A measurement of the η_c mass and full width

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Abstract

Based on 7.8 million J/ψ data collected in BES, five decay modes of η_c: $K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^\pm K^0_S\pi^\mp$ (with $K^0_S \to \pi^+\pi^-$), $\phi\phi$ (with $\phi\phi \to K^+K^-K^+K^-$) and $K^+K^-\pi^0$ from J/$\psi \to \gamma\eta_c$ have been analyzed to determine the mass of η_c to be $2976.6 \pm 2.9 \pm 1.3$ MeV. The combined analysis with BES data on $\psi(2S) \to \gamma\eta_c$ gives $m_{\eta_c} = 2976.3 \pm 2.3 \pm 1.3$ MeV and $\Gamma_{\eta_c} = 11.0 \pm 8.1 \pm 3.5$ MeV. The results are in good agreement with PDG values. The measurement of branching ratios for five decay modes of η_c have also been obtained.

14.40.Cs, 12.39.Mk, 13.25.Jx, 13.40.Hq

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For the calculation of the strength of the spin-spin interaction term in non-relativistic potential models, it is useful to know the precise mass difference between the J/$\psi(1^{--})$ and $\eta_c(0^{-+})$. The mass of J/ψ is determined with high accuracy (1×10^{-5}) to be 3096.88±0.04 MeV, but the mass of η_c is less well measured. The PDG average of m$_{\eta_c}$=2979.8±2.1 MeV is based on previous experiments from different reactions $e^+e^- \to$ J/$\psi \to \gamma\eta_c$ [1–4], $e^+e^- \to \psi(2s) \to \gamma\eta_c$ [5] and P$\bar{\text{P}} \to \gamma\gamma$ [6,7]. The different measurements have poor internal consistency, and the PDG fit to the measurements has a confidence level of only 0.001. The most recent result from E760 [6] disagrees with the result from DM2 [1] by almost four standard deviations. The measurements of the full width of Γ_{η_c} have been made by four experiments with the results $23.9^{+12.6}_{-7.1}$ from E760, $7.0^{+7.5}_{-7.0}$ from SPEC, $10.1^{+33.0}_{-8.2}$ from MARK III and 11.4±4.5 from CBAL; all are in units of MeV. So additional measurements for both m_{η_c} and Γ_{η_c} are needed to improve the situation. The mass of η_c was measured earlier by the BES collaboration based on a 3.79 million ψ(2s) data sample. A result of m$_{\eta_c}$=2975.8±3.9±1.4 MeV was obtained [8]. Here we report a measurement of the mass of η_c based on a 7.8 million J/ψ data sample collected in BES. 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 $\phi\phi \to K^+K^-K^+K^-$) and $K^+K^-\pi^0$ have been analyzed to determine the mass and width of η_c.

The Beijing Spectrometer (BES) has been described in detail in Ref [9]. Here we describe briefly those detector elements crucial to this measurement. Tracking is provided by a 10 superlayer main drift chamber (MDC). Each superlayer contains four layers of sense wires measuring both the position and the ionization energy loss (dE/dx) of charged particles. The momentum resolution is $\sigma_P/P = 1.7\%\sqrt{1+P^2}$, where P is the momentum of charged tracks in GeV/c. The resolution of the dE/dx measurement is about 9%. This provides good π/K separation in the low momentum region. An array of 48 scintillation counters surrounding the MDC measures the time-of-flight (TOF) of charged tracks with a resolution of 330ps for hadrons. Outside the TOF system is an electromagnetic calorimeter composed of streamer tubes and lead sheets with a z positional resolution of 4 cm. The energy resolution scales as $\sigma_E/E = 22\%/\sqrt{E}$, where E is the energy in GeV. Outside the shower counter is a solenoidal magnet producing a 0.4 Tesla magnetic field.

The event selections for each channel are described in detail in previous papers on partial wave analysis [10–12]. Here we only repeat some information and emphasize some considerations special to the m_{η_c} measurement. We are using event selection for five channels as follows. Candidates are selected by requiring exactly the correct number of charged tracks with a good helix fit in the polar angle range $-0.8 < \cos\theta < 0.8$ and a transverse momentum > 60 MeV/c. For four-charged-track channels, at least one photon is required in the barrel shower counter; for the $K^+K^-\pi^0$ channel, three photons in the barrel shower counter are required. A minimum energy cut of 30 MeV is imposed on these photons. Showers associated with charged tracks are also removed. Events are fitted kinematically to the 4C hypotheses: $J/\psi \to \gamma K^+K^-\pi^+\pi^-$, $J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$, $J/\psi \to \gamma K^\pm\pi^\mp\pi^+\pi^-$, $J/\psi \to \gamma\gamma\gamma K^+K^-$ and the 1C hypothesis $J/\psi \to \gamma_{miss}K^+K^-K^+K^-$, where γ_{miss} means this photon is missing; it is required that for each particular channel the confidence level is larger than 5%. The transverse momentum of the four charged tracks with respect to the photon, $P_{tr}^2 < 0.006(GeV/c)^2$, is required to reduce the backgrounds containing a π^0. A cut on the variable, $|U_{miss}| = |E_{miss} - P_{miss}| < 0.10$ GeV (for $\pi^+\pi^-\pi^+\pi^-$), < 0.12 GeV (for $K^+K^-\pi^+\pi^-$), < 0.15 GeV (for $K^\pm K_S^0\pi^\mp$) and < 0.15 GeV (for $\phi\phi$) is imposed to reject events with multiphotons and misidentified charged particle. Here, E_{miss} and P_{miss} are, respectively, the missing energy and missing momentum calculated from all charged tracks. For $K^+K^-\pi^+\pi^-$ and $\pi^+\pi^-\pi^+\pi^-$ channels, $|M_{\pi^+\pi^-\pi^0} - M_\omega| > 30$ MeV is required to remove the background from $J/\psi \to \omega\pi^+\pi^-$ and $J/\psi \to \omega K^+K^-$, where a π^0 is associated to the missing momentum. For the channel $K^\pm K_S^0\pi^\mp$ (with $K_S^0 \to \pi^+\pi^-$), we performed a cut on the $\pi^+\pi^-$ invariant mass, $|M_{\pi^+\pi^-} - M_{K_S^0}| < 25$ MeV. For the channel $\phi\phi$ (with $\phi\phi \to K^+K^-K^+K^-$), we used a double cut on the K^+K^- invariant mass $|M_{K^+K^-} - M_\phi| < 30$ MeV. For the $K^+K^-\pi^0$ channel, at least one of the three $\gamma\gamma$ invariant mass combinations must lie within 40 MeV of the π^0 mass; the one with invariant mass closest to the π^0 mass is assumed to be from π^0 decay.

According to the above criteria for event selection, we derived invariant mass spectra for different decay modes and used a MINUIT Likelihood fit to a Breit-Wigner line shape; the width of η_c, Γ was convolved with a Gaussian of mass resolution σ, plus a polynomial function to represent the background. Invariant mass distributions for the individual channels in the η_c region are show in Figs. 1(a) to 1(e). The number of fitted events and the mass of η_c for the individual channels are listed in Table I.

Fig. 1(f) shows the combined four-charged-track invariant mass distribution in the η_c mass region for $K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^\pm K^0_S\pi^\mp$ and $\phi\phi$ channels. m_{η_c} = 2976.7$\pm$3.4 MeV is obtained by a Minuit Likelihood fit with fixed σ and Γ. It gives a total of 100.9$\pm$19.8 events and has a χ^2/dof=14.2/20. This corresponds to a confidence level of 81.9%. If σ=13.3 MeV is fixed and the mass, number of events and Γ are floated, m_{η_c}=2976.7$\pm$3.0 MeV.

The systematic error of the η_c measurement is estimated by the following considerations. The masses of the three ^3P charmonium states are measured in a number of experiments and the reported values have good internal consistency. We use these to estimate the level of any systematic error on the overall mass scale by comparing the results from similar fits for the three χ_c masses with their PDG values; 1.0 MeV is taken as the systematic error on the mass scale. The systematic errors originating from the cut conditions are mainly from the probability of χ^2 and the minimum energy of photon cuts. For example, when the probability of χ^2 is varied between the extreme values of 1% and 10%, the central value of m_{η_c} shifts by 0.8 MeV. When the minimum energy of the photon is changed from 30 MeV to 50 MeV, the central value of m_{η_c} shifts by 0.2 MeV. The systematic errors associated with the uncertainties in the experimental resolution and the full width of the η_c are small. For example, when the experimental resolution is varied between the extreme values of 11.0 and 15.0 MeV, and the full width is changed from 10.0 to 16.0MeV, we found that shifts of the central value of the mass are less than 0.2 MeV. So the overall systematic error of this measurement is estimated as 1.3 MeV.

Taking the weighted average with the result from the decay channel $K^+K^-\pi^0$ (see Table I), we get m_{η_c}=2976.6$\pm$2.9 $\pm$ 1.3 MeV for five channels. Combining the result with that from BES analysis of $\psi(2S) \to \gamma\eta_c$, namely $m_{\eta_c} = 2975.8 \pm 3.9 \pm 1.4$MeV [8], we obtain a weighted average $m_{\eta_c} = 2976.3 \pm 2.3 \pm 1.3$MeV. Here, since most of the systematic error regarding the mass positions are almost certainly common between the J/ψ and ψ' measurements, we use the systematic error from J/ψ as the combined one.

The full width of η_c can be found by fitting the combined events from J/ψ and $\psi(2S)$. Fig. 2 shows the combined four-charged-track invariant mass distribution in the η_c mass region for $J/\psi \to \gamma\eta_c$ (with $\eta_c \to K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^\pm K^0_S\pi^\mp$ and $\phi\phi$) and $\psi(2S) \to \gamma\eta_c$ (with $\eta_c \to K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^\pm K^0_S\pi^\mp$ and $K^+K^-K^+K^-$). A full width of η_c: $\Gamma = 11.0 \pm 8.1$ MeV is given by a MINUIT likelihood fit, fixing σ at 13.3 MeV. It gives a total of 168.3 ± 26.8 events and has a χ^2/dof=15.0/21. This corresponds to a confidence level of 82.1%.

The systematic error of the width measurement is about 3.5 MeV, including the uncertainty of mass resolution σ (2.5 MeV) and the uncertainty of cut conditions (2.5 MeV).

Table II shows branching ratios of the five different decay modes. The main contribution to the systematic error is from the uncertainty in the total number of J/ψ events and the main cut criteria. Most branching ratios obtained by this experiment are in good consistency with the result from DM2 [1]. But some of them are less than the result from MARK III [2].

In summary, based on 7.8 million J/ψ data from BES, we have analyzed five decay modes of η_c from $J/\psi \to \gamma\eta_c$ to determine the mass of η_c to be $2976.6 \pm 2.9 \pm 1.3$ MeV. Combining the result with BES analysis of $\psi(2S) \to \gamma\eta_c$, we find $m_{\eta_c} = 2976.3 \pm 2.3 \pm 1.3$ MeV and $\Gamma_{\eta_c} = 11.0 \pm 8.1 \pm 3.5$ MeV. The mass measurement of η_c from BES is in good agreement with the PDG value of 2979.8 ± 2.1 MeV, but 3.8σ below the E760 result of $2988.3^{+3.3}_{-3.1}$ MeV. Fig. 3 shows the results of this measurement and the BES ψ(2s) measurement, together with the four previous measurement having the smallest error. The curve in Fig. 3 allows a determination of the values of χ^2 versus m_{η_c} for a fit including all existing measurements. The minimum value, χ^2/dof=22.2/8 occurs at 2979.2 ± 0.9 MeV. The high χ^2 value is predominantly due to the poor agreement between the DM2 and E760 measurement. The two measurements of BES reduce the new world average for the mass by 0.6 MeV.

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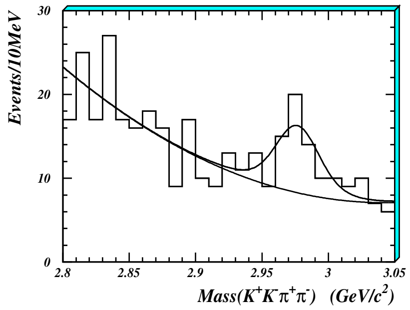
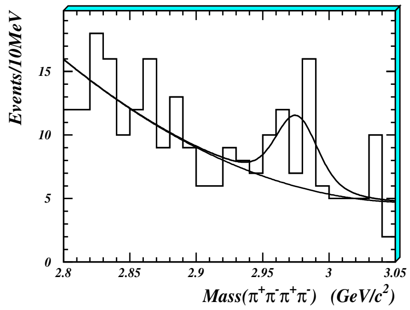
FIGURES



(a) $m_{K^+K^-\pi^+\pi^-}$ distribution



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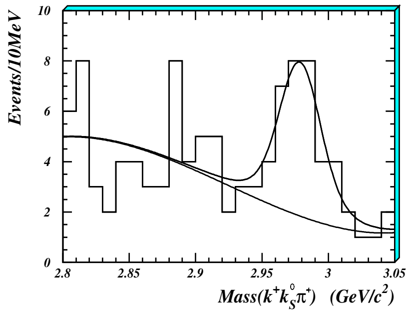
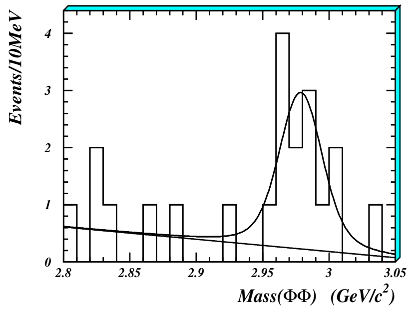
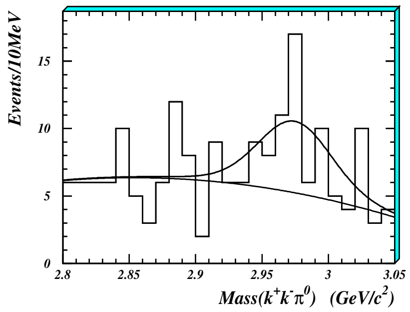


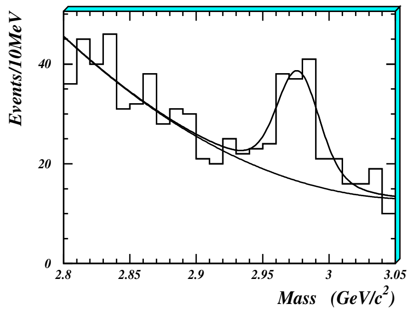
(c) $m_{K^\pm K^0_S\pi^\mp}$ distribution



(d) $m_{\phi\phi}$ distribution



(e) $m_{K^+K^-\pi^0}$ distribution



(f) Combined four-charged-track mass distribution of (a), (b), (c) and (d)

FIG. 1. Invariant mass distributions in the η_c region

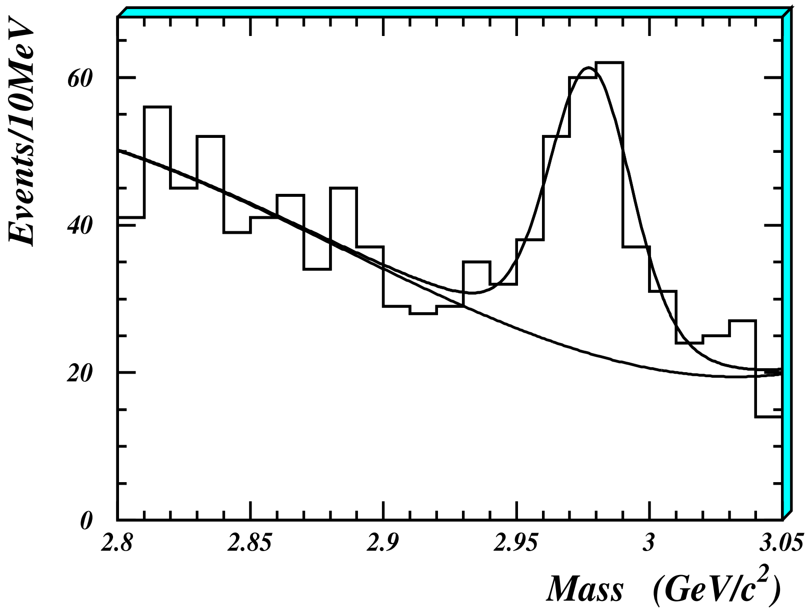


FIG. 2. The combined four-charged-track invariant mass distribution in the η_c region for $J/\psi \to \gamma\eta_c$ (with $\eta_c \to K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^\pm K^0_S\pi^\mp$ and $\phi\phi$) and $\psi(2S) \to \gamma\eta_c$ (with $\eta_c \to K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^\pm K^0_S\pi^\mp$ and $K^+K^-K^+K^-$).

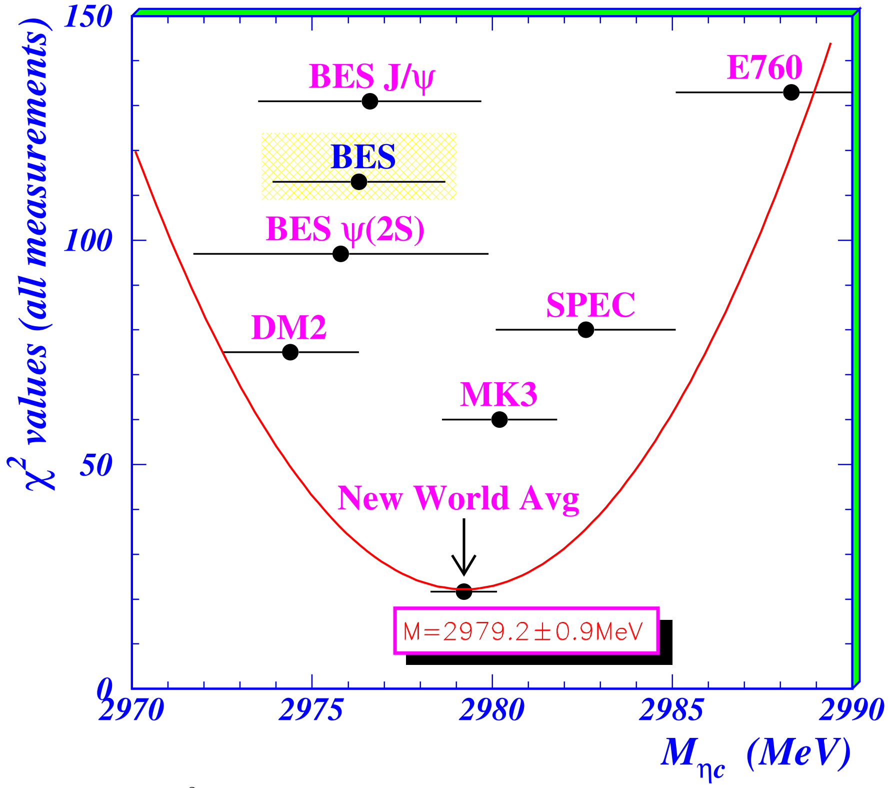


FIG. 3. The curve of χ^2 versus $m_{\eta c}$ for a fit that includes all existing measurements and BES measurements (BES $J\psi$, BES $\psi(2S)$ and BES average) as well as the four other results with the smallest errors, indicated as data points.(The height of data point has no meaning here.)

TABLES

TABLE I. The number of fitted events and the mass for individual channels; errors are statistical. Γ is the full width of η_c fixed at the PDG value. σ is the mass resolution given by the Monte Carlo simulation.

Channel	No. of events	mass(MeV)	Γ(MeV)	σ(MeV)
$K^+K^-\pi^+\pi^-$	37.3 ± 13.4	2976.6 ± 6.3	13.2	13.7
$\pi^+\pi^-\pi^+\pi^-$	24.9 ± 11.2	2975.5 ± 7.3	13.2	12.8
$K^\pm K^0_S\pi^\mp \to K^\pm\pi^\mp\pi^+\pi^-$	27.5 ± 10.4	2978.6 ± 5.2	13.2	13.1
$\phi\phi \to K^+K^-K^+K^-$	12.4 ± 3.3	2978.7 ± 6.1	13.2	13.2
$K^+K^-\pi^0$	39.4 ± 15.2	2975.1 ± 9.9	13.2	25.0

TABLE II. Branching ratios for different decay modes; they have been corrected for isospin where necessary.

Decay mode	Branching ratios
$\eta_c \to X$	$B(J/\psi \to \gamma\eta_c, \eta_c \to X) \times 10^{-4}$
$K^+K^-\pi^+\pi^-$	$0.67 \pm 0.24 \pm 0.20$
$\pi^+\pi^-\pi^+\pi^-$	$0.58 \pm 0.26 \pm 0.17$
$K^\pm K^0_S\pi^\mp$	$1.28 \pm 0.48 \pm 0.38$
$\phi\phi$	$0.40 \pm 0.26 \pm 0.12$
$K^+K^-\pi^0$	$1.58 \pm 0.61 \pm 0.55$