Search for $\eta_c$ Decays into $\pi\pi$ and $K\bar{K}$

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Abstract. Using 58 million $J/\psi$ events taken with the BESII detector, a search for $\eta_c$ CP violating decays into $\pi\pi$ and $K\bar{K}$ has been performed. No clear $\eta_c$ signal is observed, and upper limits for $B(\eta_c \to \pi\pi)$ and $B(\eta_c \to K\bar{K})$ are given at the 90% confidence level, $B(J/\psi \to \gamma \eta_c) \cdot B(\eta_c \to \pi^+\pi^-) \times 1.1 \times 10^{-5}$, $B(J/\psi \to \gamma \eta_c) \cdot B(\eta_c \to \pi^0\pi^0) < 0.71 \times 10^{-5}$, $B(J/\psi \to \gamma \eta_c) \cdot B(\eta_c \to K^+K^-) < 0.96 \times 10^{-5}$ and $B(J/\psi \to \gamma \eta_c) \cdot B(\eta_c \to K^0\bar{K}^0) < 0.53 \times 10^{-5}$.

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1 Introduction

Finding the source of CP violation is one of the most important goals of particle physics. Violation of CP symmetry has important consequences; it is one of the key ingredients for the baryon-antibaryon asymmetry in our universe. Early in 1964, CP violation was discovered in the neutral K meson system [1], and later experimental groups provided evidence for direct CP violation [2]. Almost four decades after the original discovery, CP violation in the B meson system has been established [3]. CP violation can be experimentally searched for in processes, such as meson decays [4] and neutrino oscillation [5], and by measuring the electric dipole moments of neutrons [6], electrons [7] and atoms [8].

A total of 58 million J/ψ events has been collected with the updated Beijing Spectrometer (BESII) [9], and this sample offers opportunities to search for new physics in J/ψ and ηc decays. In this letter, a search for CP violating ηc decays into ππ and K̄K is reported using J/ψ → γηc decays.

2 The BES detector

BESII is a conventional solenoidal magnet detector that is described in detail in Ref. [9]. A 12-layer vertex chamber (VC) surrounding the beam pipe provides track and trigger information. A forty-layer main drift chamber (MDC), located radially outside the VC, provides trajectory and energy loss (dE/dx) information for tracks over 85% of the total solid angle. The momentum resolution is σp/p = 0.017√(1+p²) (p in GeV/c), and the dE/dx resolution for hadron tracks is ~ 8%. An array of 48 scintillation counters surrounding the MDC measures the time-of-flight (TOF) of tracks with a resolution of ~ 200 ps for hadrons. Radially outside the TOF system is a 12 radiation length, lead-gas barrel shower counter (BSC). This measures the energies of electrons and photons over ~ 80% of the total solid angle with an energy resolution of σE/E = 22% / √(E in GeV). Outside of the solenoidal coil, which provides a 0.4 Tesla magnetic field over the tracking volume, is an iron flux return that is instrumented with three double layers of counters that identify muons of momentum greater than 0.5 GeV/c.

In the analysis, a GEANT3-based Monte Carlo simulation program (SIMBES) with detailed consideration of detector performance is used. The consistency between data and Monte Carlo has been checked in many high purity physics channels, and the agreement is reasonable [10]. The detection efficiency for each decay mode is determined taking into account the decay angular distributions in the Monte Carlo simulation. The angle (θ) between the directions of e⁺ and ηc in the laboratory frame is generated according to a 1 + cos²θ distribution, and uniform phase space is used for the ηc decaying into ππ and K̄K.

3 Event selection

Charged tracks are reconstructed using hits in the MDC, and they are required to have a good helix fit and satisfy |cosθ| < 0.8, where θ is the polar angle of the track. For all decays except J/ψ → γK̄K⁰K⁰, the point of closest approach of each track to the beam line must satisfy √(x⁰₀ + y⁰₀) < 2cm, |z₀| < 20cm, where x₀ and y₀ are the coordinates transverse to the beam line and z₀ is the distance along the beam line from the interaction point.

A neutral cluster is considered to be an isolated photon candidate when the energy deposited in the BSC is greater than 0.05 GeV, the first hit in the beginning six radiation lengths, the angle between the nearest charged track and the cluster is greater than 18°, and the difference between the angle of the cluster development direction in the BSC and the photon emission direction is less than 30°. More than one photon per event is allowed because of the possibility of fake photons coming from interactions of charged tracks with the shower counter and from other background sources.

3.1 ηc → π⁺π⁻

To select ηc → π⁺π⁻ candidates, the total number of hit layers in the muon counter is required to be less than four in order to remove (γ)µ⁺µ⁻ events, and the sum of E⁺/P⁺ and E⁻/P⁻ is required to be less than 1 to remove the large background from (radiative) Bhabha events, where E⁺/P⁺ (E⁻/P⁻) are the energy measured in the BSC and the momentum of the π⁺(π⁻), respectively. At least one track is required to be identified as a pion using TOF or dE/dx information. In order to reduce background from events with π⁰, P₂ = 4Pmiss² sin²θγ/2 is required to be less than 0.002 (GeV/c)², where Pmiss is the missing momentum of the charged particles, and θγ is the angle between the missing momentum and the photon direction. To further suppress the dominant ρπ background, events with more than one photon and satisfying |mγγ − 0.135| < 0.065 GeV/c² are rejected, where mγγ is the invariant mass of two isolated photons. Finally, to obtain better mass resolution and to suppress backgrounds further, events are kinematically fitted with four constants (4C) to the J/ψ → γπ⁺π⁻ and J/ψ → γK⁺K⁻ hypotheses and are required to satisfy χ²π⁺π⁻ < 10 and χ²K⁺K⁻ < χ²K⁺K⁻. If there is more than one photon, the fit is repeated using all permutations, and the combination with the lowest fit χ² is retained. The π⁺π⁻ invariant mass spectrum of events surviving selection is shown in Fig. 1(a). No ηc signal is observed.

For ηc → π⁰π⁰, the π⁰ mesons are identified through π⁰ → γγ. Four constraint kinematic fits to J/ψ → γπ⁰π⁰ are performed using all combinations of five photons, and the combination of photons with the smallest χ² is selected...
and is required to satisfy $\chi^2_{\eta J/\psi < 10}$. To select $\pi^0$s, the combination with the smallest $\delta_{\pi^0}$ is chosen, where

$$
\delta_{\pi^0} = \sqrt{(m_{\gamma_1 \gamma_2} - m_{\pi^0})^2 + (m_{\gamma_1 \gamma_2} - m_{\omega})^2},
$$

and $|m_{\gamma_1 \gamma_2} - m_{\pi^0}| < 0.065 \text{ GeV}/c^2$ and $|m_{\gamma_1 \gamma_2} - m_{\omega}| < 0.065 \text{ GeV}/c^2$ are required. To reduce background from events with $\omega$, events with the invariant mass of a $\pi^0$ and one photon satisfying $|m_{\gamma_2 \omega} - m_{\omega}| < 0.030 \text{ GeV}/c^2$ are rejected. The $\pi^0\pi^0$ mass spectrum after applying these selection criteria is shown in Fig.1(b). No evident $\eta_c$ is observed in the mass spectrum.

3.2 $\eta_c \rightarrow K\bar{K}$

The total number of hit layers in the muon counter is required to be less than four to remove $J/\psi \rightarrow \gamma\mu^+\mu^-$ background. Candidate $\eta_c \rightarrow K^+K^-$ events are required to have $P_T^{\eta_c} < 0.0020 \text{ GeV}/c^2$ to eliminate $\pi^0$ background. To further reduce $J/\psi \rightarrow \pi^0 K^+K^-$ and $J/\psi \rightarrow \pi^0\pi^+\pi^-$ contamination, events surviving the above criteria and to suppress backgrounds further, the two charged tracks and one photon in the event are 4-C kinematically fitted to the $J/\psi \rightarrow \gamma\pi^+\pi^-$ and $J/\psi \rightarrow \gamma K^+K^-$ hypotheses and $\chi^2_{K^+K^-} < 10$ and $\chi^2_{\pi^0\pi^+\pi^-} < \chi^2_{\pi^0\pi^+\pi^-}$ are required.

The $K^+K^-$ mass spectrum is shown in Fig.2(a). No $\eta_c$ signal is evident.

For the decay $\eta_c \rightarrow K^0_S K^0_S$, $K^0_S$ mesons are identified through $K^0_S \rightarrow \pi^+\pi^-$. To ensure that the two charged pions are from the same $K^0_S$ vertex, $|z_1 - z_2|$ and $|z_3 - z_4|$ must be less than 0.06 m, where $z_1$ and $z_2$ are the $Z$ coordinates of point of closest approach of the track to the beam axis of the first two pions, $z_3$ and $z_4$ are those of the second two pions. Candidate events must satisfy $\delta_{K^0_S}^2 < (0.020 \text{ GeV}/c^2)^2$, where $\delta_{K^0_S}^2 = (m_{\pi^+\pi^-} - (1 - m_{K^0})^2) + (m_{\pi^+\pi^-} - (2 - m_{K^0})^2)$ and $m_{\pi^+\pi^-}$ is calculated at the $K^0_S$ decay vertex. The main backgrounds from $\gamma K^0_S K^+\pi^+$ and $\gamma K^0_S K^0_S\pi^0$ events are suppressed by requiring the 4-C kinematic fit $\chi^2_{\pi^+\pi^-} < 10$. The distribution of $K^0_S K^0_S$ invariant mass is shown in Fig. 2(b). No $\eta_c$ signal is seen.

4 Background estimation

Backgrounds in the various processes except $\eta_c \rightarrow K^0_S K^0_S$ are estimated using Monte Carlo simulation. Possible backgrounds and their contribution are listed in Table 1. The number of background event from Monte Carlo are normalized to data according to the corresponding luminosity (or known branching fraction) and efficiency of the samples. The main background comes from $J/\psi \rightarrow (\gamma)\mu^+\mu^-$ and $J/\psi \rightarrow (\gamma)e^+e^-$ for $\eta_c \rightarrow \pi^+\pi^-$, from $J/\psi \rightarrow \omega\pi^0$ for $\eta_c \rightarrow \pi^0\pi^0$, and from $J/\psi \rightarrow K^+K^- + c.c$ for $\eta_c \rightarrow K^+K^-$. The shape of the background from Monte Carlo simulation is consistent with that of data.

For the decay $\eta_c \rightarrow K^0_S K^0_S$, non $K^0_S$ background is estimated using the $\delta_{K^0_S}^2$ sideband region, defined by $0.0008 < \delta_{K^0_S}^2 < 0.0012 \text{ (GeV}/c^2)^2$. The sideband histogram in Fig. 2(b) has 18 background events in total. The shape of the background estimated by sideband is consistent with that of data.

In fitting data, the backgrounds are fitted with polynomial function.

5 Systematic errors

Systematic errors on the results arise from the uncertainties in the number of $J/\psi$ events, the secondary branching fractions of the decay modes considered, the estimation of the selection efficiency, and the determination of the background. The various contributions to the systematic error are listed for all decay modes in Table 2.

1. The MDC tracking efficiency has been measured using channels like $J/\psi \rightarrow \Lambda\Lambda$ and $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow \mu^+\mu^-$. It is found that the Monte Carlo simulation agrees with data within $1 - 2\%$ [10] for each charged track. Therefore $4\%$ is taken as the systematic error for $J/\psi \rightarrow \gamma\pi^+\pi^-$ and for $J/\psi \rightarrow \gamma K^+K^-$, $8\%$ for $J/\psi \rightarrow \gamma K^0_S K^0_S$.

2. The systematic error on the pion identification efficiency is found by comparing the efficiency difference between data and Monte Carlo. It has been studied in detail using the decay $J/\psi \rightarrow \rho\pi$ [10], where it is found that the identification efficiency for data is in good agreement with that of Monte Carlo. For the study of $\eta_c \rightarrow \pi^+\pi^-$, particle identification is only required for one pion, and its systematic error is negligible.

3. The systematic error from the kinematic fit has been estimated using $J/\psi \rightarrow \rho\pi$ [13] and $J/\psi \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^0$ decays where it is possible to identify events cleanly without a kinematic fit. The results are $4.0\%$ and $4.3\%$ for the above two decay modes. Here $5\%$ is taken as the systematic error from the kinematic fit for all decay modes studied in this paper.

4. The photon detection efficiency has been studied using $J/\psi \rightarrow \rho\pi^0$ [14], and the difference between data and Monte Carlo simulation is about $2\%$ for each photon. The resulting systematic errors on the branching fractions in this analysis range from $2\%$ to $10\%$ depending on the decay mode.

5. The systematic error coming from $\mu$ counter simulation is estimated by studying the behavior of two pions in the $\mu$ counter from the decays $J/\psi \rightarrow \rho^+\pi^-$ and $J/\psi \rightarrow \rho^-\pi^+$. The result indicates that the difference between data and Monte Carlo simulation is $1.2\%$ which is taken as the systematic error.

6. The systematic error arising from $\pi^0$ reconstruction is estimated by studying $J/\psi \rightarrow \rho\pi^0$. We find the $m_{\gamma\gamma}$ distribution from data is in good agreement with that from Monte Carlo. The difference is about $0.4\%$. 

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Fig. 1. Distributions of $\pi\pi$ invariant mass near the $\eta_c$ mass region, where (a) is for $\eta_c \rightarrow \pi^+\pi^-$ and (b) is for $\eta_c \rightarrow \pi^0\pi^0$. The points with error bars are data, and the histograms are Monte Carlo simulated background. The smooth curves in the plots are the best fits to the data, while the shaded histograms are the expected shapes of an $\eta_c$ signal as determined by Monte Carlo simulation (not normalized).

Fig. 2. Distribution of $K\bar{K}$ invariant mass near the $\eta_c$ mass region, where (a) is for $\eta_c \rightarrow K^+K^-$ and (b) is for $\eta_c \rightarrow K_0^0\bar{K}_0^0$. The points with error bars are data, the histogram in (a) is Monte Carlo simulated background, and the histogram in (b) is background estimated using the $\delta_{K_0^0}$ sideband. The smooth curves in the plots are the best fits to the data, while the shaded histograms are the expected shapes of an $\eta_c$ signal as determined by Monte Carlo simulation (not normalized).

Table 1. Dominant sources of background in the $\eta_c \rightarrow \pi^+\pi^-$, $\eta_c \rightarrow \pi^0\pi^0$, and $\eta_c \rightarrow K^+K^-$. Here $N_{data}$ and $N_{bkg}$ are the numbers of events and estimated backgrounds in the $2\sigma$ wide $\eta_c$ mass region, respectively (normalized).

| Process | $N_{bkg}$ | $N_{bkg}$ | $N_{bkg}$ | $N_{bkg}$ |
|---------|-----------|-----------|-----------|-----------|
| $(\gamma)\mu^+\mu^-$ | 585 | $\omega\pi^0(\gamma\pi^0\pi^0)$ | 53 | $K^+K^- + c.c.$ | 7 |
| $(\gamma)e^+e^-$ | 281 | $\omega f_2(1270)(\gamma\pi^0\pi^0)$ | 11 | $\rho\pi$ | 5 |
| $\rho\pi$ | 9 | $\gamma\pi^0\pi^0\eta$ | 9 | $(\gamma)\mu^+\mu^-$ | 5 |
| $\gamma K^+K^-$ | 5 | $\gamma\eta(\gamma\pi^0\pi^0\eta)$ | 5 | $\gamma\pi^+\pi^-$ | 1 |
| $\gamma\pi^+\pi^-\pi^0\pi^0(\gamma\pi^0\pi^0)$ | 4 |  |  |  |
| sum | 880 ± 30 | 82 ± 8 | 18 ± 1 |  |
| $N_{data}$ | 872 | 84 | 25 |  |
Table 2. Systematic errors for the four decay modes (%).

| Sources                 | $\eta_c \rightarrow \pi^+\pi^-$ | $\eta_c \rightarrow \pi^0\pi^0$ | $\eta_c \rightarrow K^+K^-$ | $\eta_c \rightarrow K^0\bar{K}^0$ |
|-------------------------|---------------------------------|---------------------------------|----------------------------|---------------------------------|
| MDC tracking            | 4                               | 4                              | 8                          | 8                               |
| Photon efficiency       | 2                               | 10                             | 2                          | 2                               |
| Kinematic fit           | 5                               | 5                              | 5                          | 5                               |
| $\mu$ counter simulation| 1.2                             | 1.2                            | -                          | -                               |
| $\pi^0$ reconstruction  | -                               | 0.9                            | -                          | -                               |
| Mass spectrum fitting   | 2.9                             | 4.0                            | 9.4                        | 5.6                             |
| Background uncertainty  | 11.8                            | 5.8                            | 6.5                        | 8.1                             |
| Total number of $J/\psi$| 4.7                             | 4.7                            | 4.7                        | 4.7                             |
| Total                   | 14.7                            | 14.1                           | 14.1                       | 14.6                            |

Table 3. Numbers used in the calculation of upper limits of branching fraction at the 90% confidence level and the upper limits for all modes.

| Decay modes   | $N_s^{UL}$ | $\epsilon$ (%) | Systematic error (%) | Br.       |
|---------------|------------|-----------------|----------------------|-----------|
| $J/\psi \rightarrow \gamma \eta_c, \eta_c \rightarrow \pi^+\pi^-$ | $< 60.2$ | $10.9 \pm 0.1$ | 14.7 | $< 1.1 \times 10^{-5}$ |
| $J/\psi \rightarrow \gamma \eta_c, \eta_c \rightarrow \pi^0\pi^0$ | $< 27.0$ | $7.7 \pm 0.1$ | 14.1 | $< 0.71 \times 10^{-5}$ |
| $J/\psi \rightarrow \gamma \eta_c, \eta_c \rightarrow K^+K^-$ | $< 30.1$ | $6.3 \pm 0.1$ | 14.1 | $< 0.96 \times 10^{-5}$ |
| $J/\psi \rightarrow \gamma \eta_c, \eta_c \rightarrow K^0\bar{K}^0$ | $< 12.5$ | $10.1 \pm 0.1$ | 14.6 | $< 0.53 \times 10^{-5}$ |
| $\eta_c \rightarrow \pi^+\pi^-$ | -         | -               | 3.4 | $< 1.1 \times 10^{-3}$ |
| $\eta_c \rightarrow \pi^0\pi^0$ | -         | -               | 3.3 | $< 0.71 \times 10^{-3}$ |
| $\eta_c \rightarrow K^+K^-$ | -         | -               | 3.3 | $< 0.96 \times 10^{-3}$ |
| $\eta_c \rightarrow K^0\bar{K}^0$ | -         | -               | 3.4 | $< 0.53 \times 10^{-3}$ |

Therefore 0.9% is regarded as the systematic error for $J/\psi \rightarrow \gamma \pi^0\pi^0$.

7. The uncertainties of the $\eta_c$’s mass and width are also systematic errors in the upper limit determination. When doing the fit to the mass spectrum, we fix the $\eta_c$’s mass and width to their PDG values. Changing the $\eta_c$’s mass and width by one standard deviation from the PDG values in fitting the mass spectrum gives systematic errors from 2.9% to 9.4%.

8. Another systematic error arises from the uncertainty of the background shape. Changing the order of the background polynomial and the fitting range gives systematic errors from 5.8% to 11.8% for the different decay modes.

9. The uncertainty on the number of $J/\psi$ events introduces a systematic error of 4.7% [15], common for all decay modes.

The systematic errors from the above sources are listed in Table 2. The total uncertainty is the sum in quadrature of the individual contributions.

6 Results

Since no evident $\eta_c$ signal is observed in the four decay modes, we determine upper limits on the branching fractions ($B$) with the following formula

$$B = \frac{N_s^{UL}}{\epsilon \cdot N_{J/\psi}},$$

where $N_s^{UL}$ is the upper limit on the number of observed events for the $\eta_c$ signal, $\epsilon$ is the detection efficiency obtained from Monte Carlo simulation, $N_{J/\psi}$ is the total number of $J/\psi$ events, $(57.7 \pm 2.7) \times 10^6$ [15], which is obtained from inclusive 4-prong hadronic decays. For the decay $\eta_c \rightarrow K^0\bar{K}^0$, this should be divided by the square of the $K^0\bar{K}^0 \rightarrow \pi^+\pi^-$ branching fraction, when calculating the branching fraction of $\eta_c \rightarrow K^0\bar{K}^0$.

Using a Breit Wigner fit to the data, the result is consistent with no signal. We determine a Bayesian 90% confidence level upper limit on $N_s$ by finding the value $N_s^{UL}$ such that

$$\frac{\int_0^{N_s^{UL}} LdN_s}{\int_0^{\infty} LdN_s} = 0.90,$$

where $N_s$ is the number of signal events, and $L$ is the value of the likelihood as a function of $N_s$.

The values of $N_s^{UL}$, $\epsilon$, and the upper limits on the branching fractions for all decay modes are listed in Table 3, where $N_s^{UL}$ and $B$ are given at a Bayesian 90% confidence level. The systematic errors are included by lowering the efficiencies by one standard deviation. When the upper limits on $B(\eta_c \rightarrow \pi^+\pi^-\pi^0\pi^0$, $K^+K^-$, $K^0\bar{K}^0$) are derived in Table 3, an additional systematic uncertainty of 30.8% from $B(J/\psi \rightarrow \gamma \eta_c)$,(1.3$\pm$0.4)% [16], is included in the total systematic errors.

7 Summary

Based on 58 million $J/\psi$ events taken at BESII, a search for $\eta_c$ rare decays into $\pi\pi$ and $K\bar{K}$ has been performed. No
clear \( \eta_c \) signal is observed, and upper limits for \( \eta_c \to \pi\pi \) and \( \eta_c \to K\bar{K} \) have been obtained at the 90\% confidence level for the first time

\[
B(J/\psi \to \gamma \eta_c) \cdot B(\eta_c \to \pi^+\pi^-) < 1.1 \times 10^{-5}, \\
B(J/\psi \to \gamma \eta_c) \cdot B(\eta_c \to \pi^0\pi^0) < 0.71 \times 10^{-5}, \\
B(J/\psi \to \gamma \eta_c) \cdot B(\eta_c \to K^+K^-) < 0.96 \times 10^{-5}, \\
B(J/\psi \to \gamma \eta_c) \cdot B(\eta_c \to K^0\bar{K}^0) < 0.53 \times 10^{-5}.
\]

These results provide experimental limits for theoretical models predicting how much CP violation there may be in \( \eta_c \) meson decays.

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