Search for C-parity violation in $J/\psi \to \gamma\gamma$ and $\gamma\phi$

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Using 1.06×10^8 $\psi(3686)$ events recorded in e^+e^- collisions at $\sqrt{s}$ = 3.686 GeV with the BESIII at the BEPCII collider, we present searches for C-parity violation in $J/\psi \to \gamma\gamma$ and $\gamma\phi$ decays via $\psi(3686) \to J/\psi\pi^+\pi^-$. No significant signals are observed in either channel. Upper limits on the branching fractions are set to be $\mathcal{B}(J/\psi \to \gamma\gamma) < 2.7 \times 10^{-7}$ and $\mathcal{B}(J/\psi \to \gamma\phi) < 1.4 \times 10^{-6}$ at the 90% confidence level. The former is one order of magnitude more stringent than the previous upper limit, and the latter represents the first limit on this decay channel.

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I. INTRODUCTION

The charge conjugation (C) operation transforms a particle into its antiparticle and vice versa. In the Stan-

dard Model (SM), C invariance is held in strong and electromagnetic (EM) interactions. Until now, no C-violating processes have been observed in EM interactions [1]. While both C-parity and P-parity can be vio-

lated in the weak sector of the electroweak interactions in the SM, evidence for C violation in the EM sector would immediately indicate physics beyond the SM.

Tests of C invariance in EM interactions have been carried out by many experiments [1]. In J/ψ decays, however, only the channel $J/\psi \to \gamma\gamma$ has been studied [2–5], and the corresponding best upper limit on the branching fraction is 5×10^{-6}, measured by the CLEO Collaboration. In this paper, we report on searches for the decays of $J/\psi \to \gamma\gamma$ and $\gamma\phi$ via $\psi(3686) \to J/\psi\pi^+\pi^-$. The analysis is based on a data sample corresponding to 1.06×10^8 $\psi(3686)$ events collected at $\sqrt{s} = 3.686$ GeV (referred to as on-resonance data) [6] and a data set of 44.5 pb^{-1} collected at 3.650 GeV (referred to as off-resonance data) [7] with the Beijing Spectrometer (BESIII).

II.   BESIII AND BEPCII

The BESIII detector at the BEPCII [8] double-ring e^+e^- collider is a major upgrade of the BESII experiment at the Beijing Electron-Positron Collider (BEPC) [9] for studies of physics in the τ-charm energy region [10]. The design peak luminosity of BEPCII is 10^{33} cm^{-2} s^{-1} at a beam current of 0.93 A. Until now, the achieved peak luminosity is 7.08×10^{32} cm^{-2} s^{-1} at 3773 MeV. The BESIII detector, with a geometrical acceptance of 93% of 4π, consists of the following main components. (1) A small-celled main drift chamber (MDC) with 43 layers is used to track charged particles. The average single-wire resolution is 135 μm, and the momentum resolution for 1 GeV/c charged particles in a 1 T magnetic field is 0.5%. (2) An EM calorimeter (EMC) is used to measure photon energies. The EMC is made of 6240 CsI (Tl) crystals arranged in a cylindrical shape (barrel) plus two end caps. For 1.0 GeV photons, the energy resolution is 2.5% in the barrel and 5% in the end-caps, and the position resolution is 6 mm in the barrel and 9 mm in the end caps. (3) A time-of-flight system (TOF) is used for particle identification. It is composed of a barrel made of two layers, each consisting of 88 pieces of 5 cm thick and 2.4 m long plastic scintillators, as well as two end-caps with 96 fan-shaped, 5 cm thick, plastic scintillators in each end cap. The time resolution is 80 ps in the barrel and 110 ps in the end caps, providing a K/π separation of more than 2σ for momenta up to about 1.0 GeV/c. (4) The muon chamber system is made of resistive plate chambers arranged in 9 layers in the barrel and 8 layers in the end-caps and is incorporated into the return iron yoke of the superconducting magnet. The position resolution is about 2 cm.

The optimization of the event selection and the estimation of background contributions from $\psi(3686)$ decays are performed through Monte Carlo (MC) simulations. The GEANT4-based simulation software BOOST [11] includes the geometric and material description of the BESIII detectors, the detector response and digitiza-

tion models, as well as a record of the detector running conditions and performances. The production of the $\psi(3686)$ resonance is simulated by the MC event generator KKMC [12], while the decays are generated by EVT-GEN [13] for known decay modes with branching ratios being set to the PDG [14] world average values, and by LUNDCHARM [15] for the remaining unknown decays. The process of $\psi(3686) \to J/\psi\pi^+\pi^-$ is generated according to the formulas and measured results in Ref. [16], which takes the small D-wave contribution into account. The signal channels, $J/\psi \to \gamma\gamma$ and $\gamma\phi$, are generated according to phase space. The process $\phi \to K^+K^-$ is generated using a $\sin^2\theta$ distribution, where θ is the helicity angle of the kaon defined in the ϕ center-of-mass system. To obtain upper limits from the measured distributions, we test both the Bayesian method [17] and the Feldman-Cousins construction [18] and choose for each channel the method resulting in the most stringent upper limit.

III.   SEARCH FOR $J/\psi \to \gamma\gamma$

To search for $J/\psi \to \gamma\gamma$ via $\psi(3686) \to J/\psi\pi^+\pi^-$, candidate events with the topology $\gamma\gamma\pi^+\pi^-$ are selected using the following criteria. For each candidate event, we require that at least two charged tracks are reconstructed in the MDC and that the polar angles of the tracks satisfy $|\cos\theta| < 0.93$. The tracks are required to pass within ±10 cm of the interaction point along the beam direction and within ±1 cm in the plane perpendicular to the beam. Photon candidates are reconstructed by clusters of energy deposited in the EMC. The energy deposited in the TOF counter in front of the EMC is included to improve the reconstruction efficiency and the energy resolution. Photon candidates are required to have deposited energy larger than 25 MeV in the barrel region ($|\cos\theta| < 0.80$) or 50 MeV in the end-cap region ($0.86 < |\cos\theta| < 0.92$). Showers on the edge of the barrel and end-caps are poorly measured and are excluded. EMC cluster timing requirements ($0 \leq t \leq 14$ in units of 50 ns) are used to suppress electronic noise and energy deposits unrelated to the event. Only events with exactly two photon candidates are retained for further analysis. In addition, the energies of both photons are required to be greater than 1.0 GeV.

Two oppositely charged tracks, with momentum less than 0.45 GeV/c, are selected and assumed to be pions without particle identification. We impose $|\cos\theta_{\pi^+\pi^-}| < 0.95$ to exclude random combinations and reject backgrounds from $e^+e^- \to \gamma\gamma e^+e^-$ events, where $\theta_{\pi^+\pi^-}$ is the angle between the two oppositely charged tracks.

A kinematic fit enforcing energy-momentum conservation is performed under the $\gamma\gamma\pi^+\pi^-$ hypothesis, and the obtained χ^2_{4C} value of the fit is required to be $\chi^2_{4C} < 40$ to accept an event for further analysis. After applying the previous selection criteria, only one combination is found in each event, both in data and simulation.

The candidate signal events are studied by examining

the invariant mass recoiling against $\pi^+\pi^-$, $M_{\pi^+\pi^-}^{\rm rec}$, which is calculated using the momentum vectors of the corresponding tracks measured in the MDC. Figure 1 shows the resulting distribution of $M_{\pi^+\pi^-}^{\rm rec}$ from the candidates for $\psi(3686) \to J/\psi\pi^+\pi^-, J/\psi \to \gamma\gamma$ from on-resonance data. A J/ψ signal is clearly observed, which, as indicated by the studies described later, is dominated by backgrounds. The $M_{\pi^+\pi^-}^{\rm rec}$ spectrum is fitted using an unbinned maximum likelihood fit. The J/ψ signal line shape is extracted from a control sample, $\psi(3686) \to J/\psi\pi^+\pi^-, J/\psi \to \mu^+\mu^-$, selected from the on-resonance data. A first-order Chebychev polynomial is used to describe the non-peaking background. The fit determines the number of observed events to be $N^{\rm obs} = 29.2 \pm 7.1$.
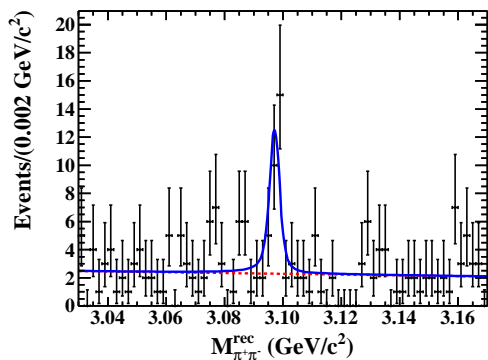
Figure 1. The $M_{\pi^+\pi^-}^{\rm rec}$ (calculated from MDC measurements) distribution for $\psi(3686) \to J/\psi\pi^+\pi^-, J/\psi \to \gamma\gamma$ candidate events from on-resonance data. The solid curve shows the global fit results and the dashed line indicates the non-peaking backgrounds.

The main peaking backgrounds come from $\psi(3686) \to J/\psi\pi^+\pi^-, J/\psi \to \gamma\pi^0, \gamma\eta, \gamma\eta_c$ and 3γ $(\pi^0/\eta/\eta_c \to \gamma\gamma)$. Large exclusive MC samples are generated to study the peaking backgrounds, where $J/\psi \to \gamma\pi^0$ and $\gamma\eta$ are generated by the HELAMP generator of EVTGEN [13] to model the angular distribution; the other exclusive MC samples are generated according to phase space. The same signal extraction procedure is performed on each exclusive MC sample. Then the contribution of each individual process is estimated by normalizing the yields separately according to the equivalent generated luminosities and the branching fractions taken from the PDG [1]. The normalized number of background events for the peaking backgrounds are summarized in Table I. Contributions from other background channels such as $J/\psi \to \gamma f_2, f_2 \to \pi^0\pi^0$ and $J/\psi \to \gamma\eta', \eta' \to \pi^0\pi^0\eta, \eta \to \gamma\gamma$ are negligible. The backgrounds from continuum processes are studied with the off-resonance data. No peaking background is identified from those. Summing up the contributions of the individual channels, we obtain a total of 45.3 ± 2.5 expected peaking background events (see Table I).

Since the two decay channels $J/\psi \to \gamma\pi^0$ and $J/\psi \to \gamma\eta$ are expected to yield the dominant contribution to the peaking background, we perform further studies on these channels. We examine the branching fractions with 106 M simulated inclusive $\psi(3686)$ events and find good agreement between the branching fractions used as input to the simulation and the one measured on this MC sample. We also roughly measure the branching fractions of both channels with the same data set and find results consistent with those listed at PDG [1]. The smooth backgrounds visible in Fig. 1 are also reasonably well described by the background sources mentioned above. These studies indicate that the above background estimation is reliable.

Table I. The expected number of peaking background events ($N^{\rm bkg}$) for $J/\psi \to \gamma\gamma$. The uncertainties include the statistical uncertainty and uncertainty of all intermediate resonance decay branching fractions.

Background channel	Expected counts ($N^{\rm bkg}$)
$J/\psi \to \gamma\pi^0, \pi^0 \to 2\gamma$	18.5 ± 1.9
$J/\psi \to \gamma\eta, \eta \to 2\gamma$	24.6 ± 1.6
$J/\psi \to \gamma\eta_c, \eta_c \to 2\gamma$	1.3 ± 0.3
$J/\psi \to 3\gamma$	0.9 ± 0.3
Total	45.3 ± 2.5

After subtracting the background events from the total yields, we obtain the net number of events as $N^{\rm net} = -16.1 \pm 7.5$. Both methods to obtain upper limits are tested, and the Feldman-Cousins method, the one resulting in a more stringent upper limit, is chosen. According to the Feldman-Cousins method, assuming a Gaussian distribution and constraining the net number to be nonnegative, the upper limit on the number of $J/\psi \to \gamma\gamma$ events is estimated to be $N_{\rm sig}^{\rm up} = 2.8$ at the 90% confidence level (C.L.).

IV.   SEARCH FOR $J/\psi \to \gamma\phi$

To search for $J/\psi \to \gamma\phi$ via $\psi(3686) \to J/\psi\pi^+\pi^-$, candidate events with the topology $\gamma K^+K^-\pi^+\pi^-$ are selected using the following criteria. The selection criteria for charged tracks and photons are the same as those listed in Section III. Candidate events must have four charged tracks with zero net charge and at least one photon with energy greater than 1.0 GeV. The selection criteria for $\pi^+\pi^-$ are the same as before except that we require $\cos\theta_{\pi^+\pi^-} < 0.95$ in this case to exclude random combinations.

For other charged particles, the particle identification (PID) confidence levels are calculated from the dE/dx and time-of-flight measurements under a pion, kaon or proton hypothesis. For kaon candidates, we require that the confidence level for the kaon hypothesis is larger than

the corresponding confidence levels for the pion and proton hypotheses. Two kaons with opposite charge are required in each candidate event.

All combinations of the four charged tracks with one high energetic photon are subjected to a kinematic fit imposing energy-momentum conservation. Candidates with $\chi^2_{4C} < 40$ are accepted. If more than one combination from photons satisfies the selection criteria in an event, only the combination with the minimum χ^2_{4C} is retained. Finally, only events are retained in which the mass recoiling against the di-pion system satisfies $3.082 < M^{rec}_{\pi^+\pi^-} < 3.112$ GeV/c^2.

The candidate signal events are studied by examining the invariant K^+K^- mass, $M_{K^+K^-}$, where the momenta obtained from the kinematic fit are used to improve the mass resolution. Figure 2 shows the resulting $M_{K^+K^-}$ spectrum for $\psi(3686) \rightarrow J/\psi\pi^+\pi^-, J/\psi \rightarrow \gamma\phi, \phi \rightarrow K^+K^-$ candidates selected from on-resonance data.

An unbinned maximum likelihood fit is performed to extract the number of reconstructed candidate events from the K^+K^- invariant-mass spectrum. The ϕ signal line shape is extracted from a MC simulation. A first order Chebychev polynomial is used to describe the background, which is shown in Fig. 2. The fit yields 0.0 ± 4.6 events.

An MC study shows that there are no peaking background contributions. The main possible non-peaking backgrounds come from $\psi(3686) \rightarrow J/\psi\pi^+\pi^-, J/\psi \rightarrow \gamma f_2(1270), \pi^0 K^+K^-$ and $\pi^0 a_2^0$. There are no candidates from the off-resonance data observed; we therefore neglect the contribution from continuum processes.

To obtain the upper limit, both methods are tested and in this case the Bayesian method is chosen. We determine the upper limit on the observed number of events (N^{up}_{sig}) with the Bayesian method at the 90% C.L. as

$$\frac{\int_0^{N^{up}_{sig}} \mathcal{L}dN_{sig}}{\int_0^{\infty} \mathcal{L}dN_{sig}} = 0.90,$$

where $\mathcal{L}$ is the value of likelihood as a function of N_{sig}. The upper limit on the number of $J/\psi \rightarrow \gamma\phi$ is determined to be 6.9.

V. SYSTEMATIC UNCERTAINTIES

The systematic uncertainties in the measurements are summarized in Table II.

The uncertainties in the tracking efficiency and kaon identification have been studied in Ref. [19], which are 2.0% per track and 2.0% per kaon, respectively.

The energies of the photons in both channels are greater than 1.0 GeV. The uncertainty due to the detection efficiency of high energy photons is estimated to be less than 0.25% using $J/\psi \rightarrow \gamma\eta'$, described in Ref. [20]. We therefore assign 0.25% per photon as the systematic uncertainty for photon detection.
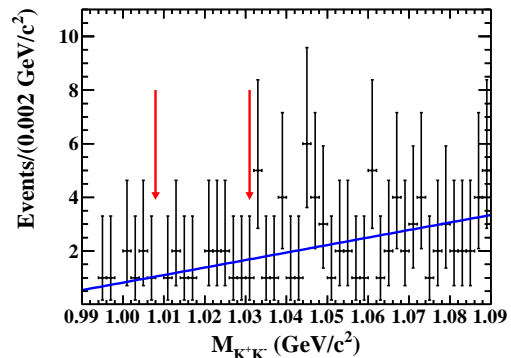

Figure 2. The $M_{K^+K^-}$ distribution for $\psi(3686) \rightarrow J/\psi\pi^+\pi^-, J/\psi \rightarrow \gamma\phi, \phi \rightarrow K^+K^-$ candidate events from on-resonance data. The solid line shows the global fit results and the dashed line shows the background, and they are overlap each other. The region between the arrows contains about 90% of the signal according to MC simulation.

The uncertainty of the kinematic fit for the $J/\psi \rightarrow \gamma\gamma$ channel is estimated from a control sample of $\psi(3686) \rightarrow \gamma\eta', \eta' \rightarrow \gamma\rho^0, \rho^0 \rightarrow \pi^+\pi^-$. The efficiency is obtained from the change in the yield of η' signal by a fit to the $\gamma\pi^+\pi^-$ invariant-mass spectrum with or without the requirement of $\chi^2_{4C} < 40$ of the kinematic fit. The systematic uncertainty is determined to be 1.9%. The uncertainty of the kinematic fit for the $J/\psi \rightarrow \gamma\phi$ channel is estimated to be 3.5% from $\psi(3686) \rightarrow \gamma\chi_{cJ}, \chi_{cJ} \rightarrow K^+K^-\pi^+\pi^-$.

The uncertainty associated with the requirement on the number of good photons (N_γ) for the $J/\psi \rightarrow \gamma\gamma$ channel is estimated by using a control sample of $\psi(3686) \rightarrow J/\psi\pi^+\pi^-, J/\psi \rightarrow \gamma\eta, \eta \rightarrow \gamma\gamma$ events. The differences of selection efficiencies with and without the N_γ requirement ($N_\gamma = 3$ for the control sample) between data and MC is 3.0%, which is taken as the systematic uncertainty due to the N_γ requirement.

By comparing the differences of selection efficiencies with and without the $\cos\theta_{\pi^+\pi^-}$ requirement between data and MC, the uncertainties due to this requirement for both channels are estimated to be 0.9% and 0.8%, respectively.

The uncertainty due to the requirement of $M^{rec}_{\pi^+\pi^-}$ to be within the J/ψ signal region for $J/\psi \rightarrow \gamma\phi$ is estimated as 1.4% by comparing the selection efficiencies between data and MC.

The uncertainties due to the details of the fit procedure are estimated by repeating the fit with appropriate modifications. Different fit ranges (4 ranges) and different orders of the polynomial (1st and 2nd orders) are used in the fits. For $J/\psi \rightarrow \gamma\gamma$, the uncertainty is estimated by averaging the differences of the obtained yields with respect to the values derived from the standard fit. For $J/\psi \rightarrow \gamma\phi$, the uncertainty is estimated as the maximum

difference between the obtained upper limits and the upper limit derived from the standard fit. The uncertainties from fitting are estimated as 2.7% and 1.5%, respectively.

The branching fractions for $\psi(3686) \to J/\psi\pi^+\pi^-$ and $\phi \to K^+K^-$ decays are taken from the PDG [1]. The uncertainties of the branching fractions are taken as systematic uncertainties in the measurements, which are 1.2% and 1.0%, respectively.

The uncertainty in the number of $\psi(3686)$ events is 0.81%, which is measured by inclusive hadronic decays [6].

Adding the uncertainties in quadrature yields total systematic uncertainties of 6.3% and 10.0% for $J/\psi \to \gamma\gamma$ and $J/\psi \to \gamma\phi$, respectively.

Table II. Summary of the systematic uncertainties (%).

Sources	$J/\psi \to \gamma\gamma$	$J/\psi \to \gamma\phi$
Tracking	4.0	8.0
Kaon identification	-	4.0
Photon detection	0.5	0.3
Kinematic fit	1.9	3.5
Number of photons	3.0	-
$\cos\theta_{\pi^+\pi^-}$ requirement	0.9	0.8
$M^{\rm rec}_{\pi^+\pi^-}$ requirement	-	1.4
Fitting	2.7	1.5
$\mathcal{B}(\psi(3686) \to J/\psi\pi^+\pi^-)$	1.2	1.2
$\mathcal{B}(\phi \to K^+K^-)$	-	1.0
Number of $\psi(3686)$	0.8	0.8
Total	6.3	10.0

VI. RESULTS

Since no significant signals are observed, the upper limits on the branching fractions are determined by

$$\mathcal{B}(J/\psi \to f) < \frac{N^{\rm up}_{\rm sig}}{N^{\rm tot}_{\psi(3686)} \times \epsilon \times \mathcal{B}_i \times (1 - \Delta_{\rm sys})}, \quad (1)$$

where $N^{\rm up}_{\rm sig}$ is the upper limit on the number of observed events for the signal channel; f represents $\gamma\gamma$ or $\gamma\phi$; ϵ is the detection efficiency determined by MC simulation; $N^{\rm tot}_{\psi(3686)}$ is the total number of $\psi(3686)$ events, $(106.41 \pm 0.86) \times 10^6$; $\mathcal{B}_i$ denotes the branching fractions involved (such as $\mathcal{B}(\psi(3686) \to J/\psi\pi^+\pi^-) = (34.0 \pm 0.4)\%$ and $\mathcal{B}(\phi \to K^+K^-) = (48.9 \pm 0.5)\%$) [1]; $\Delta_{\rm sys}$ is the total systematic uncertainty, and $1/(1 - \Delta_{\rm sys})$ is introduced to estimate a conservative upper limit on the branching fraction. The individual values are summarized in Table III.

Inserting $N^{\rm up}_{\rm sig}$, $N^{\rm tot}_{\psi(3686)}$, ϵ, $\mathcal{B}_i$ and $\Delta_{\rm sys}$ into Eq.(1), we obtain

$$\mathcal{B}(J/\psi \to \gamma\gamma) < 2.7 \times 10^{-7}$$

and

$$\mathcal{B}(J/\psi \to \gamma\phi) < 1.4 \times 10^{-6}.$$

Table III. Results for both channels.

	$\gamma\gamma$	$\gamma\phi$
$N^{\rm obs}$	29.2 ± 7.1	0.0 ± 4.6
$N^{\rm bkg}$	46.5 ± 2.5	negligible
$N^{\rm up}_{\rm sig}$(90% C.L.)	2.8	6.9
ϵ (%)	30.72 ± 0.07	30.89 ± 0.07
$\mathcal{B}(J/\psi \to)$ (this work)	$< 2.7 \times 10^{-7}$	$< 1.4 \times 10^{-6}$
$\mathcal{B}(J/\psi \to)$ (PDG [1])	$< 50 \times 10^{-7}$	-

VII. SUMMARY

In this paper, we report on searches for $J/\psi \to \gamma\gamma$ and $J/\psi \to \gamma\phi$. No significant signal is observed. We set the upper limits $\mathcal{B}(J/\psi \to \gamma\gamma) < 2.7 \times 10^{-7}$ and $\mathcal{B}(J/\psi \to \gamma\phi) < 1.4 \times 10^{-6}$ at the 90% C.L. for the branching fractions of J/ψ decays into $\gamma\gamma$ and $\gamma\phi$, respectively. The upper limit on $\mathcal{B}(J/\psi \to \gamma\gamma)$ is one order of magnitude more stringent than the previous upper limit, and $\mathcal{B}(J/\psi \to \gamma\phi)$ is the first upper limit for this channel. Our results are consistent with C-parity conservation of the EM interaction.

VIII. ACKNOWLEDGEMENTS

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