A measurement of the η_c mass and full width

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June 15, 1999

Abstract

Based on 7.8 million J/ψ data collected in the 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 $2976.6\pm2.9\pm1.0$ MeV. To combine the results from BES data analysis of $\psi(2S)\to\gamma\eta_c$, $m_{\eta_c}=2976.3\pm2.3\pm0.8$ MeV and $\Gamma_{\eta_c}=11.0\pm8.1\pm3.5$ MeV are obtained. The results are in good agreement with PDG values. The measurement of branching ratios for five decay modes of η_c have been obtained also.

1 Introduction

For the calculation of the strength of the spin-spin interaction term in non-relativistic potential models it is used to know the precise mass difference between the J/$\psi(1^{--})$ and $\eta_c(0^{-+})$. The mass of J/ψ is well 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_{η_c}=2979.8 ±2.1 MeV is based on previous experiments from different reactions $e^+e^-\to$ J/$\psi\to\gamma\eta_c$ [1, 2, 3, 4], $e^+e^-\to\psi(2s)\to\gamma\eta_c$ [5] and P$\bar{\rm P}\to\gamma\gamma$ [6, 7]. The different measurements have poor internal consistency, 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 deviation. The measurements for full width of Γ_{η_c} have been done by four experiments and the results to be $23.9^{+12.6}_{-7.1}$ 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) were obtained. So additional measurements for both m_{η_c} and Γ_{η_c} are needed to improve the situation. The mass of η_c has been measured by BES collaboration based on 3.79 million ψ(2s) data sample. A result of m_{η_c}=2975.8±3.9±1.4 MeV has been obtained[8]. Here we report a measurement of mass of η_c based on 7.8 million J/ψ data sample collected in the 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.

2 Event Selection

The event selections for each channel are described in detail in previous partial wave analysis memo[9, 10, 11], here we only repeat some information and emphasize some special consideration to the m_{η_c} measurement. We are using event selection for five channels as follows:

- Candidates are selected by requiring exactly 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 $K^+K^-\pi^0$ channel, three photon in the barrel shower counter are required. A minimum energy cut of 30 MeV is imposed on the 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 1C hypothesis: $J/\psi \to \gamma K^+K^-K^+K^-$, requiring that for each particular channel, the confidence level is larger than 5%.

- The transverse momentum of the four charged tracks system with respect to the photon, $P_{tr}^2 < 0.006(GeV/c)^2$, is applied to reduce the backgrounds contain 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 the events with multiphoton 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 $\pi^+\pi^-\pi^+\pi^-$ channel, $|M_{\pi^+\pi^-\pi^0} - M_\omega| > 30$ MeV is required to remove the background from $J/\psi \to \omega\pi^+\pi^-$ and $J/\psi \to \omega K^+K^-$, where π^0 associated to the missing momentum.

- For $K^\pm K_S^0\pi^\mp$(with $K_S^0 \to \pi^+\pi^-$) channel, we performed a cut on the $\pi^+\pi^-$ invariant mass, $|M_{\pi^+\pi^-} - M_{K_S^0}| < 25$ MeV.

- For $\phi\phi$(with $\phi\phi \to K^+K^-K^+K^-$) channel, we used a double cut on the K^+K^- invariant mass $|M_{K^+K^-} - M_\phi| < 30$ MeV.

- For $K^+K^-\pi^0$ channel, at least one of the three $\gamma\gamma$ invariant mass combinations must be lie within 40 MeV of the π^0 mass, the one with invariant mass closest to π^0 mass is assumed from π^0 decay.

3 Monte carlo simulation

Monte carlo simulation for the five channels has been done to test the selection criteria and determine the experimental mass resolution of σ and the reconstruction efficiency of ϵ. The simulated data are subjected to the same reconstruction and selection programs as are used for the real data. The MC results are show in Table 1.

Table 1: MC results of σ and ϵ for different channels

Channel	σ(MeV)	ϵ(%)
$K^+K^-\pi^+\pi^-$	13.7	7.1
$\pi^+\pi^-\pi^+\pi^-$	12.8	5.5
$K^\pm K^0_S\pi^\mp \to K^\pm\pi^\mp\pi^+\pi^-$	13.1	4.0
$\phi\phi \to K^+K^-K^+K^-$	13.2	16.5
$K^+K^-\pi^0$	25.0	3.2

4 Results

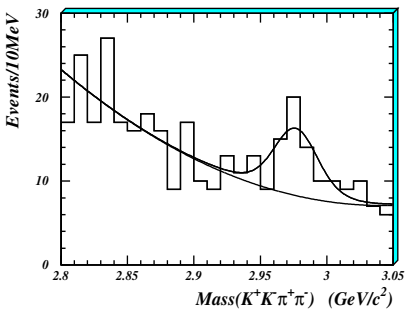
4.1 Mass of η_c

According to the above event selection criteria, we got invariant mass spectra for different decay modes and used a MINUIT Likelihood fit to a Breit-Wigner line shape with Γ(width of η_c) convoluted with a Gaussian with σ(mass resolution) plus a polynomial. Invariant mass distributions for the individual channels in the η_c region are show in Fig. 1(a) to 1(e). The fit values of number of events, mass of η_c for the individual channels are listed in Table 2.

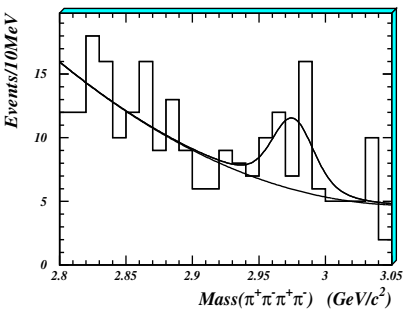
Table 2: The fit values of number of events and mass for the individual channels(errors are statistical). Γ is full width of η_c fixed at the PDG value. σ is mass resolution given by monte carlo simulation.

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

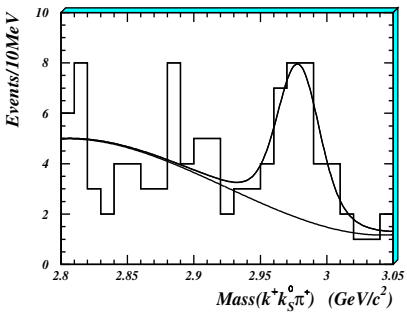
Fig. 1(f) shows the combined four-charged-track invariant mass distribution in the η_c mass region for $K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^\pm K^0_S\pi^\mp$ and $\phi\phi$ channels with closed σ. $m_{\eta_c} = 2976.7\pm3.4$ MeV is obtained by a Minuit Likelihood fit with fixing σ and Γ. It gives a total of 100.9 ± 19.8 events and has a χ^2/dof=14.2/20 with corresponds to a confidence level of



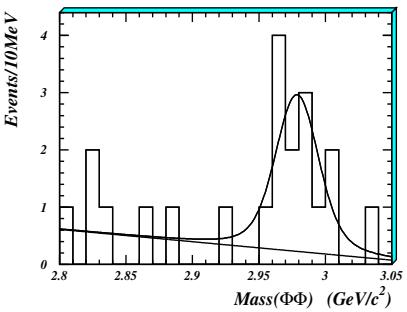
(a) $m_{K^+K^-\pi^+\pi^-}$ distribution



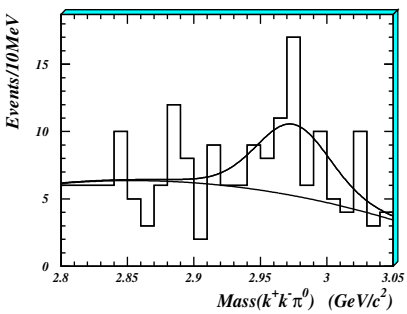
(b) $m_{\pi^+\pi^-\pi^+\pi^-}$ distribution



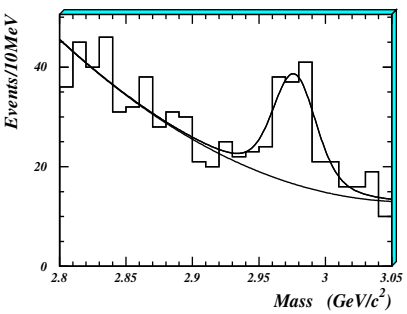
(c) $m_{K^\pm K^0_S\pi^\mp}$ distribution



(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)

Figure 1: Invariant mass distributions in the η_c region

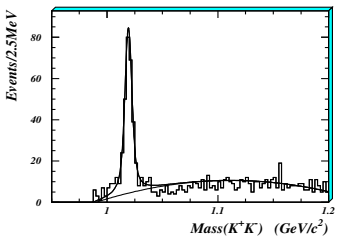
81.9%. If σ=13.3 MeV is fixed, mass, number of events and Γ are floated, m_{η_c}=2976.7±3.0 MeV is obtained.

To change the values of mass resolution σ and width Γ, we found the shifts of central value of mass are less than 0.2 MeV(see Table 3).

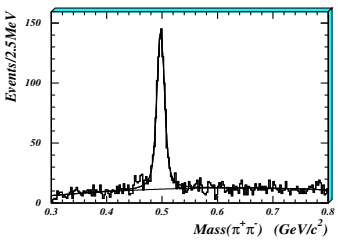
Table 3: The value of mass is not sensitive with the changes of σ and Γ

Γ(MeV)	13.2	13.2	13.2	13.2
σ(MeV)	12.0	13.0	13.3	15.0
M(MeV)	2976.6±3.2	2976.7±3.3	2976.7±3.4	2976.7±3.6
σ(MeV)	in the ranges of 11 - 14 MeV			
Γ(MeV)	10	13	14	16
M(MeV)	2976.7±3.1	2976.6±3.2	2976.6±3.1	2976.6±3.1

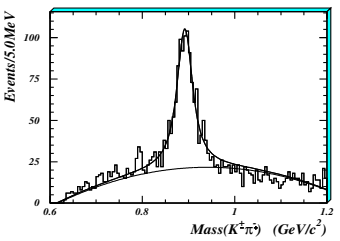
For checking mass(energy) calibration, K^o_s, ϕ and K^* peak are shown in Fig. 2(b) to 2(c).



(a) ϕ peak position



(b) K^o_s peak position



(c) K^* peak position

Figure 2: K^o_s, ϕ and K^* peak position

All of the masses consist with PDG values very well within one standard deviation. For example, Fig. 2(a) gives mass of $\phi = 1019.3 \pm 0.3$ MeV with good agreement of PDG value of 1019.413 ± 0.008 MeV. We estimate the systematic error for calibration is about 0.3

MeV. The main contribution of systematic error of the mass measurement originate from the cut condition uncertainties. 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 photon is changed from 30 MeV to 50 MeV, the central value of m_{η_c} shifts by 0.2 MeV. The overall systematic error of this measurement is then estimated as 1.0 MeV.

To take weighted average with the result from decay channel of $K^+K^-\pi^0$(see Table 2), we get m_{η_c}=2976.6$\pm$2.9 $\pm$ 1.0 MeV for five channels. To combine the result from BES data analysis of $\psi(2S) \to \gamma\eta_c$: $m_{\eta_c} = 2975.8 \pm 3.9 \pm 1.4$MeV[8], a weighted average $m_{\eta_c} = 2976.3 \pm 2.3 \pm 0.8$MeV is obtained.

4.2 Width of η_c

We combined the events got from J/ψ and $\psi(2S)$ and used a Breit-Wigner fit to get width. Fig. 3 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 with fixing σ of 13.3 MeV. It gives a total of 168.3 ± 26.8 events and has a χ^2/dof=15.0/21 with 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 condition (2.5 MeV).

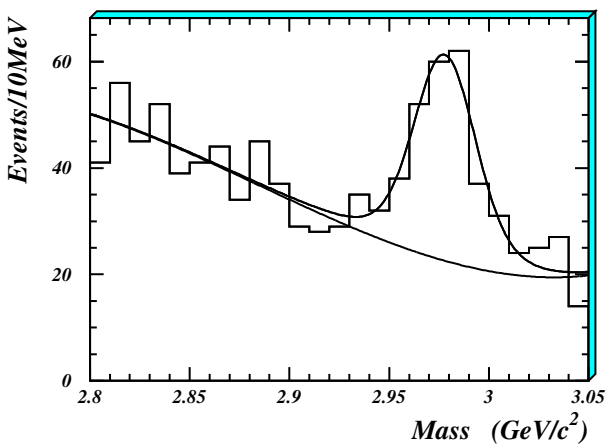


Figure 3: The combined four-charged-track invariant mass distribution in the η_c region for $J/\psi \to \gamma\eta_c$ (with $\eta_c \to K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^\pm K^0_S\pi^\mp$ and $\phi\phi$) and $\psi(2S) \to \gamma\eta_c$ (with $\eta_c \to K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^\pm K^0_S\pi^\mp$ and $K^+K^-K^+K^-$).

4.3 Branching ratios

Table 4 shows branching ratios of five different decay modes. The main contribution of systematic error is from the uncertainty of total number of J/ψ events and the main cuts criteria.

Table 4: Branching ratios for different decay modes and have been corrected for isospin where necessary.

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

5 Summary and Discussion

Based on 7.8 million J/ψ data of BES, we 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 $\pm$ 1.0 MeV. To combine the result from BES data analysis of $\psi(2S) \to \gamma\eta_c$, $m_{\eta_c} = 2976.3 \pm 2.3 \pm 0.8$ MeV is obtained. The result is in good agreement with PDG value of 2979.8$\pm$2.1 MeV, but 3.8σ below the E760 result of $2988.3^{+3.3}_{-3.1}$ MeV. Fig. 4 shows the results of this measurement and BES ψ(2s) measurement together with the four previous measurement that have the smallest error.

The curve in Fig. 4 indicates the values of χ^2 versus m_{η_c} for a fit that includes all existing measurements. The minimum value χ^2/dof=22.2/8 occurs at 2979.2$\pm$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 will make new world average mass 0.6 MeV down.

We have measured the full width of η_c to be $\Gamma = 11.0 \pm 8.1 \pm 3.5$ MeV. 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].

6 Acknowledgements

The BES collaboration acknowledges financial support from the Chinese Academy of Sciences, National Natural Science Foundation of China and the U.S. Department of Energy and thanks the staff of BEPC for the efforts of operation. We thank prof. S.L. Olsen, Prof. F. Harris and Prof. S.F. Tuan for useful suggestion and discussion. We acknowledge Prof. D.V. Bugg and Prof. B.S. Zou for the helpful suggestion on event selection.

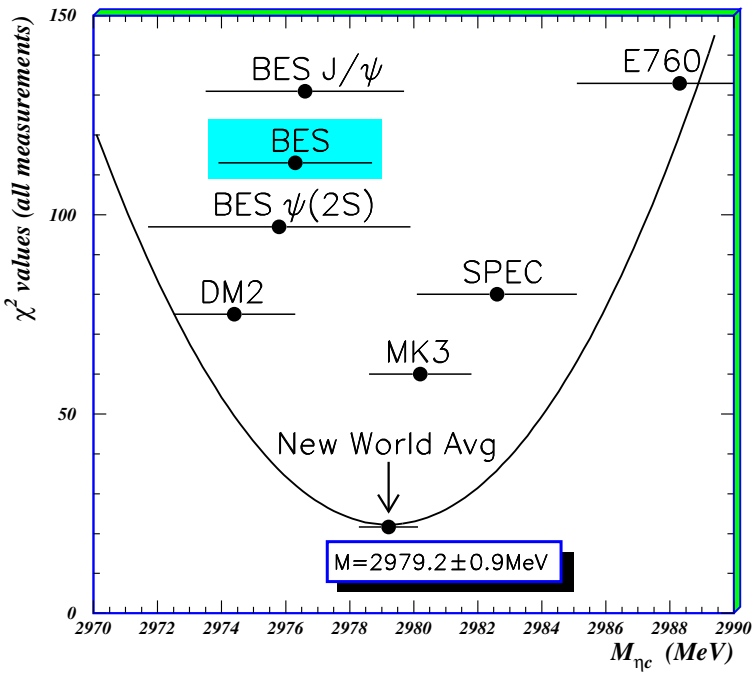


Figure 4: The curve of χ^2 versus $m_{\eta c}$ for a fit that includes all existing measurements and BES measurements (BES $J\psi$, BES $\psi(2S)$ and BES average) as well as the four other results with the smallest errors are indicated as data points.(The height of data point is no meaningful.)

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