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Search for η_c decays into $\pi\pi$ and $K\bar{K}$

The BES Collaboration

M. Ablikim[1], J.Z. Bai[1], Y. Ban[11], J.G. Bian[1], X. Cai[1], H.F. Chen[16], H.S. Chen[1], H.X. Chen[1], J.C. Chen[1], Jin Chen[1], Y.B. Chen[1], S.P. Chi[2], Y.P. Chu[1], X.Z. Cui[1], Y.S. Dai[18], Z.Y. Deng[1], L.Y. Dong[1,a], Q.F. Dong[14], S.X. Du[1], Z.Z. Du[1], J. Fang[1], S.S. Fang[2], C.D. Fu[1], C.S. Gao[1], Y.N. Gao[14], S.D. Gu[1], Y.T. Gu[4], Y.N. Guo[1], Y.Q. Guo[1], Z.J. Guo[15], F.A. Harris[15], K.L. He[1], M. He[12], Y.K. Heng[1], H.M. Hu[1], T. Hu[1], G.S. Huang[1,b], X.P. Huang[1], X.T. Huang[12], X.B. Ji[1], X.S. Jiang[1], J.B. Jiao[12], D.P. Jin[1], S. Jin[1], Yi Jin[1], Y.F. Lai[1], G. Li[2], H.B. Li[1], H.H. Li[1], J. Li[1], R.Y. Li[1], S.M. Li[1], W.D. Li[1], W.G. Li[1], X.L. Li[8], X.Q. Li[10], Y.L. Li[4], Y.F. Liang[13], H.B. Liao[6], C.X. Liu[1], F. Liu[6], Fang Liu[16], H.H. Liu[1], H.M. Liu[1], J. Liu[11], J.B. Liu[1], J.P. Liu[17], R.G. Liu[1], Z.A. Liu[1], F. Lu[1], G.R. Lu[5], H.J. Lu[16], J.G. Lu[1], C.L. Luo[9], F.C. Ma[8], H.L. Ma[1], L.L. Ma[1], Q.M. Ma[1], X.B. Ma[5], Z.P. Mao[1], X.H. Mo[1], J. Nie[1], S.L. Olsen[15], H.P. Peng[16], N.D. Qi[1], H. Qin[9], J.F. Qiu[1], Z.Y. Ren[1], G. Rong[1], L.Y. Shan[1], L. Shang[1], D.L. Shen[1], X.Y. Shen[1], H.Y. Sheng[1], F. Shi[1], X. Shi[11,c], H.S. Sun[1], J.F. Sun[1], S.S. Sun[1], Y.Z. Sun[1], Z.J. Sun[1], Z.Q. Tan[4], X. Tang[1], Y.R. Tian[14], G.L. Tong[1], G.S. Varner[15], D.Y. Wang[1], L. Wang[1], L.S. Wang[1], M. Wang[1], P. Wang[1], P.L. Wang[1], W.F. Wang[1,d], Y.F. Wang[1], Z. Wang[1], Z.Y. Wang[1], Zhe Wang[1], Zheng Wang[2], C.L. Wei[1], D.H. Wei[1], N. Wu[1], X.M. Xia[1], X.X. Xie[1], B. Xin[8], G.F. Xu[1], Y. Xu[10], M.L. Yan[16], F. Yang[10], H.X. Yang[1], J. Yang[16], Y.X. Yang[3], M.H. Ye[2], Y.X. Ye[16], Z.Y. Yi[1], G.W. Yu[1], C.Z. Yuan[1], J.M. Yuan[1], Y. Yuan[1], S.L. Zang[1], Y. Zeng[7], Yu Zeng[1], B.X. Zhang[1], B.Y. Zhang[1], C.C. Zhang[1], D.H. Zhang[1], H.Y. Zhang[1], J.W. Zhang[1], J.Y. Zhang[1], Q.J. Zhang[1], X.M. Zhang[1], X.Y. Zhang[12], Yiyun Zhang[13], Z.P. Zhang[16], Z.Q. Zhang[5], D.X. Zhao[1], J.W. Zhao[1], M.G. Zhao[10], P.P. Zhao[1], W.R. Zhao[1], Z.G. Zhao[1,e], H.Q. Zheng[11], J.P. Zheng[1], Z.P. Zheng[1], L. Zhou[1], N.F. Zhou[1], K.J. Zhu[1], Q.M. Zhu[1], Y.C. Zhu[1], Y.S. Zhu[1], Yingchun Zhu[1,f], Z.A. Zhu[1], B.A. Zhuang[1], X.A. Zhuang[1], B.S. Zou[1,⋆]

[1] Institute of High Energy Physics, Beijing 100049, People's Republic of China
[2] China Center for Advanced Science and Technology(CCAST), Beijing 100080, People's Republic of China
[3] Guangxi Normal University, Guilin 541004, People's Republic of China
[4] Guangxi University, Nanning 530004, People's Republic of China
[5] Henan Normal University, Xinxiang 453002, People's Republic of China
[6] Huazhong Normal University, Wuhan 430079, People's Republic of China
[7] Hunan University, Changsha 410082, People's Republic of China
[8] Liaoning University, Shenyang 110036, People's Republic of China
[9] Nanjing Normal University, Nanjing 210097, People's Republic of China
[10] Nankai University, Tianjin 300071, People's Republic of China
[11] Peking University, Beijing 100871, People's Republic of China
[12] Shandong University, Jinan 250100, People's Republic of China
[13] Sichuan University, Chengdu 610064, People's Republic of China
[14] Tsinghua University, Beijing 100084, People's Republic of China
[15] University of Hawaii, Honolulu, HI 96822, USA
[16] University of Science and Technology of China, Hefei 230026, People's Republic of China
[17] Wuhan University, Wuhan 430072, People's Republic of China
[18] Zhejiang University, Hangzhou 310028, People's Republic of China

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Abstract. Using 58 million J/ψ events taken with the BESII detector, a search for η_c CP violating decays into $\pi\pi$ and $K\bar{K}$ has been performed. No clear η_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, $B(J/\psi \to \gamma\eta_c) \cdot B(\eta_c \to \pi^+\pi^-) < 1.1 \times 10^{-5}$, $B(J/\psi \to \gamma\eta_c) \cdot B(\eta_c \to \pi^0\pi^0) < 0.71 \times 10^{-5}$, $B(J/\psi \to \gamma\eta_c) \cdot B(\eta_c \to K^+K^-) < 0.96 \times 10^{-5}$, and $B(J/\psi \to \gamma\eta_c) \cdot B(\eta_c \to K_S^0K_S^0) < 0.53 \times 10^{-5}$.

[a] Current address: Iowa State University, Ames, IA 50011-3160, USA
[b] Current address: Purdue University, West Lafayette, IN 47907, USA
[c] Current address: Cornell University, Ithaca, NY 14853, USA
[d] Current address: Laboratoire de l'Accéleratear Linéaire, Orsay, 91898, France
[e] Current address: University of Michigan, Ann Arbor, MI 48109, USA
[f] Current address: DESY, 22607 Hamburg, Germany

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 η_c decays. In this letter, a search for CP violating η_c decays into $\pi\pi$ and $K\bar{K}$ is reported using $J/\psi \to \gamma\eta_c$ decays.

2 The BES detector

BESII is a conventional solenoidal magnet detector that is described in detail in [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 $\sigma_p/p = 0.017\sqrt{1+p^2}$ (p in GeV/c), and the dE/dx resolution for hadron tracks is $\sim 8\%$. 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 $\sim 80\%$ of the total solid angle with an energy resolution of $\sigma_E/E = 22\%/\sqrt{E}$ (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 η_c in the laboratory frame is generated according to a $1+\cos^2\theta$ distribution, and uniform phase space is used for the η_c decaying into $\pi\pi$ and $K\bar{K}$.

* e-mail: zhangbx@ihep.ac.cn or fangss@ihep.ac.cn

3 Event selection

Charged tracks are reconstructed using hits in the MDC, and they are required to have a good helix fit and satisfy $|\cos\theta| < 0.8$, where θ is the polar angle of the track. For all decays except $J/\psi \to \gamma K^0_S K^0_S$, the point of closest approach of each track to the beam line must satisfy $\sqrt{x_0^2+y_0^2} < 2$ cm, $|z_0| < 20$ cm, where x_0 and y_0 are the coordinates transverse to the beam line and z_0 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 is 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 $\eta_c \to \pi\pi$

To select $\eta_c \to \pi^+\pi^-$ candidates, the total number of hit layers in the muon counter is required to be less than four in order to remove $(\gamma)\mu^+\mu^-$ events, and the sum of E_{π^+}/P_{π^+} and E_{π^-}/P_{π^-} is required to be less than 1 to remove the large background from (radiative) Bhabha events, where $E_{\pi^+}(E_{\pi^-})$ and $P_{\pi^+}(P_{\pi^-})$ are the energy measured in the BSC and the momentum of the $\pi^+(\pi^-)$, 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 π^0, $P^2_{\rm tr} = 4|\boldsymbol{P}_{\rm miss}|^2\sin^2\theta_\gamma/2$ is required to be less than 0.002 (GeV/c)^2, where $\boldsymbol{P}_{\rm miss}$ is the missing momentum of the charged particles, and θ_γ is the angle between the missing momentum and the photon direction. To further suppress the dominant $\rho\pi$ background, events with more than one photon and satisfying $|m_{\gamma\gamma} - 0.135| < 0.065$ GeV/c^2 are rejected, where $m_{\gamma\gamma}$ 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 constaints (4C) to the $J/\psi \to \gamma\pi^+\pi^-$ and $J/\psi \to \gamma K^+K^-$ hypotheses and are required to satisfy $\chi^2_{\gamma\pi^+\pi^-} < 10$ and $\chi^2_{\gamma\pi^+\pi^-} < \chi^2_{\gamma K^+K^-}$. If there is more than one photon, the fit is repeated using all permutations, and the combination with the lowest fit χ^2 is retained. The $\pi^+\pi^-$ invariant mass spectrum of events surviving selection is shown in Fig. 1a. No η_c signal is observed.

For $\eta_c \to \pi^0\pi^0$, the π^0 mesons are identified through $\pi^0 \to \gamma\gamma$. Four constraint kinematic fits to $J/\psi \to \gamma\pi^0\pi^0$ are performed using all combinations of five photons, and the combination of photons with the smallest χ^2 is selected and is required to satisfy $\chi^2_{5\gamma} < 10$. To select π^0s, the combination with the smallest δ_{π^0} is chosen, where

$$\delta_{\pi^0} = \sqrt{(m_{\gamma_1\gamma_2} - m_{\pi^0})^2 + (m_{\gamma_3\gamma_4} - m_{\pi^0})^2},$$

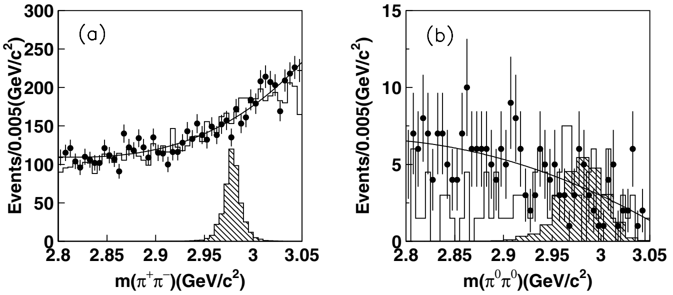

Fig. 1. Distributions of $\pi\pi$ invariant mass near the η_c mass region, where **a** is for $\eta_c \to \pi^+\pi^-$ and **b** is for $\eta_c \to \pi^0\pi^0$. The points with error bars are data, and the histograms are Monte Carlo simulated background. The smooth curves in the plots are the best fits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

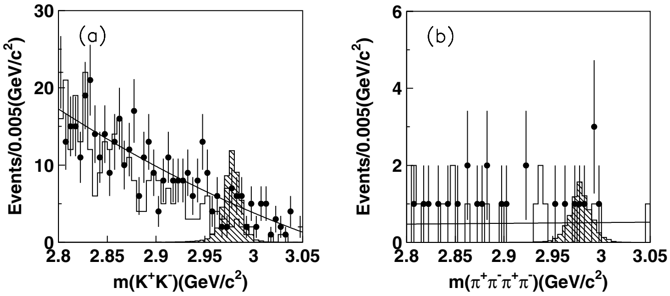

Fig. 2. Distribution of $K\bar{K}$ invariant mass near the η_c mass region, where **a** is for $\eta_c \to K^+K^-$ and **b** is for $\eta_c \to K^0_S K^0_S$. The points with error bars are data, the histogram in **a** is Monte Carlo simulated background, and the histogram in **b** is background estimated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

and $|m_{\gamma_1\gamma_2} - m_{\pi^0}| < 0.065\,\mathrm{GeV}/c^2$ and $|m_{\gamma_3\gamma_4} - m_{\pi^0}| < 0.065\,\mathrm{GeV}/c^2$ are required. To reduce background from events with ω, events with the invariant mass of a π^0 and one photon satisfying $|m_{\gamma\pi^0_{1(2)}} - m_\omega| < 0.030\,\mathrm{GeV}/c^2$ are rejected. The $\pi^0\pi^0$ mass spectrum after applying these selection criteria is shown in Fig. 1b. No evident η_c is observed in the mass spectrum.

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

The total number of hit layers in the muon counter is required to be less than four to remove $J/\psi \to \gamma\mu^+\mu^-$ background. Candidate $\eta_c \to K^+K^-$ events are required to have $P^2_{\mathrm{tr}} < 0.002\ (\mathrm{GeV/c})^2$ to eliminate π^0 background. To further reduce $J/\psi \to \pi^0K^+K^-$ and $J/\psi \to \pi^0\pi^+\pi^-$ contamination, events surviving the above criteria and with two or more photons are kinematically fitted to these hypotheses, and events with a fit $\chi^2 < 50$ and with a photon pair invariant mass within $0.065\,\mathrm{GeV}/c^2$ of the π^0 mass are rejected. Finally, to obtain better mass resolution and to suppress backgrounds further, the two charged tracks and one photon in the event are 4-C kinematically fitted to the $J/\psi \to \gamma\pi^+\pi^-$ and $J/\psi \to \gamma K^+K^-$ hypotheses and $\chi^2_{\gamma K^+K^-} < 10$ and $\chi^2_{\gamma K^+K^-} < \chi^2_{\gamma\pi^+\pi^-}$ are required.

The K^+K^- mass spectrum is shown in Fig. 2a. No η_c signal is evident.

For the decay $\eta_c \to K^0_S K^0_S$, K^0_S mesons are identified through $K^0_S \to \pi^+\pi^-$. To ensure that the two charged pions are from the same K^0_S vertex, $|z_1 - z_2|$ and $|z_3 - z_4|$ are required to 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 $\delta^2_{K^0_S} < (0.020\mathrm{GeV}/c^2)^2$, where $\delta^2_{K^0_S} = [m_{\pi^+\pi^-}(1) - m_{K^0_S}]^2 + [m_{\pi^+\pi^-}(2) - m_{K^0_S}]^2$ and $m_{\pi^+\pi^-}$ is calculated at the K^0_S decay vertex. The main backgrounds from $\gamma K^0_S K^\pm\pi^\mp$ and $\gamma K^0_S K^0_S \pi^0$ events are suppressed by requiring the 4-C kinematic fit $\chi^2_{\gamma 4\pi} < 10$. The distribution of $K^0_S K^0_S$ invariant mass is shown in Fig. 2b. No η_c signal is seen.

4 Background estimation

Backgrounds in the various processes except $\eta_c \to K^0_S K^0_S$ 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 backgrounds come from $J/\psi \to (\gamma)\mu^+\mu^-$ and $J/\psi \to (\gamma)e^+e^-$ for $\eta_c \to \pi^+\pi^-$, from $J/\psi \to \omega\pi^0$

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

$\eta_c \to \pi^+\pi^-$	N_{bkg}	$\eta_c \to \pi^0\pi^0$	N_{bkg}	$\eta_c \to K^+K^-$	N_{bkg}
$(\gamma)\mu^+\mu^-$	585	$\omega\pi^0(\gamma 2\pi^0)$	53	$K^{*+}K^- + c.c.$	7
$(\gamma)e^+e^-$	281	$\omega f_2(1270)(\gamma 3\pi^0)$	11	$\rho\pi$	5
$\rho\pi$	9	$\gamma\pi^0\pi^0\eta$	9	$(\gamma)\mu^+\mu^-$	5
γK^+K^-	5	$\gamma\eta'(\gamma\pi^0\pi^0\eta)$	5	$\gamma\pi^+\pi^-$	1
		$\omega\pi^0\pi^0(\gamma 3\pi^0)$	4		
sum	880 ± 36		82 ± 8		18 ± 1
N_{data}	872		84		25

Table 2. Systematic errors for the four decay modes (%)

Sources	$\eta_c \to \pi^+\pi^-$	$\eta_c \to \pi^0\pi^0$	$\eta_c \to K^+K^-$	$\eta_c \to K_S^0K_S^0$
MDC tracking	4	–	4	8
Photon efficiency	2	10	2	2
Kinematic fit	5	5	5	5
μ counter simulation	1.2	–	1.2	–
π^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/ψ	4.7	4.7	4.7	4.7
Total	14.7	14.1	14.1	14.6

for $\eta_c \to \pi^0\pi^0$, and from $J/\psi \to K^{*+}K^- + c.c$ for $\eta_c \to K^+K^-$. The shape of the background from Monte Carlo simulation is consistent with that of data.

For the decay $\eta_c \to K_S^0K_S^0$, non K_S^0 background is estimated using the $\delta^2_{K_S^0}$ sideband region, defined by $0.0008 < \delta^2_{K_S^0} < 0.0012$ $(\mathrm{GeV/c^2})^2$. The sideband histogram in Fig. 2b 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/ψ 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 $J/\psi \to \Lambda\bar{\Lambda}$ and $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to \mu^+\mu^-$. 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 $J/\psi \to \gamma\pi^+\pi^-$ and for $J/\psi \to \gamma K^+K^-$, 8% for $J/\psi \to \gamma K_S^0K_S^0$.
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 $J/\psi \to \rho\pi$ [10], where it is found that the identification efficiency for data is in good agreement with that of Monte Carlo. For the study of $\eta_c \to \pi^+\pi^-$, 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 $J/\psi \to \rho\pi$ [13] and $J/\psi \to \pi^+\pi^-\pi^+\pi^-\pi^0$ 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 $J/\psi \to \rho^0\pi^0$ [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 μ counter simulation is estimated by studying the behavior of two pions in the μ counter from the decays $J/\psi \to \rho^+\pi^-$ and $J/\psi \to \rho^-\pi^+$. 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 π^0 reconstruction is estimated by studying $J/\psi \to \rho^0\pi^0$. We find the $m_{\gamma\gamma}$ distribution from data is in good agreement with that from Monte Carlo. The difference is about 0.4%. Therefore 0.9% is regarded as the systematic error for $J/\psi \to \gamma\pi^0\pi^0$.
7. The uncertainties of the η_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 η_c's mass and width to their PDG values. Changing the η_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/ψ 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 η_c signal is observed in the four decay modes, we determine upper limits on the branching fractions (B) with the following formula

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

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.
$J/\psi \to \gamma\eta_c, \eta_c \to \pi^+\pi^-$	< 60.2	10.9 ± 0.1	14.7	$< 1.1 \times 10^{-5}$
$J/\psi \to \gamma\eta_c, \eta_c \to \pi^0\pi^0$	< 27.0	7.7 ± 0.1	14.1	$< 0.71 \times 10^{-5}$
$J/\psi \to \gamma\eta_c, \eta_c \to K^+K^-$	< 30.1	6.3 ± 0.1	14.1	$< 0.96 \times 10^{-5}$
$J/\psi \to \gamma\eta_c, \eta_c \to K_S^0K_S^0$	< 12.5	10.1 ± 0.1	14.6	$< 0.53 \times 10^{-5}$
$\eta_c \to \pi^+\pi^-$	–	–	34.1	$< 1.1 \times 10^{-3}$
$\eta_c \to \pi^0\pi^0$	–	–	33.9	$< 0.71 \times 10^{-3}$
$\eta_c \to K^+K^-$	–	–	33.9	$< 0.96 \times 10^{-3}$
$\eta_c \to K_S^0K_S^0$	–	–	34.1	$< 0.53 \times 10^{-3}$

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

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

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

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}, ϵ, 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($\eta_c \to \pi^+\pi^-$,$\pi^0\pi^0$,K^+K^-, $K_S^0K_S^0$) are derived in Table 3, an additional systematic uncertainty of 30.8% from B($J/\psi \to \gamma\eta_c$),$(1.3 \pm 0.4)\%$ [16], is included in the total systematic errors.

7 Summary

Based on 58 million J/ψ events taken at BESII, a search for η_c rare decays into $\pi\pi$ and $K\bar{K}$ has been performed. No clear η_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

$$B(J/\psi \to \gamma\eta_c) \cdot B(\eta_c \to \pi^+\pi^-) < 1.1 \times 10^{-5},$$

$$B(J/\psi \to \gamma\eta_c) \cdot B(\eta_c \to \pi^0\pi^0) < 0.71 \times 10^{-5},$$

$$B(J/\psi \to \gamma\eta_c) \cdot B(\eta_c \to K^+K^-) < 0.96 \times 10^{-5},$$

$$B(J/\psi \to \gamma\eta_c) \cdot B(\eta_c \to K_S^0K_S^0) < 0.53 \times 10^{-5}.$$

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

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