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Analysis of $\gamma\gamma \to J/\psi\gamma$

Y.Seino*[a], H.Miyata[a], K.Hayasaka[a], for the Belle collaboration
[a] *Niigata University, Niigata 950-2181*
E-mail: seino@hep.sc.niigata-u.ac.jp

The production of charmonium states from two-photon collisions has been measured and searched for by the Belle Collaboration at the KEKB e^+e^- collider. In this analysis, the process $\gamma\gamma \to X \to J/\psi\gamma$, $J/\psi \to \ell^+\ell^-(\ell = e \,\text{or}\, \mu)$ is analyzed by using a 971.1 fb^{-1} Belle data sample, where X is a charmonium state. Previously, Belle and CLEO collaborations have reported measurements of $\gamma\gamma \to \chi_{c2}(1P) \to J/\psi\gamma$, $J/\psi \to \ell^+\ell^-$ using 32.6 fb^{-1} [1] and 14.4 fb^{-1} [2] data samples, respectively. By analyzing an about 30 times larger data sample, we perform a more precise measurement of the $\chi_{c2}(1P)$ and search for other charmonium(-like) states. From the Monte Carlo samples the detection efficiency is estimated to be 7-15% under some conditions. Also shown are the results of a feasibility study using a signal MC sample from which the expected accuracy for a measurement of the $\chi_{c2}(1P)$ is evaluated. We obtain the expected error to be $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))\mathcal{B}(\chi_{c2}(1P)\to J/\psi\gamma)\,\mathcal{B}(J/\psi\to\ell^+\ell^-)$=13.5±0.2 $(stat.)$±0.5$(syst.)$ eV for the central value of the previous measurement. It turns out that the statistical error will be 1.5%. This result is 6.5 times more precise than the previous one [1].

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*Speaker.

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1. Introduction

Two-photon decay widths ($\Gamma_{\gamma\gamma}$) provide important information for testing models describing quark-antiquark interactions. In particular, it is important to measure the two-photon decay widths of a P-wave charmonium, which is close to the boundary between perturbative and nonperturbative quantum chromodynamics (QCD). Various theoretical models predict the value of $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ to be within the range 0.28-0.93 keV [3]. The precise measurement will help to improve our understanding of quarkonium.

We analyze the channel of $\gamma\gamma \to X \to J/\psi\gamma$, $J/\psi \to \ell^+\ell^-$ ($\ell = e$ or μ), where X is a charmonium state. In the previous Belle research [1], $\gamma\gamma \to \chi_{c2}(1P) \to J/\psi\gamma$ was analyzed based on a 32.6 fb^{-1} data sample. Here we will perform a more precise measurement of $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$, search for and measure some other charmonium(-like) states by analyzing an about 30 times larger data sample.

In this paper, we estimate the detection efficiency under some conditions and perform the fitter test using Monte Carlo (MC) samples to perform a feasibility study.

2. Belle Experiment

The experimental data sample was accumulated by the Belle detector [4, 5] at the asymmetric-energy KEKB e^+e^- collider [6, 7]. This analysis will use the almost full Belle data sample (971.1 fb^{-1}).

The Belle detector consists of various subsystems: a silicon vertex detector (SVD), a central drift chamber (CDC), aerogel threshold Cherenkov counters (ACC), time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprising CsI(Tl) crystals (ECL) are arranged inside a superconducting solenoid coil that provides a 1.5 T magnetic field while an iron flux-return yoke is arranged outside the coil to detect K_L^0 mesons and identify muons.

3. MC Study

3.1 Behavior of detection efficiency for some conditions

We use the TREPS MC code [8] for event generation of two-photon processes. To estimate the detection efficiency for different angular distributions and masses of charmonia, Monte Carlo (MC) samples of $\gamma\gamma \to X$ (assumed charmonium state) $\to J/\psi\gamma$, $J/\psi \to \ell^+\ell^-(\ell = e\, or\, \mu)$ are generated.

The following selection criteria for $\gamma\gamma{\to}X{\to}J/\psi\gamma$ are adopted. (1) There are only two oppositely charged tracks, where both tracks satisfy the condition in the laboratory frame: $-0.47 \leq \cos\theta \leq 0.82$, with θ the polar angle; $|dz| \leq 3$ cm, $|dr| \leq 1$ cm, with dz, dr the impact parameters relative to the beam interaction point(IP) along the z axis and the transverse plane, respectively; $|\Delta dz| \leq 1$ cm, with Δdz the difference between the dz's of the two tracks; $p_t \geq 0.4$ GeV/c; $|\boldsymbol{p}_{+-}| <$ 6 GeV/c, $1.5 \leq M_{+-} \leq 4.5$ GeV/c^2, with $|\boldsymbol{p}_{+-}|$ and M_{+-} the scalar sum of the momenta and the invariant mass of the two charged tracks. (2) The opening angle (α) of the two tracks satisfies $\cos\alpha > -0.997$. (3) There is only one cluster in the ECL with an energy $E_\gamma \geq 0.2$ GeV at the condition that the cluster is isolated from the nearest charged track by an angle greater than 18°. (4) The total energy deposited in the ECL is less than 6 GeV. (5) For rejection of the ISR

(Initial-State Radiation) process, the square of the recoil mass, $M^2_{\rm rec} = (E^*_{\rm beam} - E^*_{+-})^2 - |\boldsymbol{p}^*_{+-}|^2$, is larger than 5.0 GeV$^2/c^4$, where $E^*_{\rm beam}$, E^*_{+-} and $|\boldsymbol{p}^*_{+-}|$ are the beam energy, the sum of the energy and the scalar sum of the momenta of two charged tracks in the c.m. frame of the e^+e^- beams. (6) The absolute value of the total transverse momentum in the c.m. frame of the e^+e^- beams, $|\boldsymbol{p}^{*\rm tot}_t| = |\boldsymbol{p}^{*+}_t + \boldsymbol{p}^{*-}_t + \boldsymbol{p}^{*\gamma}_t|$ is less than 0.15 GeV/c, and the absolute value of the sum of the transverse momenta of two charged tracks, $|\boldsymbol{p}^{*+}_t + \boldsymbol{p}^{*-}_t|$, is larger than 0.1 GeV/c, where $\boldsymbol{p}^{*+}_t$, $\boldsymbol{p}^{*-}_t$ and $\boldsymbol{p}^{*\gamma}_t$ are the transverse momentum of the positive track, the negative track and the photon, respectively. (7) For electron pairs, both tracks are required to have $E/p \geq 0.8$, where E is the energy deposit on ECL, and p is the momentum measured by CDC. For muon pairs, both tracks are required to have $E/p \leq 0.4$.

The angular distributions of the final-state particles are determined by the following parameters. If three parameters, $\boldsymbol{l}$ (the magnitude of the angular momentum coupling of the spin with final-state γ and the orbital angular momentum of the γ and J/ψ), J (spin of X) and λ (helicity of X) are determined, the angular distributions are calculated as

$$f(\theta,\theta^*,\phi^*) = \sum_{m=1,-1} \sum_{m''=\frac{1}{2},-\frac{1}{2}} \Big| \sum_{m'=1,0,-1} C^{1\times \boldsymbol{l}=J}_{m'+m=\lambda'} d^J_{\lambda\lambda'}(\theta) d^1_{m'(2m'')}(\theta^*) e^{im'\phi^*} \Big|^2.$$

Here, θ is the polar angle of the photon in the $\ell^+\ell^-\gamma$ c.m. frame, θ^* and ϕ^* are the polar and azimuthal angles of ℓ^- in the x-z plane of the J/ψ and $\ell^+\ell^-$ c.m. frame, where the z-axis is along the direction of the J/ψ and the x-axis is in the $J/\psi\gamma$ scattering plane, λ' is the helicity of X after θ rotation, m, m' and m'' are the helicity of the photon, J/ψ and $\ell^\pm$, C and d are the Clebsch-Gordan coefficient and rotational matrix, respectively.

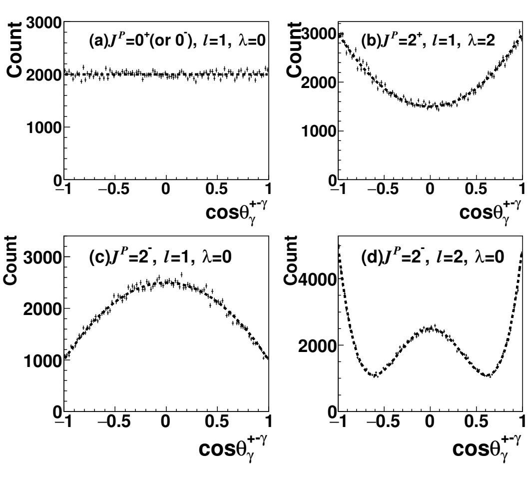

Figure 1: The distributions for cosine of polar angle of the photon in the $l^+l^-\gamma$ c.m. frame from MC

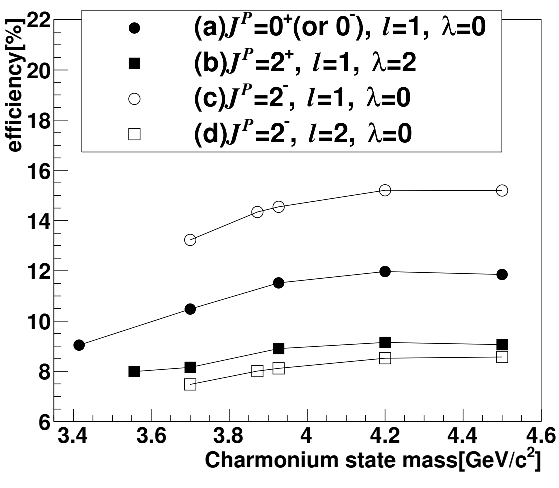

Figure 2: The summary of detection efficiency for each type of MC sample

We generate the signal MC samples having angular distributions of the four different types and some charmonium masses and estimate the detection efficiency. The four different angular distributions, which are possible in two-photon processes, correspond to the following assumed charmonium states: (a) $J^P = 0^+ (\,{\rm or}\, 0^-)$ and $\boldsymbol{l} = 1$ (E1 transition), $\lambda = 0$, (b) $J^P = 2^+$ and $\boldsymbol{l} = 1$ (E1

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transition), $\lambda = 2$, (c) $J^P = 2^-$ and $\boldsymbol{l} = 1$ (M1 transition), $\lambda = 0$, (d) $J^P = 2^-$ and $\boldsymbol{l} = 2$ (E2 transition), $\lambda = 0$. We appropriately select some points from 3.1 to 4.5 GeV/c^2 as an assumed charmonium state mass. Figure 1 shows the distributions for cosine of the polar angle of the photon in the $\ell^+\ell^-\gamma$ c.m. frame ($\theta_\gamma^{+-\gamma}$) for each type of the MC samples with a charmonium mass(4.2 GeV/c^2) from generator information. Each dotted curve shows a theoretical formula, $f(\theta)$, obtained from an integral of $f(\theta, \theta^*, \phi^*)$ by θ^* and ϕ^*. Figure 2 shows the detection efficiency of each type of the MC sample for different angular distributions and charmonium masses after event selection. As a result, the detection efficiency is estimated to be 7-15%.

3.2 Fitter test and Expected value of $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$

We perform a fitter test using the toy MC based on the PDFs defined by the signal MC and the background curve evaluated in the previous analysis [1] in order to evaluate the yield of $\chi_{c2}(1P)$ signal events which will be obtained by a fit. The expected yields (generated yield in the toy MC) of signal and background events are estimated by an extrapolation from the previous result [1]. We perform a fit of 5000 toy MC samples. Figure 3 shows the ΔM distribution for one toy MC sample (closed circles with error bars), where ΔM is the mass difference between $M_{+-\gamma}$ and M_{+-}. Here, $M_{+-\gamma}$ is the invariant mass of the two charged tracks and the photon. Signal (dashed line) and background (solid line) parts are fitted with a Crystal Ball function, where all the parameters are floated, and a function (ΔM-a)$^{-\text{b}}$/(1+exp(-c(ΔM-d))), where a, b, c, d are fixed at the previous values [1] and only the fraction is floated. The dotted line shows the total fit function. Figure 4 is the pull distribution as a result of the fitter test, where pull is defined as $(Y^{\text{fit}} - Y^{\text{gen}})/\sigma^{\text{fit}}$. Here, Y^{fit} is yield of the fit result and Y^{gen} is the generated yield of the signals at toy MC. In addition, σ^{fit} is the fit result error. By Fig. 4 we confirm that the fitter is stable.

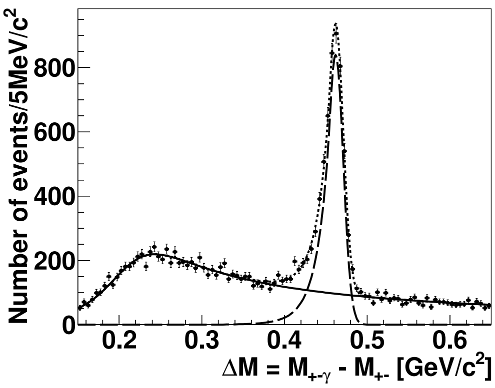

Figure 3: The mass-difference distribution of a toy MC sample

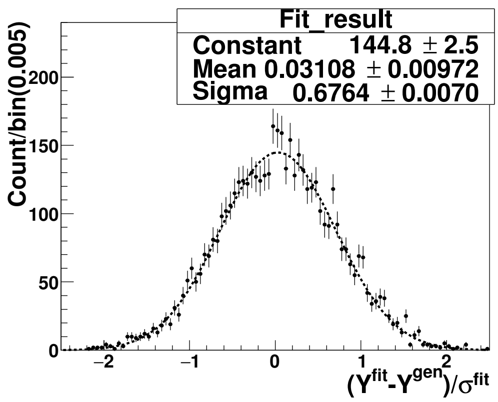

Figure 4: The pull distribution of toy MCs

From the previous analysis [1], the two-photon decay width of the $\chi_{c2}(1P)$ is related to the $\chi_{c2}(1P)$ signal event yield as

$$\begin{aligned}\frac{\text{Yield}}{\int \mathcal{L}dt} &= 20\pi \frac{L_{\gamma\gamma}(m_{\chi_{c2}(1P)})\eta}{(c/\hbar)^2 m^2_{\chi_{c2}(1P)}} \Gamma_{\gamma\gamma}(\chi_{c2}(1P)) \times \mathcal{B}(\chi_{c2}(1P) \to J/\psi\gamma)\mathcal{B}(J/\psi \to \ell^+\ell^-) \\ &= (0.309\text{fb/eV})\Gamma_{\gamma\gamma}(\chi_{c2}(\text{1P})) \times \mathcal{B}(\chi_{c2}(\text{1P}) \to \text{J}/\psi\gamma)\mathcal{B}(\text{J}/\psi \to \ell^+\ell^-),\end{aligned}$$

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where $\int \mathcal{L}dt$ is the integrated luminosity, η(=0.066) is the detection efficiency, $m_{\chi_{c2}(1P)}$(=3.556 GeV/c^2) is the $\chi_{c2}(1P)$ mass and $L_{\gamma\gamma}(m_{\chi_{c2}(1P)})(= 7.75 \times 10^{-4}$ GeV^{-1}) is the two-photon luminosity function at the $\chi_{c2}(1P)$ mass and $\sqrt{s}$=10.58 GeV.

From the uncertainty obtained from the MC study, we have evaluated the expected error of $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ with a 971.1 fb^{-1} Belle data sample for the central value of the previous measurement. The result is

$$\Gamma_{\gamma\gamma}(\chi_{c2}(1P))\mathcal{B}(\chi_{c2}(1P) \to J/\psi\gamma)\mathcal{B}(J/\psi \to \ell^+\ell^-) = 13.5 \pm 0.2(stat.) \pm 0.5(syst.) \text{ eV},$$

where the first and second errors are statistical and systematic, respectively. Here, we assume that the systematic error is 4% due to reduction of theoretical uncertainty of the two-photon luminosity function and more precise estimation of the other error sources than before. As a reference, the result of the previous Belle measurement was $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))\mathcal{B}(\chi_{c2}(1P)\to J/\psi\gamma)\ \mathcal{B}(J/\psi\to\ell^+\ell^-)$=13.5 $\pm$1.3 $(stat.)\pm$1.1$(syst.)$ eV [1].

4. Summary

To test models describing the nature of quarkonium systems, we perform a precise measurement of $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ and search for and measure some other charmonium(-like) states by analyzing the channel of $\gamma\gamma \to X \to J/\psi\gamma$, $J/\psi \to \ell^+\ell^-$ with a 971.1 fb^{-1} Belle data sample. We estimate the detection efficiency of signal MC under some conditions and confirm the stability of a fit by performing the fitter test at MC study. The detection efficiency is estimated to be 7-15%. We understand behavior of the detection efficiency for different angular distributions and charmonium masses. We evaluate the expected accuracy for $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))\mathcal{B}(\chi_{c2}(1P)\to J/\psi\gamma)\mathcal{B}(J/\psi\to\ell^+\ell^-)$. It turns out that the statistical error will be 1.5%. This result is 6.5 times more precise than the previous one [1].

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