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Measurements of the Mass and Full-Width of the η_c Meson

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Abstract

In a sample of 58 million J/ψ events collected with the BES II detector, the process $\mathrm{J}/\psi \to \gamma\eta_c$ is observed in five different decay channels: $\gamma K^+K^-\pi^+\pi^-$, $\gamma\pi^+\pi^-\pi^+\pi^-$, $\gamma K^\pm K^0_S\pi^\mp$ (with $K^0_S \to \pi^+\pi^-$), $\gamma\phi\phi$ (with $\phi \to K^+K^-$) and $\gamma p\bar{p}$. From a combined fit of all five channels, we determine the mass and full-width of η_c to be $m_{\eta_c} = 2977.5 \pm 1.0$ (stat.) ± 1.2 (syst.) MeV/c^2 and $\Gamma_{\eta_c} = 17.0 \pm 3.7$ (stat.) ± 7.4 (syst.) MeV/c^2.

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Since 1980, numerous efforts have been made to determine the mass and full width of the η_c [1–11]. However, from a theoretical point of view, the accuracies of these experimental measurements are still not sufficient. For instance, in order to calculate the strength of the spin-spin interaction term in non-relativistic potential models, it is necessary to know precisely the mass difference between the J/$\psi(1^{--})$ and $\eta_c(0^{-+})$. While the mass of the J/ψ is determined with high accuracy to be 3096.88±0.04 MeV/c^2, the η_c mass is measured with much less accuracy to be 2979.7 ± 1.5 MeV/c^2, an average by the Particle Data Group (PDG) [12] of 10 measurements with an internal confidence level of only 0.001. Different measurements of the full width of the η_c also have poor internal consistency. The PDG [12] determines an average value for the η_c full width of $16.0^{+3.6}_{-3.2}$ MeV/c^2 from six experiments, whose experimental results vary from 7 MeV/c^2 to 27 MeV/c^2, with large errors. Such an accuracy is inadequate for some studies of charmonium physics [13] and additional, more precise measurements of both m_{η_c} and Γ_{η_c} are needed.

The η_c mass and width have been measured previously by the BES collaboration with data samples of 3.79 million ψ(2S) events [9] and 7.8 million J/ψ events [11] collected with the BES I detector [14]. In the latter sample, the process J/$\psi \to \gamma\eta_c$ was observed in five different η_c decay channels: $K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^\pm K^0_S\pi^\mp$ (with $K^0_S \to \pi^+\pi^-$), $\phi\phi$ (with $\phi \to K^+K^-$) and $K^+K^-\pi^0$, and the mass of the η_c was determined to be 2976.6 ± 2.9 (stat.)± 1.3 (syst.) MeV/c^2. Combined with the results from $\psi(2S) \to \gamma\eta_c$, the mass and the full width of η_c were determined to be $m_{\eta_c} = 2976.3 \pm 2.3$ (stat.) $\pm$ 1.2 (syst.) MeV/c^2 and $\Gamma_{\eta_c} = 11.0 \pm 8.1$ (stat.) $\pm$ 4.1 (syst.) MeV/c^2.

In this paper we present results with much higher statistics using a recent sample of 58 million J/ψ events obtained with the upgraded BESII detector [15]. The upgrade from BES I to BES II includes the replacement of the inner drift chamber with a straw-tube vertex chamber (VC), composed of 12 tracking layers arranged around a beryllium beam pipe and with a spatial resolution of about 90 μm; a new barrel time-of-flight counter (BTOF) with a time resolution of 180 ps; and a new main drift chamber (MDC), which has 10 tracking layers providing a dE/dx resolution of $\sigma_{dE/dx} = 8.4\%$ and a momentum resolution of $\sigma_p/p = 1.7\%\sqrt{1+p^2}$ (p in GeV) for charged tracks. These upgrades augment the pre-existing calorimeter and muon tracking systems. The barrel shower counter (BSC), which covers 80% of 4π solid angle, has an energy resolution of $\sigma_E/E = 22\%/\sqrt{E}$ (E in GeV) and a spatial resolution of 7.9 mrad in ϕ and 2.3 cm in z. The μ identification system consists of three double layers of proportional tubes interspersed in the iron flux return of the magnet. They provide coordinate measurements along the muon trajectories with resolutions of 3 cm and 5.5 cm in ϕ and z, respectively.

The η_c mass and width are measured using the reactions 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 $p\bar{p}$. Event selection criteria for each channel are described in detail in our previous papers [16,17,18]. Here we repeat only the essential information and emphasize those considerations that are unique to the m_{η_c} and Γ_{η_c} measurements.

Candidate events are required to have the correct number of charged tracks for a given hypothesis. Each track must be well fit to a helix in the polar angle range $|\cos\theta| < 0.84$ and have a transverse momentum above 60 MeV/c. For the decay channels $J/\psi \to \gamma K^+K^-\pi^+\pi^-$, $J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$, $J/\psi \to \gamma K^\pm\pi^\mp\pi^+\pi^-$ and $J/\psi \to \gamma p\bar{p}$, at least one photon with energy $E_\gamma > 30$ MeV is required in the barrel shower counter

Events are kinematically fitted with four constraints (4C) to the hypotheses: $J/\psi \to \gamma K^+K^-\pi^+\pi^-$, $J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$, $J/\psi \to \gamma K^\pm\pi^\mp\pi^+\pi^-$, and $J/\psi \to \gamma p\bar{p}$. A one-constraint(1C) fit is performed for the $J/\psi \to \gamma_{miss}K^+K^-K^+K^-$ hypothesis, where γ_{miss} indicates that this photon is not detected. Events with a χ^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 a kinematic fit with four constraints to the hypotheses: $J/\psi \to K^+K^-\pi^+\pi^-$, $J/\psi \to \pi^+\pi^-\pi^+\pi^-$ and $J/\psi \to K^\pm\pi^\mp\pi^+\pi^-$. Backgrounds from the J/ψ peak are removed by requiring that $\chi^2(J/\psi \to K^+K^-\pi^+\pi^-) > 20.0$ (for $K^+K^-\pi^+\pi^-$); $\chi^2(J/\psi \to \pi^+\pi^-\pi^+\pi^-) > 10.0$ (for $\pi^+\pi^-\pi^+\pi^-$) and $\chi^2(J/\psi \to K^\pm\pi^\mp\pi^+\pi^-) > 10.0$ (for $K^\pm K^0_S\pi^\mp$). For the $J/\psi \to \gamma p\bar{p}$ 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/ψ veto, do not distort the invariant mass distributions around the η_c signal peak.

Two additional variables are used to reject events with wrong final state assignments. The first variable, $|U_{miss}| = |E_{miss} - P_{miss}|$, is used to reject events with multi-photons and misidentified charged particles. Here, E_{miss} and P_{miss} are, respectively, the missing energy and momentum calculated using measured quantities for charged tracks. A second variable, $P^2_{t\gamma} = 4|P_{miss}|^2\sin^2(\theta_{t\gamma}/2)$, where $\theta_{t\gamma}$ is the angle between the missing momentum and the photon direction, is used to reduce backgrounds from π^0's. The specific values of the selection requirements for these two kinematic variables are summarized in Table 1. Additional requirements to remove backgrounds from a few specific channels are summarized in Table 2.

For $J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$ candidate events with more than one γ, we suppress π^0 background by requiring that $\mid M(\gamma_1\gamma_2) - M(\pi^0) \mid > 60$ MeV/c^2 if $\vec{P}_{miss}$ is in the same plane as the two photons γ_1 and γ_2, i.e. $\hat{P_{miss}} \cdot (\hat{r_{\gamma 1}} \times \hat{r_{\gamma 2}}) < 0.15$. Here, $\hat{P_{miss}}$ is the unit vector of the missing momentum for all charged tracks;

Table 1
Cuts imposed on $|U_{miss}|$ and $P^2_{t\gamma}$ for event selection.

mode ($J/\psi \to \gamma X$)	$\mid U_{miss} \mid$ (GeV/c^2)	$P^2_{t\gamma}$ [(GeV/c)^2]
$\gamma K^+K^-\pi^+\pi^-$	< 0.15	< 0.002
$\gamma\pi^+\pi^-\pi^+\pi^-$	< 0.10	< 0.0015
$\gamma K^\pm K^0_S\pi^\mp$ ($\gamma K^\pm\pi^\mp\pi^+\pi^-$)	–	< 0.003
$\gamma p\bar{p}$	< 0.15	< 0.003

Table 2
Cuts to remove backgrounds from specific channels.

mode ($J/\psi \to \gamma X$)	cut	background
$\gamma K^+K^-\pi^+\pi^-$	$\lvert M_{\pi^+\pi^-\pi^0} - M_\omega\rvert > 40$ MeV/c^2	$J/\psi \to \omega K^+K^-$
$\gamma K^+K^-\pi^+\pi^-$	$\lvert M_{K^+K^-} - M_\phi\rvert > 20$ MeV/c^2	$J/\psi \to \phi\pi^+\pi^-$
$\gamma\pi^+\pi^-\pi^+\pi^-$	$\lvert M_{\pi^+\pi^-\pi^0} - M_\omega\rvert > 40$ MeV/c^2	$J/\psi \to \omega\pi^+\pi^-$
$\gamma\pi^+\pi^-\pi^+\pi^-$	$\lvert M_{\pi^+\pi^-} - M_{K^0_S}\rvert > 25$ MeV/c^2	$J/\psi \to \gamma K^0_S K^0_S$

$\hat{r_{\gamma 1}}$ and $\hat{r_{\gamma 2}}$ are unit vectors for the γ_1 and γ_2 directions determined from the BSC; and $M(\gamma_1\gamma_2)$ is the invariant mass of $\gamma_1\gamma_2$. When we calculate $M(\gamma_1\gamma_2)$, it is assumed that the missing particle decays to γ_1 and γ_2, and $M(\gamma_1\gamma_2)$ can be obtained by using P_{miss} and the angles between $\vec{P}_{miss}$ and the γ direction. The advantage of this technique is that it uses the momenta of charged tracks measured by the MDC, which has good momentum resolution, and is independent of the photon energy measurement. For $J/\psi \to \gamma K^+K^-\pi^+\pi^-$, $\gamma K^\pm K^0_S\pi^\mp$, and $\gamma p\bar{p}$, we require that $\mid M(\gamma_1\gamma_2) - M(\pi^0) \mid \; > 50$ MeV/c^2 when $\hat{P_{miss}} \cdot (\hat{r_{\gamma 1}} \times \hat{r_{\gamma 2}}) < 0.14$.

For the $K^\pm K^0_S\pi^\mp$ (with $K^0_S \to \pi^+\pi^-$) channel, the $\pi^+\pi^-$ invariant mass for the K^0_S candidate is required to be within 25 MeV/c^2 of the K^0_S mass. For the $\phi\phi$ (with $\phi \to K^+K^-$) channel, the invariant masses of both candidate ϕ's, corresponding to K^+K^- pairs, are required to be within 20 MeV/c^2 of the ϕ mass.

After the 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 [19] is performed for all five channels simultaneously, with the fitting function for a given channel i given by

$$f_i(m) = a_i[BW(M,\Gamma,m) \otimes GS(m,\sigma_i)] \times EFF_i(m) + (1-a_i)BG_i(m),$$

where M and Γ are the mass and width of the η_c, respectively, σ_i is the mass resolution in the η_c region, BW is a Breit-Wigner function describing the η_c signal, EFF_i is an efficiency correction function, and BG_i is a second-order

polynomial function describing the background shape. In order to include the experimental resolution, the BW function is folded with a Gaussian resolution function GS with the resolution σ_i fixed at a value determined from the Monte Carlo simulation. The parameters M and Γ and the coefficients of the polynomial function, a_i, are determined from the fit. The log likelihood function for the channel i is given by

$$S_i = -\ln L_i = -\ln(\prod_{j=1}^{N_i^{\rm event}} f_i(m_j)),$$

where $N_i^{\rm event}$ is the total number of events. The overall log likelihood function,

$$S = \sum_{i=1}^{5} S_i,$$

is minimized to obtain the fitting results from the five channels simultaneously. The fit result is shown in Fig. 1, and the fitted η_c mass and width are determined to be $m_{\eta c} = 2977.5 \pm 1.0$ MeV/c^2 and $\Gamma_{\eta c} = 17.0 \pm 3.7$ MeV/c^2. The background in Fig. 1(b),(d) and (e) can also be fitted with a linear polynomial function, with results that are almost the same.

Systematic errors in determining the η_c mass and width originate mainly from the mass-scale calibration, background shape, fitting range, difference between data and Monte Carlo simulation, J/ψ veto, and uncertainties associated with the mass resolution. We use 1.5 million $\psi(2S)$ data collected during the J/ψ run to check the mass-scale calibration. The measured χ_{c2} mass is 3555.2 ± 1.4 MeV/c^2 from decays $\psi(2S) \to \gamma\pi^+\pi^-\pi^+\pi^-$ and 3560.2 ± 6.0 MeV/c^2 from decays $\psi(2S) \to \gamma K^+K^-\pi^+\pi^-$, respectively. The combined weighted average is $m_{\chi_{c2}} = 3555.5 \pm 1.4$ MeV/c^2, a difference of 0.7 ± 1.4 MeV/c^2 from the world average obtained by the PDG [12]. In addition, we measured masses of the K_s^0, ϕ and Λ from the 58 million J/ψ data sample to check the mass-scale calibration. Results of the masses and mass differences with PDG values [12] are given in Table 3. The systematic error on the overall mass scale is estimated to be 0.8 MeV/c^2.

Table 3
Comparison of K_s^0, ϕ and Λ mass peak positions.

	K_s^0 (MeV/c^2)	ϕ (MeV/c^2)	Λ (MeV/c^2)
our measurements	496.9 ± 0.1	1019.6 ± 0.1	1115.3 ± 0.1
PDG values	497.67 ± 0.03	1019.417 ± 0.014	1115.683 ± 0.006
ΔM	-0.8 ± 0.1	0.2 ± 0.1	-0.4 ± 0.1

Table 4 summarizes all contributions to the systematic error of the mass and full-width of the η_c. The effect of the background shape is studied by using a third-order polynomial function instead of a second-order one. The upper

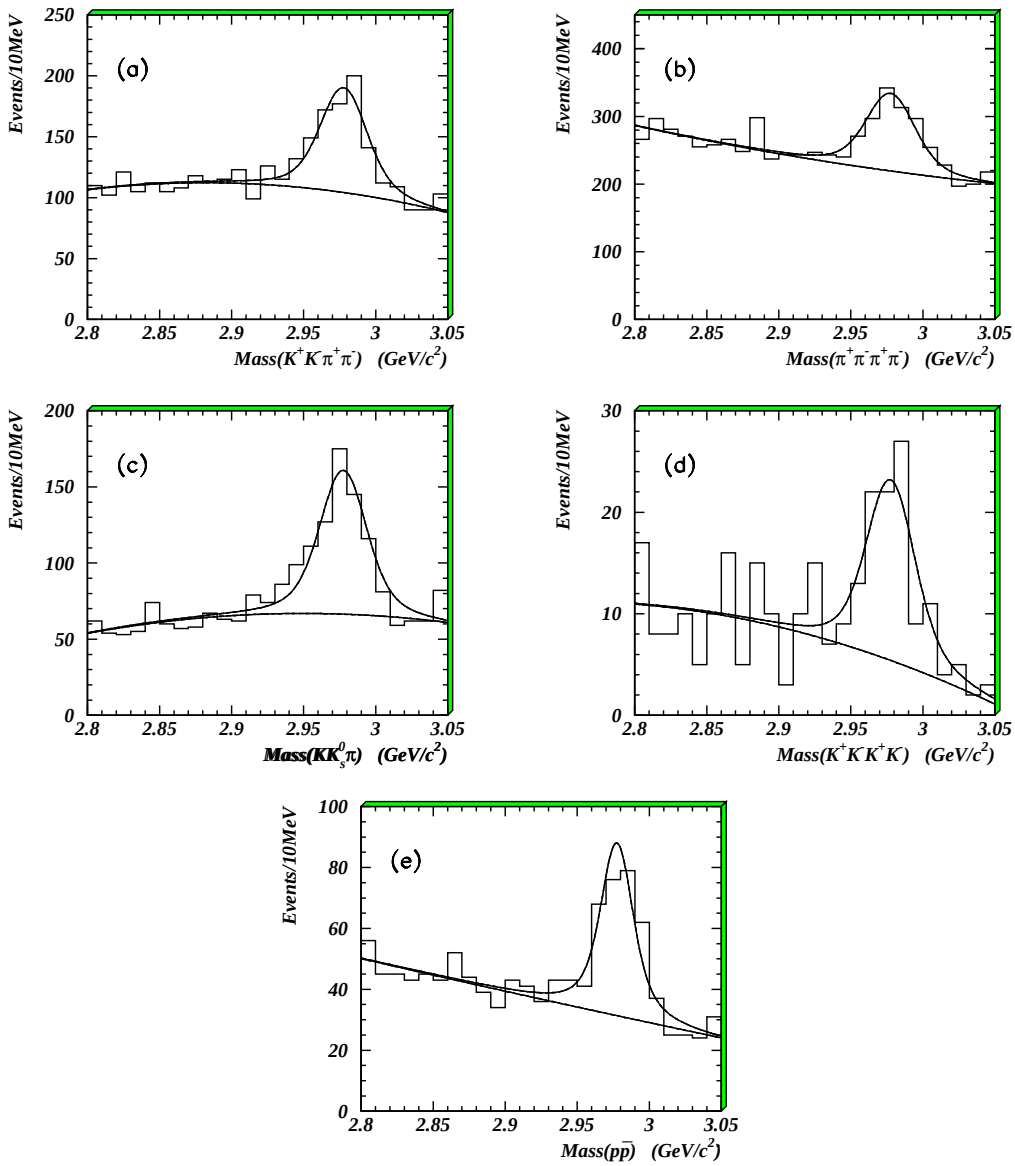

Fig. 1. The invariant mass distributions in the η_c region for channels (a) $m_{K^+K^-\pi^+\pi^-}$, (b) $m_{\pi^+\pi^-\pi^+\pi^-}$, (c) $m_{K^\pm K^0_S\pi^\mp}$, (d) $m_{\phi\phi}$ and (e) $m_{p\bar{p}}$.

fitting bound is checked by changing it from 3.05 to 3.07 GeV/c^2, and the J/ψ veto is removed from the event selection. Contributions from differences of the detection efficiency between data and Monte Carlo simulation, as well as uncertainties of the detector mass resolution, are also listed in Table 4. Assuming no correlations among the above factors, the total systematic error on the mass and width are determined to be 1.2 MeV/c^2 and 7.4 MeV/c^2, respectively, by a quadratic sum of all contributions.

In summary, we used 58 million J/ψ events collected by the BES II detector to measure the mass and full width of the η_c in five different decay modes. They are determined to be $m_{\eta_c} = 2977.5 \pm 1.0$ (stat.) $\pm$ 1.2 (syst.) MeV/c^2

and $\Gamma_{\eta_c} = 17.0 \pm 3.7$ (stat.) ± 7.4 (syst.) MeV/c^2. Figure 2 shows the BES results together with previously reported measurements. It can be seen that the η_c mass and width measurement from BES II are in good agreement with the PDG averages.

Table 4
Sources of systematic errors.

sources	error on mass (MeV/c^2)	error on width (MeV/c^2)
mass scale calibration	0.8	
background shape	0.0	3.6
fitting range	0.3	2.2
detection efficiency difference: data vs. MC	0.5	0.3
J/ψ veto	0.7	5.6
uncertainties of experimental mass resolution	0.0	2.4
total systematic error	1.2	7.4

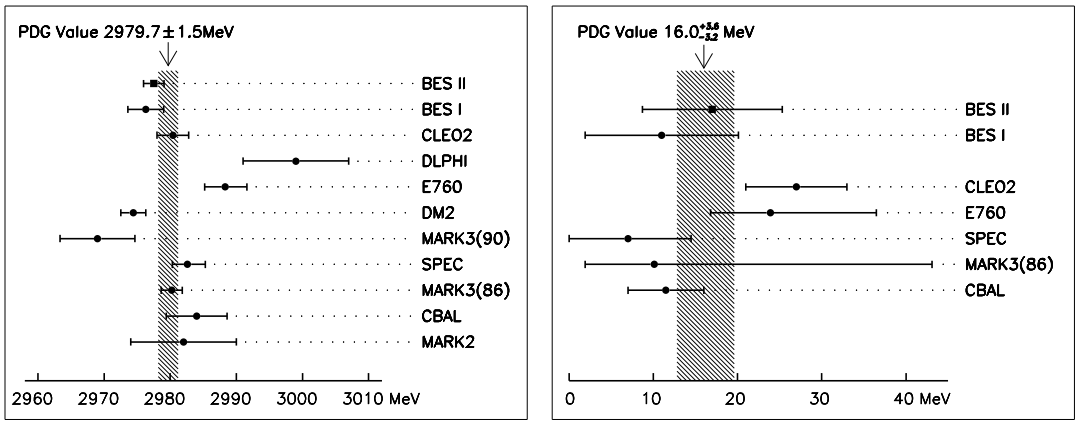

Fig. 2. Mass and full-width measurements of the η_c meson.

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