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Measurement of the mass and full width of the η_c meson

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In a sample of 7.8 million J/ψ decays collected in the Beijing Spectrometer, the process $J/\psi \rightarrow \gamma\eta_c$ is observed for five different η_c decay channels: $K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^\pm K_S^0\pi^\mp$ (with $K_S^0 \rightarrow \pi^+\pi^-$), $\phi\phi$ (with $\phi \rightarrow K^+K^-$) and $K^+K^-\pi^0$. From these signals, we determine the mass of η_c to be $2976.6 \pm 2.9 \pm 1.3$ MeV. Combining this result with a previously reported result from a similar study using $\psi(2S) \rightarrow \gamma\eta_c$ detected in the same spectrometer gives $m_{\eta_c} = 2976.3 \pm 2.3 \pm 1.2$ MeV. For the combined samples, we obtain $\Gamma_{\eta_c} = 11.0 \pm 8.1 \pm 4.1$ MeV.

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I. INTRODUCTION

A precise knowledge of the mass difference between the $J/\psi(1^{--})$ and $\eta_c(0^{-+})$ charmonium states is useful for the determination of the strength of the spin-spin interaction term in non-relativistic potential models. While the J/ψ mass has been determined with high accuracy (1 part in 10^5) to be 3096.88 ± 0.04 MeV, the mass of the η_c is less well measured. The Particle Data Group (PDG) average of m_{η_c}

$=2979.8\pm 2.1$ MeV is based on experiments using the reactions $e^+e^-\to J/\psi\to\gamma\eta_c$ [1–5], $e^+e^-\to\psi(2S)\to\gamma\eta_c$ [5] and $p\bar{p}\to\gamma\gamma$ [6,7]. These 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 Fermilab experiment E760 [6] disagrees with the result from the DM2 group [1] by almost four standard deviations. Measurements of the full width of the η_c have been made by four groups: E760 reports a result of $\Gamma_{\eta_c}=23.9^{+12.6}_{-7.1}$ MeV [6], which is larger than the results from SPEC ($7.0^{+7.5}_{-7.0}$ MeV) [7], Mark III ($10.1^{+33.0}_{-8.2}$ MeV) [2] and Crystal Ball (11.5 ± 4.5 MeV) [5]. Additional measurements for both m_{η_c} and Γ_{η_c} are needed to improve the situation. An η_c mass value of $m_{\eta_c}=2975.8\pm 3.9\pm 1.2$ MeV was reported earlier by the Beijing Spectrometer (BES) Collaboration based on an analysis of the reaction $\psi(2S)\to\gamma\eta_c$ [8]. In this paper we report a measurement of the mass of the η_c based on a data sample of 7.8 million J/ψ events 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 $\phi\to K^+K^-$) and $K^+K^-\pi^0$ have been used to determine the mass and width of the η_c.

II. BES DETECTOR AND DATA SAMPLE

The Beijing Spectrometer has been described in detail in Ref. [9]. Here we describe briefly those detector elements essential to this measurement. Charged particle tracking is provided by a 10 superlayer main drift chamber (MDC). Each superlayer contains four cylindrical layers of sense wires that measure 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 in GeV/c. The dE/dx resolution is 9% and 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 330 ps for hadrons. Outside of the TOF system is an electromagnetic calorimeter comprised of streamer tubes and lead sheets with a z position resolution of 4 cm. The energy resolution of the shower counter scales as $\sigma_E/E=22\%/\sqrt{E}$, where E is in GeV. Outside the shower counter is a solenoidal magnet that produces a 0.4 T magnetic field.

III. DATA ANALYSIS

The event selection criteria for each channel are described in detail in previous papers [10–12]. Here we repeat only the essential information and emphasize those considerations that are special to the m_{η_c} measurement. Candidates are selected by requiring the correct number of charged track candidates for the given hypothesis. These tracks must be well fit to a helix in the polar angle range $-0.8<\cos\theta<0.8$ and have a transverse momentum above 60 MeV/c. For the four-charged-track channels, at least one photon with energy $E_\gamma>30$ MeV is required in the barrel shower counter; for the $K^+K^-\pi^0$ channel, at least three $E_\gamma>30$ MeV photons are required. Showers that can be associated with charged tracks are not considered. Events are fitted kinematically with four constraints (4C) to the hypotheses: $J/\psi\to\gamma K^+K^-\pi^+\pi^-$, $J/\psi\to\gamma\pi^+\pi^-\pi^+\pi^-$, $J/\psi\to\gamma K^\pm\pi^\mp\pi^+\pi^-$, $J/\psi\to\gamma\gamma\gamma K^+K^-$. A one-constraint (1C) fit is done for the $J/\psi\to\gamma_{miss}K^+K^-K^+K^-$ hypothesis, where γ_{miss} indicates that this photon is not detected. We select those events for each particular channel that have a confidence level greater than 5%. 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 $K^\pm K^0_S\pi^\mp$) and <0.15 GeV (for $\phi\phi$) is imposed to reject events with multiphotons and misidentified charged particles. Here, E_{miss} and P_{miss} are, respectively, the missing energy and missing momentum calculated using the measured quantities for the charged tracks. Another cut on the variable, $P^2_{t\gamma}=4|P_{miss}|^2\sin^2(\theta_{t\gamma}/2)<0.006(\mathrm{GeV}/c)^2$ (for $K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$ and $K^\pm K^0_S\pi^\mp$) is used to reduce the backgrounds from π^0's, where $\theta_{t\gamma}$ is the angle between the missing momentum and the photon direction. For the $K^+K^-\pi^+\pi^-$ 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 with the missing momentum. 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 of $M_{K^0_S}$. 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 30 MeV of the ϕ mass. For the $K^+K^-\pi^0$ channel, at least one of the three $\gamma\gamma$ invariant mass combinations is required to be within 40 MeV of the π^0 mass; for events where this happens for more than one combination, the one with invariant mass closest to the π^0 mass is taken to be the candidate π^0.

IV. MASS AND WIDTH OF THE η_c MESON

Using the event selection criteria described above, we determine the invariant mass spectra for each decay mode shown in Figs. 1(a) to 1(e). The curve in each figure indicates the result of a likelihood fit using a Breit-Wigner line shape convoluted with a Gaussian mass resolution function for the η_c, plus a polynomial function to represent the background. In these fits, the η_c total width is fixed at its PDG central value of $\Gamma=13.2$ MeV, and the resolution at the Monte Carlo determined value. The number of fitted events and the mass of the η_c determined for each of the channels are listed in Table I. The experimental resolution, which varies from channel to channel, is also listed in the table.

Figure 1(f) shows the combined four-charged-track invariant mass distributions in the η_c mass region for the $K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^\pm K^0_S\pi^\mp$ and $\phi\phi$ channels, which are those with similar mass resolution. Here, a likelihood fit using a Γ fixed at the PDG value and a mass resolution (σ) fixed at the value averaged over the four channels ($\sigma_{avg}=13.3$ MeV) gives a total of 100.9 ± 19.8 η_c events and a mass $m_{\eta_c}=2976.7\pm 3.4$ MeV with a $\chi^2/\mathrm{DOF}=14.2/20$, corresponding to a confidence level of 81.9%. If

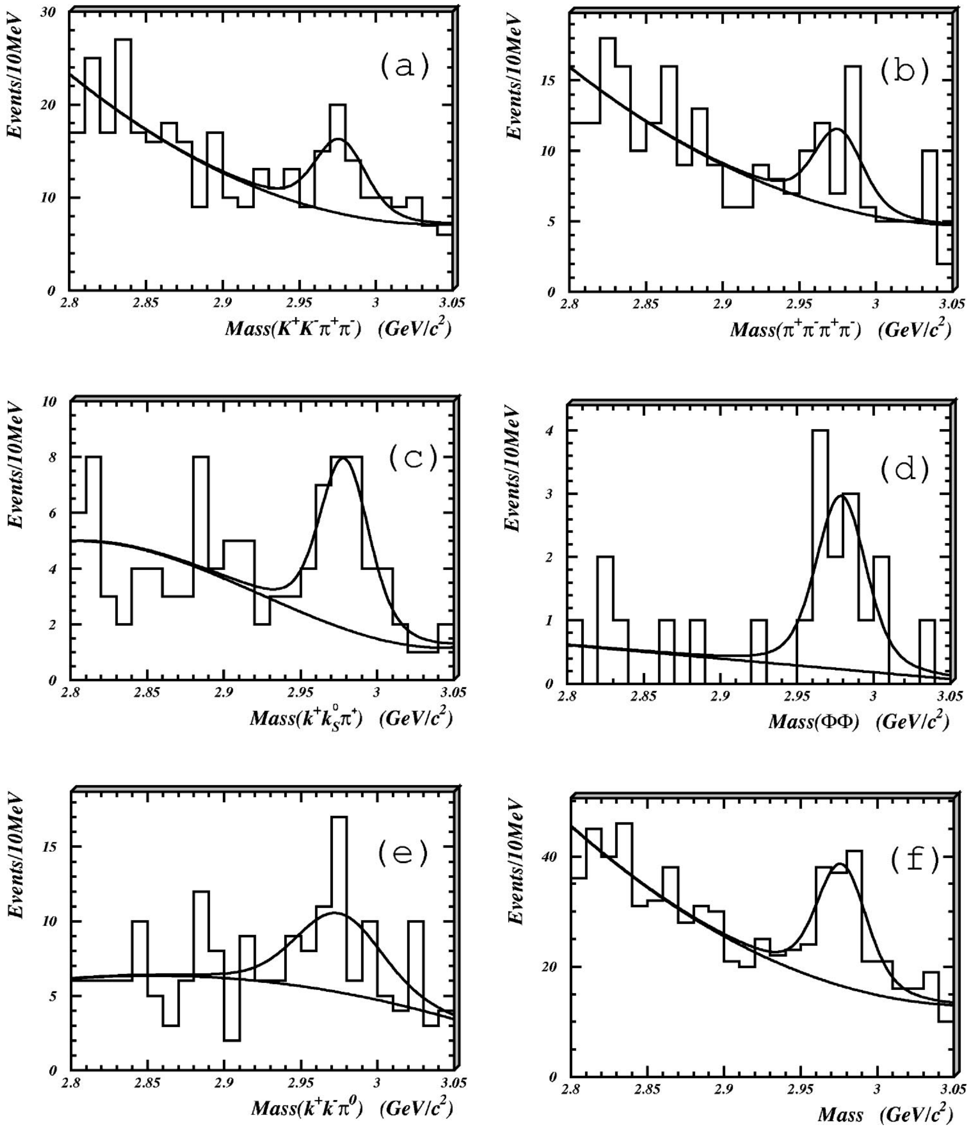

FIG. 1. The (a) $m_{K^+K^-\pi^+\pi^-}$, (b) $m_{\pi^+\pi^-\pi^+\pi^-}$, (c) $m_{K^\pm K_S^0\pi^\mp}$, (d) $m_{\phi\phi}$ and (e) $m_{K^+K^-\pi^0}$ distribution in the η_c region; (f) is the combined four-charged-track mass distribution of (a), (b), (c) and (d).

$\sigma = 13.3$ MeV is fixed and the mass, number of events, and Γ are allowed to float, the resulting mass value and number of events are $m_{\eta_c} = 2976.7 \pm 3.0$ MeV and 91.5 ± 21.2, respectively.

The main systematic errors associated with the m_{η_c} determination arise from the mass-scale calibration, the detection efficiency, and the uncertainties associated with the selection of the cut values. In the case of the $\psi(2S)$ measurement [8], the level of the systematic error on the overall mass scale of BES was estimated as 0.8 MeV by comparing the masses of the χ_{c1} and χ_{c2} charmonium states, detected in the same decay channels, with their PDG values. These masses have been measured in a number of experiments, and the reported values have good internal consistency. Because the energy

TABLE I. The number of fitted events and the mass for individual channels. The errors are statistical. Γ is the full width of the 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
$K^\pm K_S^0\pi^\mp \to K^\pm\pi^\mp\pi^+\pi^-$	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

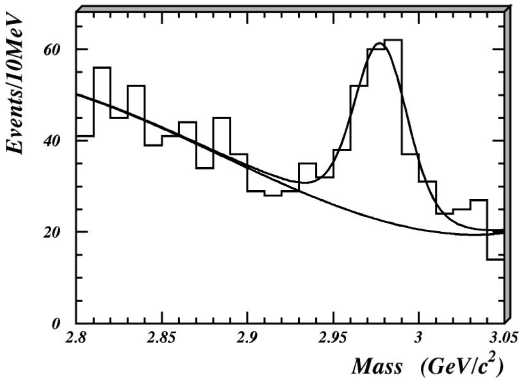

FIG. 2. The combined four-charged-track invariant mass distribution in the η_c region for $J/\psi \to \gamma\eta_c$ (with $\eta_c \to K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^\pm K^0_S\pi^\mp$ and $\phi\phi$) and $\psi(2S) \to \gamma\eta_c$ (with $\eta_c \to K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$,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

resolution for low energy γ of Barrel Shower Counter is poor, the detection efficiency at high mass side of η_c is lower than that at low mass side of η_c. We find that the shift of central value of mass of η_c is less than 0.7 MeV after making the detection efficiency to the mass spectrum. We take this as the systematic error caused by detection efficiency. Systematic errors originating from the cut conditions are mainly from the confidence-level cuts for the constrained kinematic fits and the photon minimum energy requirement. For example, when the accepted confidence level probability is varied between 1% and 10%, the central value of m_{η_c} shifts by 0.7 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 mass resolution and the full width of the η_c are small. When the experimental mass resolution is varied between the extreme values of 11.0 and 15.0 MeV, and the full width is changed from 10.0 to 16.0 MeV, we find that shifts of the mass are less than 0.2 MeV. The systematic error due to the uncertainty in the shape of the background function is small, only 0.1 MeV. The total overall systematic error of this measurement is taken to be 1.3 MeV, the sum in quadrature of all contributions.

Combining the weighted average with the result for the $K^+K^-\pi^0$ decay channel (see Table I), we obtain the result $m_{\eta_c} = 2976.6 \pm 2.9 \pm 1.3$ MeV for the five channels. Combining this result with that from the BES analysis of $\psi(2S) \to \gamma\eta_c$, namely $m_{\eta_c} = 2975.8 \pm 3.9 \pm 1.2$ MeV [8], we obtain a weighted average $m_{\eta_c} = 2976.3 \pm 2.3 \pm 1.2$ MeV. Here, since most of the systematic error in the mass scale is common between the J/ψ and $\psi(2S)$ measurements, we take the systematic error of the combined measurement to be that from the $\psi(2S)$ measurement.

The full width of the η_c was determined from a fit to the combined J/ψ and $\psi(2S)$ event samples. Figure 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 $K^+K^-K^+K^-$). An η_c full width of $\Gamma = 11.0 \pm 8.1$ MeV is given by a likelihood fit performed with the resolution fixed at $\sigma = 13.3$ MeV. This fit gives a total of 168.3 ± 26.8 η_c events with a $\chi^2/\mathrm{DOF} = 15.0/21$, corresponding to a confidence level of 82.1%. The systematic error of the width measurement is 4.1 MeV which includes the sum in quadrature of the uncertainty in the mass resolution σ (2.5 MeV), the uncertainty associated with the choice of selection cuts (2.5 MeV), and the mass dependence of the detection efficiency (2.0 MeV).

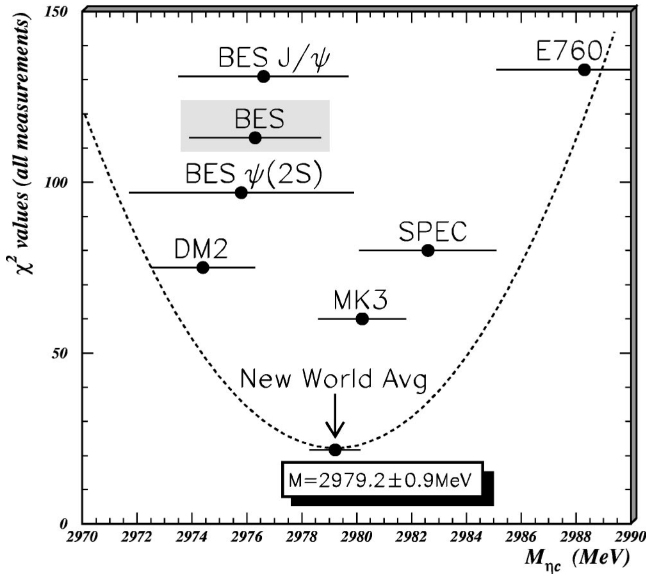

FIG. 3. The curve of χ^2 versus $m_{\eta c}$ for a fit that includes all existing measurements and BES measurements [BES J/ψ and BES $\psi(2S)$]; the BES combined results and the four other results with the smallest errors were indicated as data points. (The height of data point has no meaning here.)

V. SUMMARY

In summary, we have used the BES 7.8 million J/ψ data sample to observe the η_c in five different decay modes and determine the η_c mass to be $2976.6 \pm 2.9 \pm 1.3$ MeV. Combining this result with a prior BES analysis of $\psi(2S) \to \gamma\eta_c$, we find $m_{\eta_c} = 2976.3 \pm 2.3 \pm 1.2$ MeV. Combining the two samples, we also obtain $\Gamma_{\eta_c} = 11.0 \pm 8.1 \pm 4.1$ 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. Figure 3 shows the BES results together with the four previous measurements with the smallest errors. 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, $\chi^2/\mathrm{DOF} = 22.2/8$ occurs at 2979.2 ± 0.9 MeV. The high χ^2 value is predominantly due to the poor agreement between the DM2 and E760 measurements. The two measurements of BES reduce the new world average for the mass by 0.6 MeV.

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