of the Belle detector is given elsewhere [8]. Charged tracks are reconstructed in a central drift chamber (CDC) located in a uniform 1.5 T solenoidal magnetic field. The $z$ axis of the detector and the solenoid is along the positron beam, with the positrons moving in the $-z$ direction. Track trajectory coordinates near the collision point are measured by a silicon vertex detector (SVD). Photon detection and energy measurements are provided by a CsI(Tl) electromagnetic calorimeter (ECL). A combination of silica-aerogel Cherenkov counters (ACC), a time-of-flight counter (TOF) system consisting of a barrel of 128 plastic scintillation counters, and specific ionization $(dE/dx)$ measurements in the CDC provides $K/\pi$ separation for charged tracks over a wide momentum range. The magnet return iron is instrumented to form a $K_L$ detection and muon identification (KLM) system that detects muon tracks.

Signal candidates are triggered by a variety of track triggers that require two or more CDC tracks associated with TOF hits, ECL clusters, a total energy deposit in the ECL above a threshold (0.5 GeV), or a muon track in the KLM detector. In addition, events with a total ECL energy above 1.1 GeV are triggered by a separate trigger that require two or more CDC tracks associated with a muon track.

We select signal event candidates by reconstructing all the final state particles from $\omega \rightarrow \pi^+\pi^-\pi^0$ and $J/\psi \rightarrow l^+l^-$ ($l = e$ or $\mu$). Twelve selection criteria are imposed: (1) there are just 4 charged tracks with trans-
verse momentum $p_t > 0.1$ GeV/c originating in the beam collision region; (2) the net charge of the tracks is zero; (3) none of the tracks is identified as a kaon (we require a likelihood ratio $L(K)/L(\pi) < 0.8$, which is satisfied by 99.6% of pions but only 5% of kaons, for momenta below 0.8 GeV/c); (4) there is a net-charge-zero combination of two tracks whose invariant mass is in the $J/\psi$ mass region, $|M(l^+l^-) - M_{J/\psi}| < 0.2$ GeV/$c^2$, where $M_{J/\psi} = 3.0969$ GeV/$c^2$ and we assume the pion mass for each of the two tracks; (5) there is one or more neutral pion candidate formed by a mass-constrained fit to the four tracks and a neutral pion candidate, respectively.

For further analysis we examine only events with $W < 4.3$ GeV, where $W$ is defined by $W = M_5 - M(l^+l^-) + M_{J/\psi}$, using a refined two-lepton invariant mass ($M(l^+l^-)$) based on the lepton flavor identified by the following criteria: (8) if either of the tracks is identified as an electron, based on the ECL energy deposit, the tracks are identified as $e^+e^-$. Otherwise, if either track is identified as a muon based on KLM information, the tracks are identified as $\mu^+\mu^-$. An event that fails both tests is rejected. If one or more photons with energy between 20 and 200 MeV are found within 3° of either the $e^+$ or $e^-$ track, the energy of the most energetic photon near the track is added to the track momentum.

Following this correction, (9) we refine the $J/\psi$ selection with a more stringent requirement for the lepton-pair invariant mass, 3.07 GeV/$c^2 < M(l^+l^-) < 3.12$ GeV/$c^2$; (10) we suppress $\psi(2S)n^0$ events with the mass difference requirement, $|M(l^+l^- - \pi^+\pi^-) - M(\pi^+\pi^-)| > 0.01$ GeV/$c^2$; (11) to select $\omega$ candidates, a condition on the $\pi^+\pi^-\pi^0$ invariant mass, 0.753 GeV/$c^2 < M(3\pi) < 0.813$ GeV/$c^2$, is imposed. If there are multiple $\omega$ candidates due to multiple $\pi^0$'s in an event, we choose the one with the smallest $\chi^2$ in the $\pi^0$ mass constrained fit, in order to avoid multiple entries in the final $J/\psi$ mass spectrum. Finally, (12) we require transverse momentum balance for the 5-body system, $|\sum p_t^i| < 0.1$ GeV/c, where $p_t^i$ is the momentum of a particle in the $e^+e^-$ c.m. frame, in the plane perpendicular to the beam direction.

**FIG. 1:** (a) The $M(l^+l^-)$ distribution just after the dilepton selection. (b) The $M(l^+l^- - \pi^+\pi^-) - M(l^+l^-)$ distribution after the tight $J/\psi$ selection. Events between the arrows are rejected as consistent with $\psi(2S)$ production.

Figures 1(a) and 1(b) show the distributions of $M(l^+l^-)$ just after requirement (8) and the mass difference $M(l^+l^- - \pi^+\pi^-) - M(l^+l^-)$ just after requirement (9), respectively. The $\psi(2S)$ contribution is effectively removed by criterion (10) above.

The main background process is multi-pion production from two-photon processes. However, after all selection requirements are applied, non-$\omega J/\psi$ backgrounds are rather small, as shown in the scatter plot in Fig. 2(a) for the samples where only the selection criteria that satisfy $W \leq 3.85$ GeV.

In Figs. 2(b) and 2(c), the experimental $M(l^+l^-)$ and $M(3\pi)$ distributions are compared with the signal Monte Carlo (MC) events which are generated using spin-parity ($J^P$) and mass ($W$) of the $\omega J/\psi$ system to be $0^+$ and 3.93 GeV/$c^2$, respectively. Details of the signal MC generation are given below. We confirm that the experimental mass distributions are consistent with those of signal MC events.

We find that there are two events in the signal region with multiple $\omega$ candidates, out of 73 events in total; we choose only one combination in each event, according to criterion (11). The fraction is consistent with the 1–2% multiple candidate rate expected from the signal MC sample.

We show the $W$ distribution for the final $\gamma\gamma \rightarrow \omega J/\psi$ candidate events in Fig. 3. There is a prominent resonance-like peak around 3.92 GeV. It is far above the non-$\omega J/\psi$ background contribution, which is estimated from the events in the $\omega$ and $J/\psi$ mass sidebands (shown as shaded histograms for comparison); we define eight sideband regions in the plane of Fig. 2(a) with the same $W$ distribution for the opposite-side particle; for clarity, we exclude events below the $\omega J/\psi$ threshold, $W \leq 3.85$ GeV.
distribution over the eight regions. We modify the $W$ value of each sideband event plotted in Fig. 3, shifting it by the difference between the sum of mass coordinates of the central point of the signal region ($3.878$ GeV) from that of the sideband region where the event is found, for comparison to the signal-event distribution.

Figure 4(a) shows a scatter plot of the transverse momentum balance vs. $W$ after requirement (11). A prominent concentration of events near $W = 3.89 - 3.95$ GeV and $|\sum p_t^e| < 0.05$ GeV/c is visible; a comparison of the $|\sum p_t^e|$ projection with signal MC is shown in Fig. 4(b). Based on these results, and the shape in $W$ (Fig. 3), we conclude that the concentration of events is due to a resonance formed in two-photon collisions.

The $W$ distribution for the final candidate events is fitted by an incoherent sum of resonant and background components. We adopt an $S$-wave Breit-Wigner function with a variable width for the resonant component, $(2N_R/\pi)M^2\Gamma/\left[(W^2 - M^2)^2 + M^2\Gamma^2\right]$ and $\Gamma' = \Gamma(p^*/p_0^*)$, where $p^*$ is the momentum of the two-body decay to $\omega J/\psi$, in the rest frame of a parent particle of mass $W$; $p_0^*$ is the value for $W = M$. The nominal mass ($M$), width ($\Gamma$) and yield parameter ($N_R$) are treated as fit parameters.

We represent the background component by a quadratic function of $p^*$ that vanishes at the nominal $\omega J/\psi$ threshold, $M_{th} = 3.8796$ GeV/c$^2$. We also add a constant term, to represent the high $W$ tail, which, as the sideband study suggests, is dominated by non-$\omega J/\psi$ events. The sum of the two components has a functional form, $(ap^* + bp^*^2) + c\theta(W - M_{th})$, where $\theta(x)$ is a unit step function that is non-zero only for $x > 0$. The parameters $a$, $b$ and $c$ are floated within the constraint that each of the two background components must be non-negative throughout the fitting region.

The fit takes into account the $W$ resolution in the measurement, which is approximated by a double-Gaussian function from the signal MC events (59% of the signal has a resolution $\sigma$ of 4.5 MeV, while the remainder has $\sigma = 16$ MeV with the peak position displaced by $-4$ MeV). We perform an unbinned maximum likelihood fit in the region $3.875$ GeV < $W$ < $4.2$ GeV. The signal candidates with the smallest $W$ are the two events with $W$ between $3.879$ and $3.880$ GeV.

The $W$ dependences of the efficiency and luminosity function are taken into account in the fitting function. The efficiency is determined using signal MC events as described in detail later. We use the $W$ dependence of the efficiency for $J^P = 0^+$ for the nominal fit. Between the threshold and $3.96$ GeV, the $W$-dependence is weak: the efficiency varies by 10% only, and has a minimum near $W = 3.92$ GeV.

The obtained resonance parameters for the mass and the width are as follows:

\[
M = \left(3915 \pm 3 \pm 2\right) \text{MeV}/c^2, \\
\Gamma = \left(17 \pm 10 \pm 3\right) \text{MeV},
\]

where the first and second errors are statistical and systematic, respectively. The estimated yield from the resonant component in the fit is $49 \pm 14 \pm 4$ events in the region below $4.2$ GeV. The statistical significance of the resonant peak is $7.7\sigma$, which is determined from the difference of the logarithmic likelihoods, $-2\ln(L/L_0)$, taking the difference of the number of degrees of freedom in the fits into account, where $L_0$ and $L$ are the likelihoods of the fits with and without a resonant component, respectively. The relevant fit curves are shown in Fig. 3. The $\chi^2$ of the nominal fit, determined using $10$-MeV-width binning in the range $3.85$–$4.2$ GeV, is $27.3$, for $29$ degrees of freedom.

The systematic errors quoted above are determined from a study of alternate fits: we use a Breit-Wigner function with a constant width; we enlarge the invariant-mass resolution by 20% (an over-estimate of the data-Monte Carlo difference allowed by the fit); we change the upper limit of the fit region in $W$ to $4.1$ GeV and $4.3$ GeV, respectively. The changes in the central values of the corresponding resonance parameter are combined in quadrature. We also take into account the uncertainty of the mass scale, estimated to be $1$ MeV/$c^2$, in the measurement of $M$. There is no significant change in the parameters if $J^P = 2^+$ is assumed; the changes of mass and width are less than $0.1$ MeV/$c^2$ and $0.3$ MeV, respectively. The resonant contribution for the $J^P = 2^+$ assumption is $1.0$ event smaller than that for $J^P = 0^+$.

The efficiency for selecting $\gamma\gamma \rightarrow \omega J/\psi$ events is determined using signal MC events generated by TREPS.
Based on the efficiencies calculated for the two assumptions, 0\( \pm \) 20\% in the MC. We sum the uncertainties in quadrature, and find 11\% in total.

Treating the observed structure as a resonance denoted by \( X(3915) \), we derive the product of the two-photon decay width and the branching fraction to \( \omega J/\psi \), using the yield parameter \( N_R \) from the fit and the selection efficiency. We obtain

\[
\Gamma_{\gamma\gamma}(X(3915))\mathcal{B}(X(3915) \rightarrow \omega J/\psi) \\
= \begin{cases} 
(61 \pm 17 \pm 8) \text{ eV for } J^P = 0^+ \\
(18 \pm 5 \pm 2) \text{ eV for } J^P = 2^+, \text{ helicity-2}.
\end{cases}
\]

Based on this result, and the measured width \( \Gamma \), the product of the two partial widths of the \( X(3915) \), \( \Gamma_{\gamma\gamma}(X)\Gamma_{\omega J/\psi}(X) \) is of order \( 10^3 \text{ keV}^2 \). If we assume \( \Gamma_{\omega J/\psi} \sim \mathcal{O}(1 \text{ keV}) \), typical for an excited charmonium state, this implies \( \Gamma_{\omega J/\psi} \sim \mathcal{O}(1 \text{ MeV}) \); a rather large value for a charmonium-transition partial width of such a state. This value of the product of the partial decay widths is roughly compatible with the prediction assuming the \( D^*D^* \) bound-state model [8].

To conclude, we have observed a resonance-like enhancement in the \( \gamma\gamma \rightarrow \omega J/\psi \) process with a statistical significance of 7.7\sigma, which contains 49 \( \pm 14 \pm 4 \) events in the peak component. The mass and width have been measured to be \( M = (3915 \pm 3 \pm 2) \text{ MeV}/c^2 \) and \( \Gamma = (17 \pm 10 \pm 3) \text{ MeV} \), respectively. These values are consistent with those of the \( Y(3940) \), which is seen in the \( \omega J/\psi \) final state [9, 2], and close to those of the \( Z(3930) \), which is seen in \( \gamma\gamma \rightarrow DD \) [2].

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