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Measurement of the resonance parameters of the charmonium ground state, $\eta_c(1^1S_0)$

Fermilab E835 Collaboration

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Abstract

The resonance parameters of the charmonium ground state, $\eta_c(1^1S_0)$, have been measured by means of the reaction $\bar{p}p \to \eta_c \to \gamma\gamma$. The mass and total width are determined to be $2984.1 \pm 2.1 \pm 1.0$ MeV/c^2 and $20.4^{+7.7}_{-6.7} \pm 2.0$ MeV, respectively. The product of branching ratios $B(\bar{p}p \to \eta_c)B(\eta_c \to \gamma\gamma)$ is determined to be $(22.4^{+3.8}_{-3.7} \pm 2.0) \times 10^{-8}$, from which $B(\eta_c \to \gamma\gamma) = (1.87^{+0.32+0.95}_{-0.31-0.50}) \times 10^{-4}$, and $\Gamma(\eta_c \to \gamma\gamma) = 3.8^{+1.1+1.9}_{-1.0-1.0}$ keV are derived using $B(\eta_c \to \bar{p}p) = (12 \pm 4) \times 10^{-4}$ from the literature.

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The $\eta_c(1^1S_0)$ state of charmonium, occupies a special place in the study of heavy quarkonia. It is the only ground state of a heavy quarkonium system which has been experimentally identified and it is the only confirmed heavy quarkonium singlet state. Knowledge of the parameters of the η_c is important for the understanding and testing of models of QCD [1–3].

The η_c, however, presents a challenge to experiment. It cannot be formed directly in e^+e^- annihilation and its indirect production via M1 radiative decay of J/ψ and ψ' leads to small branching ratios. The η_c can be produced exclusively in photon–photon fusion and inclusively in decays of B mesons; the large luminosities available at the B factories make this a promising approach. At present, however, the uncertainties in η_c resonance parameters remain large [4] and even with improved statistics, the above techniques depend critically on detailed understanding of the calibration and resolution of the final state detector.

Our experiment was designed to study charmonium resonances by their direct formation in proton–antiproton annihilation. The mass and width of the charmonium state are determined from the resonance excitation curve obtained by varying the energy of the antiproton beam and measuring the resonance cross section at different values of the proton–antiproton center-of-mass energy. With this technique, the systematic uncertainties in the mass and width measurements are much reduced since they depend only on the knowledge of the antiproton beam momentum and its momentum spread.

To obtain a clear signal for charmonium formation in the presence of the large $\bar{p}p$ inelastic cross section we concentrate on charmonium decays to electromagnetic final states. In this Letter we present the results of our study of the reaction:

$$\bar{p}p \to \eta_c \to \gamma\gamma \qquad (1)$$

made during the 1996–1997 run of the Fermilab experiment E835. The measurements reported here were made with a total luminosity of 18.9 pb^{-1}, a factor five larger than in our earlier measurement [5], and they result in significant improvements in the precision of the mass, width, and product of branching ratios.

The experimental technique and the apparatus used for the present measurements were the same as in [6]. The experiment was located in the AP-50 straight section of the Fermilab antiproton accumulator. A stochastically cooled beam of antiprotons circulating in the accumulator intersected a hydrogen gas jet target, producing an instantaneous luminosity of $\approx 10^{31}$ $\text{cm}^{-2}\,\text{s}^{-1}$ and an interaction region of $(6\ \text{mm})^3$. The spread (r.m.s.) of the $\bar{p}p$ center-of-mass energy was typically 0.3 MeV. The detector system was optimized for the identification and measurement of electrons (positrons) and photons; we mention only the relevant features here. Photons were measured in the central calorimeter which covered the full azimuth and from 12° to 70° in polar angle (θ). The calorimeter consisted of 1280 lead-glass Čerenkov counters arranged in a pointing geometry; each counter was equipped with an ADC and a TDC. The luminosity was measured by counting recoil protons from elastic $\bar{p}p$ scattering in three solid state detectors located at 87.5° to the beam.

The hardware trigger for these data accepted events in which either the total energy deposited in the central calorimeter was > 80% of the total energy or there were two localized energy deposits in the calorimeter with invariant mass corresponding to > 60% of the center-of-mass energy. Events with charged particles were vetoed by three sets of scintillator hodoscopes. A fast software filter reconstructed energy clusters in the calorimeter and all events which contained any pair of clusters with an invariant mass > 2.5 GeV/c^2 or where more than 90% of the initial state energy was deposited in the calorimeter were written to tape.

The method of shower reconstruction in the offline analysis has been described previously [6]. Energy clusters were characterized by a seed of minimum energy of 5 MeV and a minimum total energy of 20 MeV in the 3×3 matrix of counters centered on the seed. Energy clusters due to overlapping showers—as produced by photons from symmetric π^0 decay—were distinguished from clusters due to isolated photons by the transverse shape of the energy deposition [5]. Given the threshold for the signal to the TDC, the efficiency for timing information varied from 30% for 25 MeV clusters to 100% for clusters above 80 MeV. Clusters in the appropriate time win-

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dow (±10 ns) were labelled 'in-time'; clusters with no timing information were labelled 'undetermined'.

Events were accepted as candidates for the reaction $\bar{p}p \to \gamma\gamma$ if:

- they contained exactly 2 'in-time' photons;
- the invariant mass of these photons exceeded 2.5 GeV/c^2;
- the nominal Confidence Level (CL) of a fit to the reaction $\bar{p}p \to \gamma\gamma$ was $> 5\%$.

These requirements accept events with any number of out-of-time or 'undetermined' photons in order to avoid rejecting genuine signal because of clusters from accidental events. Since, however, $\pi^0\pi^0$ and $\pi^0\gamma$ final states are the dominant background, events in which the invariant mass of any pair of photons fell within the π^0 mass window (135 ± 35 MeV/c^2) were rejected.

To obtain cross sections, corrections were made for acceptance, for accidental vetoing in the trigger, and for the efficiency of the analysis. The CL cut efficiency was determined from a study of $\bar{p}p \to J/\psi \to e^+e^-$ data. Efficiencies that varied with luminosity and the state of the apparatus were found for each data set by superimposing Monte Carlo $\bar{p}p \to \gamma\gamma$ events on data events taken with a randomly timed trigger [7,8]. The average overall trigger and analysis efficiency was 70%.

The event sample selected contains not only the events from reaction (1), but also events from any $\bar{p}p \to \gamma\gamma$ continuum and a considerable remaining background from $\bar{p}p \to \pi^0\gamma$, and $\bar{p}p \to \pi^0\pi^0$ events where the π^0's decayed asymmetrically and the low energy daughter photons were undetected because they fell outside the acceptance or below the energy threshold of the calorimeter. This feed-down background is calculated directly and with good statistical accuracy using as input the $\bar{p}p \to \pi^0\pi^0$ and $\bar{p}p \to \pi^0\gamma$ cross sections determined simultaneously with these data [5–7]. The efficiency for identifying a π^0 was 96.8% giving a background level of 0.1% of the $\pi^0\pi^0$ cross section and 3.2% of the $\pi^0\gamma$ cross section. In practice, the $\pi^0\gamma$ final state accounts for about 75% of the feed-down background.

Fig. 1 shows the angular distribution of the data and the predicted feed-down background at $\sqrt{s} =$ 2990 MeV as a function of $\cos(\theta_{cm})$, the angle of the photons in the $\bar{p}p$ center-of-mass.

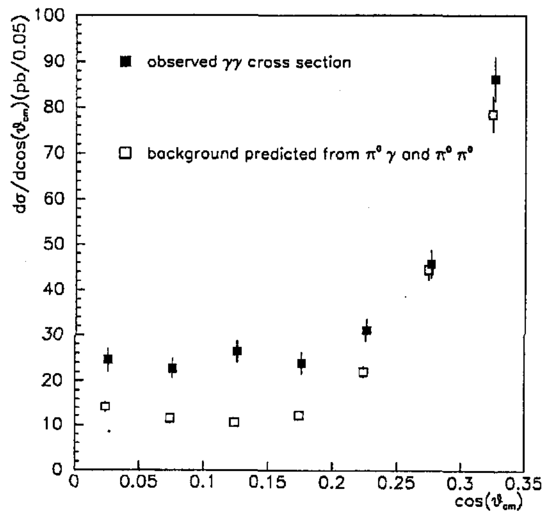

Fig. 1. Angular distribution of cross sections around $\sqrt{s} = 2990$ MeV. The solid squares are the measured cross sections; the open squares are the calculated feed-down cross sections (see text).

The signal from the decay of a $J = 0$ state is constant in $\cos(\theta_{cm})$. The rapid increase in background starting above $\cos(\theta_{cm}) = 0.2$ leads to the acceptance restriction in the analysis.

Fig. 2 shows the cross section for candidates for the reaction $\bar{p}p \to \gamma\gamma$ together with the predicted feed-down cross section for $\cos(\theta_{cm}) < 0.20$ as a function of $\sqrt{s}$. The measured cross sections (solid circles) show a clear resonance signal above a large background which is predominantly due to the feed-down. The figure contains 800 events in the resonance region, $2955 < \sqrt{s}$ (MeV) < 3010, of which about 190 are signal.

We have fit the data of Fig. 2 as the sum of a resonance and a background. The resonance is described by a Breit–Wigner form

$$\sigma_R(s) \equiv \frac{4\pi(\hbar c)^2}{(s - 4m_p^2c^4)} \frac{B_{\text{in}}B_{\text{out}}}{1 + [2(\sqrt{s} - M_R c^2)/\Gamma_R]^2}$$

characterized by a mass M_R, a width Γ_R, and a peak value proportional to the product of $B_{\text{in}} \equiv B(\eta_c \to \bar{p}p)$ and $B_{\text{out}} \equiv B(\eta_c \to \gamma\gamma)$.

Given the small amount of data outside the resonance region, we have used the calculated feed-down cross section to determine the form of the background. We find that the feed-down is well described by a

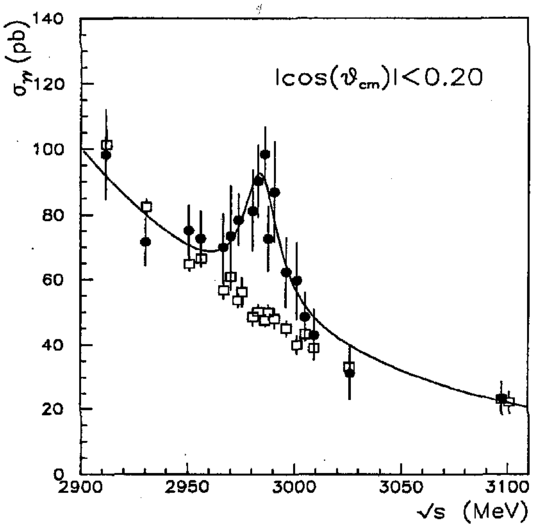

Fig. 2. Measured $\gamma\gamma$ cross sections for $\cos(\theta_{cm})_{max} = 0.20$ (solid circles). The open squares are the calculated feed-down cross section. The curve represents the best fit to a Breit–Wigner resonance on a power law background (see text).

power law characterized by a normalization A and an exponent B,

$$\sigma_{bkgd}(s) = A\left(\frac{2984}{\sqrt{s}\ (\text{MeV})}\right)^{B},$$

and use this form for the background.

We have explored fits to the data using values for the background parameters directly from the feed-down calculation, allowing the background normalization to be a free parameter keeping the exponent fixed to the feed-down value, and allowing both the normalization and the exponent to be free parameters. The resonance parameters from all these fits are in excellent agreement, the only difference being a small increase in the statistical uncertainties. Significantly, the ratio of the free normalization parameter A to the feed-down value was found to be 0.99 ± 0.05. This implies that the continuum $\bar{p}p \to \gamma\gamma$ cross section for $\cos(\theta_{cm}) < 0.20$ is less than 4 pb at $\sqrt{s}$ of 2984 MeV, a lower limit than can be inferred from $\gamma\gamma \to \bar{p}p$ experiments [9,10].

The uncertainties due to the event selection, from the choice of angular range and from the background treatment have been estimated by varying the cuts and the acceptance; the associated systematic errors are ± 1 MeV/c^2 in M_R, ± 2 MeV in Γ_R, and $\pm 2 \times 10^{-8}$ in $B_{in}B_{out}$. The systematic uncertainty in the mass from the uncertainty in the mean energy of the antiproton beam is estimated to be 0.2 MeV/c^2. The systematic error in the width measurement due to point uncertainties in the mean energy of the antiproton beam and from uncertainties in the energy spread of the beam is less than 0.1 MeV. Statistical and systematic uncertainties in luminosity measurement, analysis efficiency and geometric acceptance are all negligible compared to the statistical uncertainties due to the size of the event sample.

Table 1
Resonance parameters for the η_c. The first error is the statistical error from the fit and the second is the systematic uncertainty. The quantities with asterisks are obtained using $B(\eta_c \to \bar{p}p)$ from the literature [4]

Parameter	Value
$M(\eta_c)$ MeV/c^2	$2984.1 \pm 2.1 \pm 1.0$
$\Gamma(\eta_c)$ MeV	$20.4^{+7.7}_{-6.7} \pm 2.0$
$B_{in}B_{out} \times 10^8$	$22.4^{+3.8}_{-3.7} \pm 2.0$
$B_{in}\Gamma(\eta_c \to \gamma\gamma) \times 10^3$ keV	$4.6^{+1.3}_{-1.1} \pm 0.4$
$^*\Gamma_{\gamma\gamma}(\eta_c)$ keV	$3.8^{+1.1+1.9}_{-1.0-1.0}$
$^*B(\eta_c \to \gamma\gamma) \times 10^4$	$1.87 \pm 0.32^{+0.95}_{-0.50}$

We take the resonance parameters from the fit to the data treating both the background normalization and exponent as free parameters. The fit is shown in Fig. 2. We include the additional systematic and statistical errors described above to obtain our final results as given in Table 1. The present mass measurement is consistent with the value $M(\eta_c) = 2988.3 \pm 3.3$ MeV/c^2 of our previous experiment [5] and is 4.4 MeV/c^2 higher than the value quoted in Ref. [4].

Interference with continuum $\gamma\gamma$ production could affect the excitation and displace the peak from the resonance mass. We have investigated this possibility by fitting the feed-down subtracted data to a resonance plus an interfering continuum. The additional parameters do not improve the quality of the fit and the value of the resonance mass changes by a small fraction of our stated uncertainty.

In Ref. [5] we also reported a width, $\Gamma(\eta_c) = 23.9^{+12.6}_{-7.1}$ MeV. This large value has been supported by the subsequent measurement of Ref. [11] and more recently by Ref. [12]. The present result confirms our previous observation with almost a factor of two smaller error.

Our value for $B(\eta_c \to \bar{p}p)B(\eta_c \to \gamma\gamma)$ is consistent with the E760 result and has a fractional error a factor of two smaller. We obtain the values of $B(\eta_c \to \gamma\gamma)$ and $\Gamma_{\gamma\gamma}(\eta_c)$ using $B(\eta_c \to \bar{p}p) = (12 \pm 4) \times 10^{-4}$ [4]; the uncertainty in $B(\eta_c \to \bar{p}p)$ is included in the systematic error. A compilation of measurements of the η_c resonance parameters is given in Fig. 3.

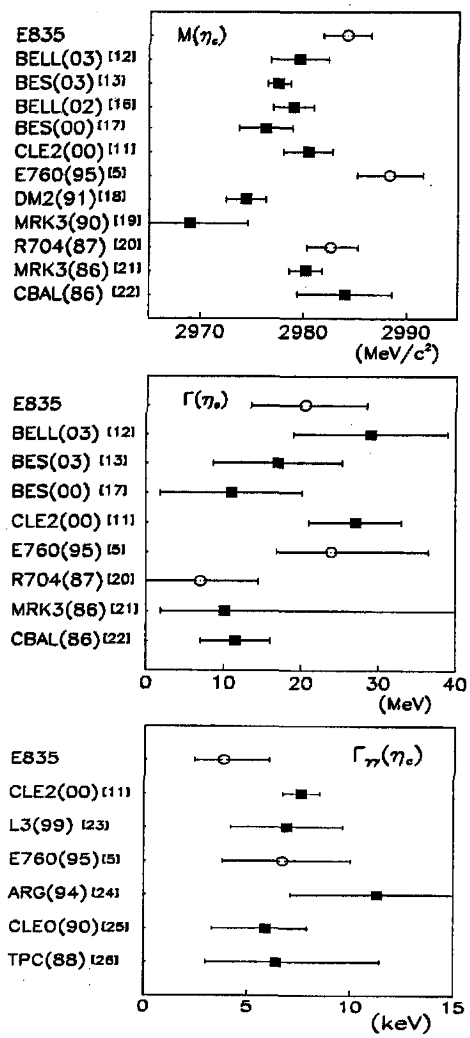

Fig. 3. A compilation of results ([5,11–13,16–26], this work) for the η_c resonance parameters, mass, total width, and the two photon partial width. Filled squares are from e^+e^- experiments, open circles are from $\bar{p}p$ experiments. The present results are at the top of each panel.

Table 2
Theoretical predictions for η_c resonance parameters

Authors (Ref.)	$\Gamma(\eta_c)$ MeV	$\Gamma_{\gamma\gamma}(\eta_c)$ keV
Novikov [27]	≈ 20	6.7
Godfrey [29]	22.1	6.76
Gupta [30]	23.0	10.9
Ackleh [31]		4.8
Munz [32]		3.5
Linde [33]		6.2–6.5
Huang [34]		5.5
Schuler [35]		7.8
Fabiano [36]		7.6 ± 1.5
This experiment	$20.4^{+7.7}_{-6.7} \pm 2.0$	$3.8^{+1.1+1.9}_{-1.0-1.0}$

The mass of the η_c was predicted soon after the discovery of the J/ψ [14] and long before it was first observed [15]. Potential model calculations either try to fit the observed $M(J/\psi) - M(\eta_c)$ splitting, or assume its experimental value in fitting the rest of the charmonium spectrum.

The total width of the η_c is expected to be mostly ($> 99\%$) hadronic, i.e., $\Gamma(\eta_c) = \Gamma(\eta_c \to h)$. Novikov et al. [27] predict a model dependent estimate of η_c width from the relation $\Gamma(^3\mathrm{P}_0)/\Gamma(^1\mathrm{S}_0) \approx 0.5$. The most accurate measurement of $\Gamma(^3\mathrm{P}_0) = 9.8 \pm 1.0$ MeV [28]. This leads to the prediction that $\Gamma(\eta_c) \approx 20$ MeV.

In a relativistic potential model calculation Godfrey and Isgur [29] predict $\Gamma(\eta_c) = 22.1$ MeV, and Gupta, Johnson and Repko [30] predict $\Gamma(\eta_c) = 23.0$ MeV. These predictions are summarized in Table 2, and they all are in good agreement with our experimental result.

The two photon radiative width has been predicted by several authors. These are also given in Table 2. Within its large systematic uncertainty, our measured two photon width is consistent with all the predictions except Gupta et al. [30].

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References

[1] G.S. Bali, K. Schilling, A. Wachter, Phys. Rev. D 56 (1997) 2566;
T. Manke, et al., Phys. Rev. D 62 (2000) 114508.

[2] E. Eichten, F.L. Feinberg, Phys. Rev. Lett. 43 (1979) 1205;
E. Eichten, F.L. Feinberg, Phys. Rev. D 23 (1981) 2724.

[3] Y.J. Ng, J. Pantaleone, S.-H.H. Tye, Phys. Rev. Lett. 55 (1985) 916;
J. Pantaleone, Y.J. Ng, S.-H.H. Tye, Phys. Rev. D 33 (1986) 777;
J. Pantaleone, Y.J. Ng, S.-H.H. Tye, Phys. Rev. D 37 (1988) 3337.

[4] K. Hagiwara, et al., Phys. Rev. D 66 (2002) 010001.

[5] T.A. Armstrong, et al., Fermilab E760 Collaboration, Phys. Rev. D 52 (1995) 4839.

[6] M. Ambrogiani, et al., Fermilab E835 Collaboration, Phys. Rev. D 62 (2000) 052002.

[7] M.D. Stancari, Ph.D. Thesis, University of California, Irvine, CA, 1999, unpublished.

[8] T. Pedlar, Ph.D. Thesis, Northwestern University, Evanston, IL, 1998, unpublished.

[9] M. Artuso, et al., CLEO Collaboration, Phys. Rev. D 50 (1994) 5484.

[10] H. Hamasaki, et al., VENUS Collaboration, Phys. Lett. B 407 (1997) 185.

[11] G. Brandenberg, et al., CLEO Collaboration, Phys. Rev. Lett. 85 (2000) 3095.

[12] Belle Collaboration, F. Fang, et al., Phys. Rev. Lett. 90 (2003) 071801.

[13] J.Z. Bai, et al., BES Collaboration, hep-ex/0301004.

[14] T. Appelquist, A. De Rujula, H.D. Politzer, S.L. Glashow, Phys. Rev. Lett. 34 (1975) 365;
See also: M.A. Shifman, A.I. Vainstein, M.B. Voloshin, V.I. Zakharov, Phys. Lett. B 77 (1978) 80.

[15] R. Partridge, et al., Phys. Rev. Lett. 45 (1980) 1150;
T.M. Himmel, et al., Phys. Rev. Lett. 45 (1980) 1148.

[16] S.K. Choi, et al., Phys. Rev. Lett. 89 (2002) 102001.

[17] J.Z. Bai, et al., Phys. Rev. D 62 (2000) 072001.

[18] D. Bisello, et al., Nucl. Phys. B 350 (1991) 1.

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

[20] C. Baglin, et al., Phys. Lett. B 187 (1987) 191.

[21] R.M. Baltrusaitis, et al., Phys. Rev. D 33 (1986) 629.

[22] J.E. Gaiser, et al., Phys. Rev. D 34 (1986) 711.

[23] M. Acciarri, et al., Phys. Lett. B 461 (1999) 155.

[24] H. Albrecht, et al., Phys. Lett. B 338 (1994) 390.

[25] W.Y. Chen, et al., Phys. Lett. B 243 (1990) 169.

[26] H. Aihara, et al., Phys. Rev. Lett. 60 (1988) 2355.

[27] V.A. Novikov, et al., Phys. Rep. 41 (1978) 1.

[28] S. Bagnasco, et al., Fermilab E835 Collaboration, Phys. Lett. B 533 (2002) 237.

[29] S. Godfrey, N. Isgur, Phys. Rev. D 32 (1985) 89.

[30] S.N. Gupta, J.M. Johnson, W.W. Repko, Phys. Rev. D 54 (1996) 2075.

[31] E.S. Ackleh, T. Barnes, Phys. Rev. D 45 (1992) 232.

[32] C. Munz, Nucl. Phys. A 609 (1996) 364.

[33] J. Linde, H. Snellmann, Nucl. Phys. A 619 (1997) 346.

[34] H.W. Huang, et al., Phys. Rev. D 54 (1996) 2123;
H.W. Huang, et al., Phys. Rev. D 56 (1997) 368.

[35] G. Schuler, F. Berends, R. van Gulik, Nucl. Phys. B 523 (1998) 423.

[36] N. Fabiano, G. Pancheri, Eur. Phys. J. C 25 (2002) 421.