Measurement of Branching Ratios for $\eta_c$

Hadronic Decays

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Abstract

In a sample of 58 million $J/\psi$ events collected with the BES II detector, the process $J/\psi \rightarrow \gamma \eta_c$ is observed in five decay channels: $\eta_c \rightarrow K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^\pm K^0_S\pi^\mp$ (with $K^0_S \rightarrow \pi^+\pi^-$), $\phi\phi$ (with $\phi \rightarrow K^+K^-$) and $p\bar{p}$. From these signals, we determine
\begin{align*}
Br(J/\psi \rightarrow \gamma \eta_c) \times Br(\eta_c \rightarrow K^+K^-\pi^+\pi^-) &= (1.5 \pm 0.2 \pm 0.2) \times 10^{-4}, \\
Br(J/\psi \rightarrow \gamma \eta_c) \times Br(\eta_c \rightarrow \pi^+\pi^-\pi^+\pi^-) &= (1.3 \pm 0.2 \pm 0.4) \times 10^{-4}, \\
Br(J/\psi \rightarrow \gamma \eta_c) \times Br(\eta_c \rightarrow K^\pm K^0_S\pi^\mp) &= (2.2 \pm 0.3 \pm 0.5) \times 10^{-4}, \\
Br(J/\psi \rightarrow \gamma \eta_c) \times Br(\eta_c \rightarrow \phi\phi) &= (3.3 \pm 0.6 \pm 0.6) \times 10^{-5} \text{ and} \\
Br(J/\psi \rightarrow \gamma \eta_c) \times Br(\eta_c \rightarrow p\bar{p}) &= (1.9 \pm 0.3 \pm 0.3) \times 10^{-5}.
\end{align*}

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Hadronic decays of the $\eta_c$ have been studied by Mark III [1,2], DM2 [3], and other experiments [4-7]. However, the branching fractions of the $\eta_c$ still have very large errors in the Particle Data Group (PDG) compilation [8]. More recently the branching fractions for $B \to \eta_c K$ decays and $B \to \eta_c K^*$ have been measured by the Belle [9,10] experiment, and their measured branching fraction for $\eta_c \to \phi\phi$ is smaller than the PDG value [8].

In a previous paper [11], based on 58 million $J/\psi$ events collected in the Beijing Spectrometer (BES II) detector at the Beijing Electron-Positron Collider, we measured the $\eta_c$ mass and width using the processes $J/\psi \to \gamma\eta_c$, $\eta_c \to K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^\pm K^0_S\pi^\mp$ (with $K^0_S \to \pi^+\pi^-$), $\phi\phi$ (with $\phi \to K^+K^-$) and $p\bar{p}$, and obtained $m_{\eta_c} = 2977.5 \pm 1.0$ (sta) $\pm 1.2$ (sys) MeV and $\Gamma_{\eta_c} = 17.0 \pm 3.7$ (sta) $\pm 7.4$ (sys) MeV. In this paper, we report measurements of the branching ratios for the same processes.

BES is a conventional solenoidal magnet detector that is described in detail in Ref. [12]; BESII is the upgraded version of the BES detector [13]. A 12-layer vertex chamber (VTC) surrounding the beam pipe provides trigger information. A forty-layer main drift chamber (MDC), located radially outside the VTC, provides trajectory and energy loss ($dE/dx$) information for charged tracks over 85\% of the total solid angle with a momentum resolution of $\sigma_p/p = 0.0178\sqrt{1+p^2}$ (p in GeV/c) and a $dE/dx$ resolution for hadron tracks of $\sim 8\%$. An array of 48 scintillation counters surrounding the MDC measures the time-of-flight (TOF) of charged tracks with a resolution of $\sim 200$ 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 $\sigma_E/E = 21%/\sqrt{E}$ (E in GeV). Outside 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.

A Geant3 based Monte Carlo, SIMBES, which simulates the detector response, including interactions of secondary particles in the detector material, is used in this analysis. Reasonable agreement between data and Monte Carlo simulation is observed in various channels tested, including $e^+e^- \to (\gamma)e^+e^-$, $e^+e^- \to (\gamma)\mu\mu$, $J/\psi \to p\bar{p}$, $J/\psi \to \rho\pi$ and $\psi(2S) \to \pi^+\pi^-J/\psi$, $J/\psi \to l^+l^-$. The event selection criteria for each channel are described in detail in our previous paper [11]. Here we repeat only the essential information and emphasize those considerations that are unique to the $\eta_c$ branching ratio measurement.

Candidate events are required to have the correct number of charged tracks for a given hypothesis. Events are kinematically fitted with four constraints (4C) to the hypotheses: $J/\psi \to \gamma K^+K^-\pi^+\pi^-$, $J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$, $J/\psi \to$
$\gamma K^{+}\pi^{+}\pi^{-}\pi^{-}$, and $J/\psi \rightarrow \gamma p\bar{p}$. A one-constraint (1C) fit is performed for the $J/\psi \rightarrow \gamma_{\text{miss}}K^{+}K^{-}K^{+}K^{-}$ hypothesis, where $\gamma_{\text{miss}}$ indicates that this photon is not detected. Events with a $\chi^2$ less than 40.0 for a particular channel are selected.

In order to remove backgrounds from non-radiative decay channels, all selected events are subjected to (4C) kinematic fits to the hypotheses: $J/\psi \rightarrow K^{+}K^{-}\pi^{+}\pi^{-}$, $J/\psi \rightarrow \pi^{+}\pi^{-}\pi^{+}\pi^{-}$, and $J/\psi \rightarrow K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ and are required to satisfy $\chi^2(J/\psi \rightarrow K^{+}K^{-}\pi^{+}\pi^{-}) > 20.0$ (for $K^{+}K^{-}\pi^{+}\pi^{-}$); $\chi^2(J/\psi \rightarrow \pi^{+}\pi^{-}\pi^{+}\pi^{-}) > 10.0$ (for $\pi^{+}\pi^{-}\pi^{+}\pi^{-}$) and $\chi^2(J/\psi \rightarrow K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}) > 10.0$ (for $K^{\pm}K^{0}_{\pi}\pi^{\mp}$). For the $J/\psi \rightarrow \gamma p\bar{p}$ channel, we require that the opening angle of the two charged tracks is smaller than 179°. A detailed Monte Carlo simulation shows that these cuts, referred to below as the $J/\psi$ veto, do not distort the invariant mass distributions around the $\eta_{c}$ signal peak.

After event selection, the invariant mass spectra for the individual decay modes are obtained, as shown in Fig. 1. An unbinned maximum likelihood fit using MINUIT [14] is performed to all five channels simultaneously. The fitting method is described in detail in our previous paper [11].

The branching ratio can be calculated using

$$Br = \frac{N_{\text{fit}}/\epsilon}{N_{J/\psi}} = \frac{N}{N_{J/\psi}},$$

where $\epsilon$ is the detection efficiency; $N = N_{\text{fit}}/\epsilon$ is the efficiency-corrected number of $\eta_{c}$ events obtained directly from the fit and corrected using $Br(K_{s}^{0} \rightarrow \pi^{+}\pi^{-})$ and $Br(\phi \rightarrow K^{+}K^{-})$ [8] where necessary; and $N_{J/\psi} = (57.7 \pm 2.72) \times 10^{6}$ [15] is the total number of $J/\psi$ events. The numbers of $\eta_{c}$ events determined from the fit and the corresponding branching ratios, by decay channel, are listed in Table 1.

Table 1

| Process | No. of events (detected) | No. of events (efficiency-corrected) | Product of branching ratios |
|---------|--------------------------|-------------------------------------|-----------------------------|
| $J/\psi \rightarrow \gamma \eta_{c}$, $\eta_{c} \rightarrow K^{+}K^{-}\pi^{+}\pi^{-}$ | 413 ± 54 | 8453 ± 1110 | $(1.5 \pm 0.2 \pm 0.2) \times 10^{-4}$ |
| $\eta_{c} \rightarrow \pi^{+}\pi^{-}\pi^{+}\pi^{-}$ | 542 ± 75 | 7643 ± 1062 | $(1.3 \pm 0.2 \pm 0.4) \times 10^{-4}$ |
| $\eta_{c} \rightarrow K^{\pm}K^{0}_{\pi}\pi^{\mp}$ | 609 ± 71 | 12516 ± 1460 | $(2.2 \pm 0.3 \pm 0.5) \times 10^{-4}$ |
| $\eta_{c} \rightarrow \phi\phi$ | 357 ± 64 | 1922 ± 357 | $(3.3 \pm 0.6 \pm 0.6) \times 10^{-5}$ |
| $\eta_{c} \rightarrow p\bar{p}$ | 213 ± 33 | 1105 ± 171 | $(1.9 \pm 0.3 \pm 0.3) \times 10^{-5}$ |

The main systematic error contributions in measuring the $\eta_{c}$ branching ratios
Fig. 1. Invariant mass distributions in the $\eta_c$ region (a) $m_{K^+K^-\pi^+\pi^-}$, (b) $m_{\pi^+\pi^-\pi^+\pi^-}$, (c) $m_{K^\pm K_0^{*0}\pi^\mp}$, (d) $m_{\phi\phi}$ and (e) $m_{p\bar{p}}$. The histograms correspond to the data; the curves are the fit result.

originates from uncertainties in the background shape parameterization used, differences between different Monte Carlo simulations of the drift chamber wire resolution, detection efficiency differences due to uncertainties in $\eta_c$ decay sequences into the final state (for $\eta_c \to \pi^+\pi^-\pi^+\pi^-$, $\eta_c \to K^+K^-\pi^+\pi^-$ and $\eta_c \to K^\pm K^0_{S\pi}^{\mp}$), differences in the photon efficiency determined using data and that determined from the Monte Carlo simulation, particle identification uncertainties, and the uncertainty in the total number of $J/\psi$ events.

In Fig. 1, second-order polynomials are used to describe the backgrounds. The systematic errors due to the background shape are studied by using instead linear polynomial functions to fit the backgrounds in Fig. 1(b), (d), and (e) and
third order polynomials to fit the backgrounds in Fig. 1(a) and (c), changing the upper fitting bound from 3.05 to 3.07 GeV/c$^2$, and removing the $J/\psi$ veto from the event selection. The relative systematic errors from these sources are listed in Table 2. Since the errors are correlated, we choose the largest one as the systematic error due to the background shape.

### Table 2
Relative systematic error caused by background shape.

| Sources              | $K^+K^-\pi^+\pi^-$ | $\pi^+\pi^-\pi^+\pi^-$ | $K^\pm K_S^0\pi^\mp$ | $\phi\phi$ | $p\bar{p}$ |
|----------------------|---------------------|--------------------------|------------------------|------------|------------|
| background polynomial| 4.4%                | 7.6%                     | 2.5%                   | 8.3%       | 3.2%       |
| fitting range        | 9.4%                | 8.4%                     | 17.2%                  | 15.5%      | 10.6%      |
| $J/\psi$ veto        | 1.7%                | 26.6%                    | 10.1%                  | 17.3%      | 15.2%      |

The relative systematic errors for the individual channels are summarized in Table 3, where the individual contributions are added in quadrature to obtain the total relative systematic error. The systematic errors on the product branching ratios are given in Table 1.

### Table 3
Relative systematic error summary.

| Sources            | $K^+K^-\pi^+\pi^-$ | $\pi^+\pi^-\pi^+\pi^-$ | $K^\pm K_S^0\pi^\mp$ | $\phi\phi$ | $p\bar{p}$ |
|--------------------|--------------------|--------------------------|------------------------|------------|------------|
| BG shape           | 9.4%               | 26.6%                    | 17.2%                  | 17.3%      | 15.2%      |
| wire resolution    | 10.4%              | 26.6%                    | 17.2%                  | 17.3%      | 15.2%      |
| $\eta_c$ decay sequences | 4.5%       | 17.1%                    | 13.1%                  | 2.9%       | 4.7%       |
| $\gamma$ efficiency| 2.0%               | 2.0%                     | 2.0%                   | 2.0%       | 2.0%       |
| particle ID        | 2.5%               | 2.7%                     | 2.2%                   | 2.5%       | 1.1%       |
| $N_{J/\psi}$       | 4.7%               | 4.7%                     | 4.7%                   | 4.7%       | 4.7%       |
| Total              | 15.8%              | 32.5%                    | 22.3%                  | 18.4%      | 16.7%      |

Using the branching fraction $Br(J/\psi \to \gamma\eta_c) = (1.3 \pm 0.4)\%$ [8], the $\eta_c$ branching fractions can be obtained. Table 4 shows the BES results together with the PDG [8] and Belle [9,10] values. The BES $Br(\eta_c \to \phi\phi)$ is smaller than the current PDG value of $(7.1 \pm 2.8) \times 10^{-3}$ and is consistent with the Belle [10] and DM2 [3] measurements within errors. The branching fractions for $\eta_c \to K^\pm K_S^0\pi^\mp$ and $\eta_c \to p\bar{p}$ are consistent with both the Belle[9] and PDG values [8]. The branching fractions for $\eta_c \to \pi^+\pi^-\pi^+\pi^-$ and $\eta_c \to K^+K^-\pi^+\pi^-$ are consistent with the PDG values [8] within errors.
Table 4
Branching fractions of the $\eta_c$ (the Belle results of $Br(\eta_c \to K^\pm K_S^0\pi^\mp)$ and $Br(\eta_c \to p\bar{p})$ are calculated from reference [10]).

| Process                  | BES(%)          | PDG02(%) [8]  | Belle(%) |
|--------------------------|-----------------|---------------|----------|
| $Br(\eta_c \to K^+K^-\pi^+\pi^-)$ | $1.2 \pm 0.4$  | $2.0^{+0.7}_{-0.6}$ | -        |
| $Br(\eta_c \to \pi^+\pi^-\pi^+\pi^-)$ | $1.0 \pm 0.5$  | $1.2 \pm 0.4$ | -        |
| $Br(\eta_c \to K^\pm K_S^0\pi^\mp)$ | $1.7 \pm 0.7$  | $\frac{1}{3}(5.5 \pm 1.7)$ | $\sim 1.8$ |
| $Br(\eta_c \to \phi\phi)$  | $0.25 \pm 0.09$ | $0.71 \pm 0.28$ | $0.18^{+0.08}_{-0.06} \pm 0.07$ |
| $Br(\eta_c \to p\bar{p})$  | $0.15 \pm 0.06$ | $0.12 \pm 0.04$ | $\sim 0.14$ |

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