BES Analysis Memo
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A measurement of the η_c mass

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-ABSTRACT-

Reactions of the type $\psi(2S) \to \gamma\eta_c$, where the η_c decays to four charged hadrons, are used to determine the mass of the η_c meson to be $M_{\eta_c} = 2975.8 \pm 3.9 \pm 1.4$ MeV. The result is substantially lower than a E760 result based on measurements of $p\overline{p} \to \gamma\gamma$ but in good agreement with recent precision measurement from DM2 based on the reaction $J/\psi \to \gamma\eta_c$.

1 Introduction

The mass difference between the J/ψ and η_c charmonium states is used to determine the strength of the spin-spin interaction term in non-relativistic potential models. The J/ψ mass is well determined from $p\overline{p} \to J/\psi \to e^+e^-$ formation experiments to be $M_{J/\psi} = 3096.88 \pm 0.04$ MeV [1]. In contrast, the η_c mass is less well measured. The Particle Data Group (PDG) [2] average of $M_{\eta_c} = 2979.8 \pm 2.1$ MeV is based on measurements using the reactions $p\overline{p} \to \gamma\gamma$ [3, 4], $e^+e^- \to J/\psi \to \gamma\eta_c$ [5, 6, 7, 8, 9] and $e^+e^- \to \psi(2S) \to \gamma\eta_c$ [8]. The different meassurements have poor internal consistency; the PDG fit to the measurements has a confidence level of only 0.001. The most recent $p\overline{p} \to \gamma\gamma$ measurement from Fermilab experiment E760 [3] disagrees with the most recent $J/\psi \to \gamma\eta_c$ result from DM2 [5] by almost four standard deviations. Additional measurements are needed to clarify the situation.

Here I report a measurement of M_{η_c} using the reaction $e^+e^- \to \psi(2S) \to \gamma\eta_c$. The sample of 3.79M $e^+e^- \to \psi(2S)$ events collected in the BES detector is used for the measurement. I consider the decays $\eta_c \to \pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-K^+K^-$, $K^+K^-K^+K^-$ and $K_sK^\pm\pi^\mp$.

2 Event selection

The event selection and the channel by channel results are described in detail in a previous analysis memo [10]. Here I repeat information relevant to the M_{η_c} measurement.

I use all of the ψ_{2S} events on the four-prong data summary tapes with four charged tracks with net charge zero and at least one γ in the polar angle region $|\cos\theta| < 0.8$. I reject events where both the highest momentum positive and negative tracks are identified as muons or where both tracks have $E_{BHC} > 0.8$ GeV. Only those γ's with opening angles relative to each of the charged tracks in the event of 18^0 or more are considered. The events are subjected to four-constraint kinematic fits to the hypotheses $\psi_{2S} \to \gamma K^+K^-K^+K^-$, $\psi_{2S} \to \gamma\pi^+\pi^-K^+K^-$, $\psi_{2S} \to \gamma\pi^+\pi^-\pi^+\pi^-$, and $\psi_{2S} \to \gamma K^{\pm}\pi^{\mp}K_s$; $K_s \to \pi^+\pi^-$. In the case of events with more than one accepted gamma-ray candidate, the fits are applied for each gamma candidate and the one that gives the best fit is chosen. For the $\gamma K^{\pm}\pi^{\mp}K_s$ mode, the $K_s \to \pi^+\pi^-$ track candidates are required to pass the KLAMSLOW secondary vertexing routine and the K_s invariant mass is included in the kinematic fit as a fifth constraint.

For each particular channel, the confidence level of the kinematic fit is required to be larger than 0.05 and also larger than that the confidence level for the fit to any of the other considered modes. I reject events where the mass recoiling against any $\pi^+\pi^-$ pair is within ± 50 MeV of $M_{J/\psi}$. For the $\pi^+\pi^-\pi^+\pi^-$ ($\pi^+\pi^-K^+K^-$) mode I reject events where the $\pi^+\pi^-$ pairs have (pair has) an invariant mass within ± 20 MeV of M_{K_s}. For the $K^{\pm}K_s\pi^{\mp}$ mode I require a good vertex fit from KLAMSLOW with $c\tau > 5.0$ mm. Backgrounds to this channel from misidentified $\psi(2S) \to \gamma K_sK_s$ decays are eliminated by requiring $M_{K^{\pm}\pi^{\mp}} > 0.85$GeV. I use the dE/dx and TOF routines developed by Dunwoodie and Li [11] to compute combined, four-track particle i.d. confidence levels for each event hypothesis. For each decay channel, I require the confidence level for the dE/dx *or* the TOF systems to be greater than 0.05.

Monte Carlo simulations of the four different decay channel is used to test the selection criteria and determine the experimental resolution. For each channel I generated 10,000 η_c's with a mass of 2980 MeV and total width of 0.1 MeV (i.e. negligibly small). The simulated data are subjected to the same reconstruction and selection programs as are used for the real data. The result is an η_c peak with an rms widths ranging from 13 MeV for $K^{\pm}\pi^{\mp}K^0$ channel to 17 MeV for the $\pi^+\pi^-K^+K^-$ and masses that are in good agreement with the input. The combined MC results for the $\pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-K^+K^-$, $K^+K^-K^+K^-$ and $K^{\pm}\pi^{\mp}K^0$ channels with relative weights of 1.0:1.0:0.1:0.1, respectively (this choice roughly reflects the contribution of each channel to the η_c signal, see Fig. 1 below) has an η_c peak with width of $\sigma = 13.3$ MeV. The efficiency for reconstructing simulated $\eta_c \to \pi^+\pi^-\pi^+\pi^-$ events as $\pi^+\pi^-K^+K^-$ is only $0.3\pm0.1\%$, which is less than 2% of that for $\pi^+\pi^-\pi^+\pi^-$. I conclude that crosstalk effects between channels are negligible.

A summary of the number of the real data events that pass each selection criterion for each mode is listed in Table 1. Invariant mass plots for the individual channels in the η_c region are shown in Fig. 1.

Table 1: A tabulation of the $\psi_{2S} \to \gamma h^+h^-h^+h^-$ selection cuts.

	The number of events surviving each requirement			
Requirement	$K^+K^-K^+K^-$	$\pi^+\pi^-K^+K^-$	$\pi^+\pi^-\pi^+\pi^-$	$K^\pm K_s\pi^\mp$
4 chrgd trks				
$\sum q = 0$				
$N_\gamma \geq 1$	820256			
$N_\mu < 2$	808334			
$N_{e^+,e^-} < 2$	780888			
$\lvert\cos\theta_{trk}\rvert < 0.8$	545920			
$\theta_{\gamma-trk} > 18^0$	530147			
$\lvert\cos\theta_\gamma\rvert < 0.8$				
χ^2 cuts (see text)	2746	7186	5820	1365
$\lvert M_{\pi\pi}^{recoil} - M_{J/\psi}\rvert > 0.05$ GeV	-	5938	3495	932
$\lvert M_{\pi\pi} - M_{K_s}\rvert > 0.02$ GeV	-	5618	3007	-
$K_s \to \pi^+\pi^-$ cuts	-	-	-	363
$M_{K^\pm\pi^\mp} > 0.85$GeV	-	-	-	289
Particle id cuts	217	1736	2618	173

3 Results

Figure 2 shows a semilog plot of the combined four-charged-track invariant mass distribution for the four modes considered. Superimposed on the plot are resolution-broadened Breit Wigner line shapes to represent the η_c and the three ^3P χ_c states,

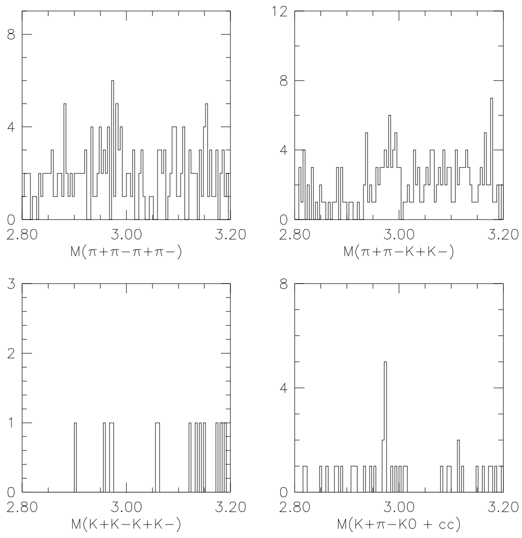

Figure 1: Invariant mass plots in the η_c region for each of the four channels considered.

with masses and total widths fixed at the PDG values. There is a clear signal for the η_c, corresponding to about 60 events.

Figure 3 shows the combined invariant mass distribution in the η_c region with an expanded mass scale (0.004 GeV bins). Superimposed on the plot is a fit to the spectrum using a resolution-smeared Breit-Wigner line shape with total width fixed at the PDG value of $\Gamma_{\eta_c} = 13.2$ MeV plus a fourth-order polynomial function to represent the background. The fit gives a total of 63.5 ± 14.4 events in the peak and has a $\chi^2/dof = 97.4/92$, which corresponds to a confidence level of 27.9%. (A fit with only the background function and no η_c has a confidence level of 0.8%.) The mass value from the fit is $M_{\eta_c} = 2975.4 \pm 4.0$ MeV.

3.1 Systematics

The masses of the three ^3P charmonium states are measured in a number of experiments and the reported values have good internal consistency. I use these to estimate the level of any systematic error on the overall mass scale by comparing the results from similar

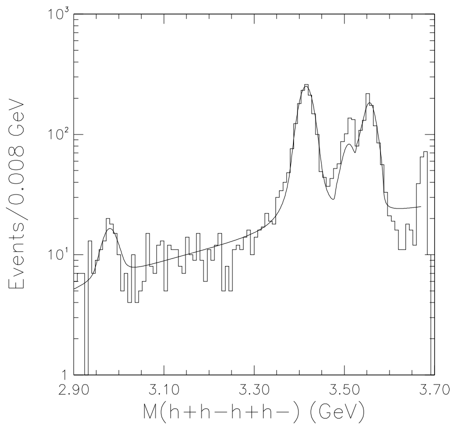

Figure 2: The four charged track invariant mass distribution for selected events. The superimposed curve includes resolution-broadened resonance functions with the PDG parameters for the η_c, χ_{c0}, χ_{c1} and χ_{c2}.

fits for the three χ_c masses with their PDG values. The results, listed in Table 2, show good agreement between this measurement and the PDG values. I Take the rms value of the differences, namely 1.0 MeV, as the systematic error on the mass scale.

Table 2: A comparison of the measured $\chi_{c0,1,2}$ masses with their PDG values. All masses are in units of MeV.

	χ_{c0}	χ_{c1}	χ_{c2}
N_{evts}:	1447 ± 48	482 ± 30	787 ± 35
This expt:	3413.5 ± 0.7	3511.0 ± 1.1	3556.8 ± 0.7
PDG:	3415.0 ± 1.0	3510.5 ± 0.1	3556.2 ± 0.1
This expt-PDG:	-1.5 ± 1.2	0.5 ± 1.1	0.6 ± 0.7

The fit in Fig. 3 keeps the mass resolution fixed at the Monte Carlo determined value of $\sigma_{res} = 13.3$ MeV and Γ_{η_c} fixed at the PDG value of $\Gamma_{\eta_c}^{PDG} = 13.2$ MeV. In Table 3, I list the values of M_{η_c} that result from using different values for the mass resolution, with the full width fixed at 13.2 MeV and for full width values of $\Gamma_{\eta_c} = \Gamma_{\eta_c}^{PDG} \pm \sigma$, with the resolution fixed at 13.3 MeV. There is not much change in the central value

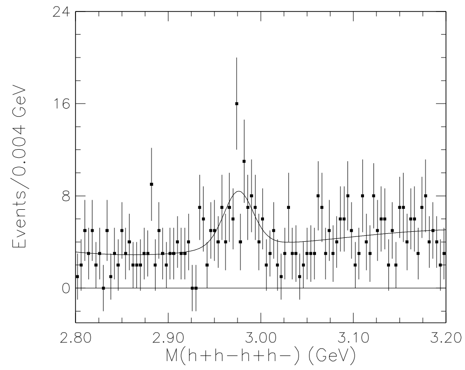

Figure 3: The four charged track invariant mass distribution for selected events in the η_c mass region. The superimposed curves are the results of a fit using a resolution-broadened Breit-Wigner line shape for the η_c and a fourth order polynomial to represent the background.

for $\pm 1\sigma$ shifts in the value used for Γ_{η_c}. When the experimental resolution is varied between the extreme values of 12.5 and 17.5 MeV, the central value of M_{η_c} shifts by 1.9 MeV. I take half of this difference, 0.95 MeV as the systematic error associated with uncertainties in the experimental resolution and the full with of the η_c.

For the total systematic error, I use the quadrature sum of the errors associated with the mass scale and the value of the mass resolution.

4 Summary

In Fig. 4, I show the results of this measurement,

$$M_{\eta_c} = 2975.8 \pm 3.9 \pm 1.4 \text{ MeV}, \tag{1}$$

together with the four previous measurements that have the smallest errors. The new BES result is in good agreement with the recent precision measurement from DM2 of $M_{\eta_c} = 2974.4 \pm 1.9$ MeV [5], but 2.4σ below the E760 result of $M_{\eta_c} = 2988.3^{+3.3}_{-3.1}$ MeV [3]. 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 $\chi^2/dof = 23.5/8$ occurs

Table 3: The variation of M_{eta_c} values for different assumptions for the experimental mass resolution and Γ_{η_c}.

$\sigma_{\rm res}$ (MeV)	M_{η_c} (MeV)
10.0	2977.2 ± 3.2
12.5	2976.3 ± 3.7
13.3	2975.8 ± 3.9
15.0	2975.4 ± 4.2
17.5	2974.4 ± 4.7
20.0	2973.8 ± 4.4
Γ_{η_c} (MeV)	
17.0	2975.8 ± 4.0
10.0	2976.3 ± 3.5

at 2979.36 ± 0.96 MeV. The high χ^2 value is predominantly due to the poor agreement between the DM2 and E760 measurements. If either measurement is omitted the χ^2 values become more reasonable. (Eliminating any other individual measurement does not have much of an effect on the χ^2 value.) The situation is summarized in Table 4.

Table 4: The results of averaging existing measurements of M_{η_c}, including the one reported here. The results for the cases where the DM2 and E760 measurements are removed from the average are also shown. All masses are in units of MeV.

	M_{η_c}	χ^2/dof
All expts	2979.38 ± 0.96	23.3/8
E760 omitted	2978.50 ± 1.01	14.8/7
DM2 omitted	2981.11 ± 1.12	14.1/7

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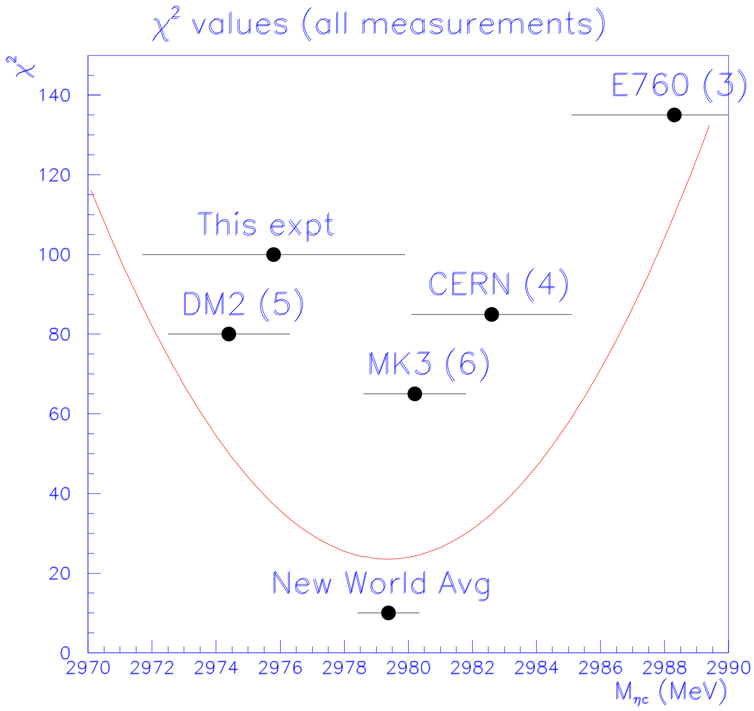

Figure 4: The smooth curve shows the variation of χ^2 versus M_{η_c} from averaging all available measurements. The measurement described here as well as the four other results with the smallest errors are indicated as data points.

References

[1] T.A. Armstrong *et al.* (E760), Phys. Rev. **D47**, 772 (1993).

[2] R.M. Barnett *et al.* (PDG), Phys. Rev. **D54**, 1 (1996).

[3] T.A. Armstrong *et al.* (E760), Phys. Rev. **D52**, 4839 (1995).

[4] C. Bagelin *et al.* , Phys. Lett. **B231**, 557 (1989).

[5] D. Bisello *et al.* (DM2), Nucl. Phys. **B350**, 1 (1991).

[6] R.M. Baltrusaitis *et al.* (Mark3), Phys. Rev. **D33**, 629 (1986). This paper reports an average of mass values determined from a number of different η_c decay modes, including the result for $\eta_c \to \phi\phi$ from R.M. Baltrusaitis *et al.* (Mark3), Phys. Rev. Lett. **52**, 2126 (1984).

[7] J.Z. Bai *et al.* (Mark3), Phys. Rev. Lett. **65**, 1309 (1990).

[8] J.E. Gaiser *et al.* (Crystal Ball), Phys. Rev. **D34**, 711 (1986). The result from this paper supercedes that of R. Partridge *et al.* (Crystal Ball), Phys. Rev. Lett. **45**, 1150 (1980), which reported an η_c mass based on a fraction of the total Crystal Ball data set.

[9] T.M. Himmel *et al.* (Mark2), Phys. Rev. Lett. **45**, 1146 (1980).

[10] S.L. Olsen, *Study of $\psi_{2S} \rightarrow \gamma\ +\ 4$ charged tracks*, BES analysis note, April 1997. Available from http://www.phys.hawaii.edu/besec/slo.html.

[11] X.H. Li and W.M. Dunwoodie, private communication.