Study of the $\chi_{c0}(1^3P_0)$ State of Charmonium Formed in $\bar{p}p$ Annihilations.

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The resonance parameters of χ_{c0}, the 1^3P_0 resonance of charmonium, have been measured at the Fermilab Antiproton Accumulator by means of the reaction $\bar{p}p \to \chi_{c0} \to \gamma J/\psi \to \gamma(e^+e^-)$. The results are $M(\chi_{c0}) = 3417.4^{+1.8}_{-1.9}\pm0.2$ MeV/c^2, $\Gamma(\chi_{c0}) = 16.6^{+5.2}_{-3.7}\pm0.1$ MeV, and $\Gamma(\chi_{c0} \to \bar{p}p)\times$ $\mathrm{B}(\chi_{c0} \to J/\psi\gamma)\times\mathrm{B}(J/\psi \to e^+e^-) = 2.89^{+0.67}_{-0.53}\pm0.14$ eV. Using known branching ratios we also obtain $\Gamma(\chi_{c0} \to \bar{p}p) = 8.0^{+1.9+3.5}_{-1.5-1.9}$ keV. These results are discussed in relation to the other χ_{cJ} states and to theoretical predictions.

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The charmonium family of $c\bar{c}$ states, with its accessible spectrum of spin-singlet, spin-triplet, L=0 and L=1 states, is a rich source of experiment data for the study of both the spin-dependence of the QCD interaction and the decays of $q\bar{q}$ bound states. In this paper we complement the results for $\chi_{c1}(^3P_1)$ and $\chi_{c2}(^3P_2)$ resonances of charmonium from our earlier experiment E760 [1] by presenting the results for the $\chi_{c0}(^3P_0)$ resonance parameters determined by the study of reaction

$$\bar{p}p \rightarrow \chi_{c0} \rightarrow \gamma J/\psi \rightarrow \gamma(e^+e^-)\,. \tag{1}$$

Our data yield directly the mass, $M(\chi_{c0})$, the total width, $\Gamma(\chi_{c0})$, and the product of branching ratios $\mathcal{B}_{in} \times \mathcal{B}_{out}$ where $\mathcal{B}_{in} = \mathcal{B}(\chi_{c0} \rightarrow \bar{p}p)$ and $\mathcal{B}_{out} = \mathcal{B}(\chi_{c0} \rightarrow \gamma J/\psi) \times \mathcal{B}(J/\psi \rightarrow e^+e^-)$. Using results from the literature for $\mathcal{B}_{out}$, we derive values for $\mathcal{B}(\chi_{c0} \rightarrow \bar{p}p)$ and, equivalently, $\Gamma(\chi_{c0} \rightarrow \bar{p}p)$. The results allow a comparison of the hadronic decays of the χ_{cJ} states, in particular the χ_{c0} and χ_{c2} resonances, both of which decay via two gluons.

Fermilab experiment E835 is devoted to the study of charmonium spectroscopy by direct formation of $c\bar{c}$ states in $\bar{p}p$ annihilation at the Fermilab Antiproton Accumulator ring. A variable density jet of clusterized hydrogen molecules ($\rho_{max} \sim 3.0 \times 10^{14}$ atoms/cm^3) [2] intersects a beam of up to 80 mA of antiprotons circulating in the Accumulator. Luminosities used in the present set of measurements were about 1×10^{31} cm^{-2}s^{-1}.

The antiproton beam is stochastically cooled such that there is an rms spread in the center-of-mass energy, $\sqrt{s}$, of about 0.4 MeV; the uncertainty in the mean center-of-mass energy at any energy point for these data is estimated to be 0.2 MeV. The $c\bar{c}$ resonance parameters can be determined precisely by measuring the excitation curve obtained by stepping the energy of the antiproton beam across the resonance. An advantage of this technique is that all $c\bar{c}$ states can be produced directly in $\bar{p}p$ annihilations and the precision of the mass and width determination of these states does not depend on the resolution of the detector system but is limited only by event statistics and the knowledge of the antiproton beam energy and energy spread.

We select electromagnetic final states as tags of charmonium formation. This makes it possible to extract a clean signal despite the large hadronic background and our experiment is optimized for the detection and identification of photons and electrons [3]. It has full coverage in azimuthal angle (ϕ), and consists of a cylindrical central detector which covers polar angles $11^\circ < \theta < 70^\circ$, and a planar forward system which covers $3^\circ < \theta < 12^\circ$. The central detector contains 3 azimuthally segmented scintillator hodoscopes, 2 sets of straw tubes for tracking in azimuth, a scintillating-fiber tracker for tracking in θ, a 16 cell threshold gas Čerenkov counter and a 1280 element lead-glass calorimeter (CCAL) for measuring the direction and energy of photons and electrons. All counters are equipped with both time and pulse-height measurement. The time measurements allow for the rejection of signals from out-of-time events, while pulse-height measurement on the scintillation hodoscopes and Čerenkov counters allow rejection of e^+e^- pairs from photon conversions and Dalitz decays. A luminosity monitor [4] provides absolute luminosity with a statistical precision of better than 0.1% and an estimated systematic error of $\pm 2.5\%$ by measuring $\bar{p}p$ forward elastic scattering through the detection of proton recoils near 90°.

The hardware trigger was designed to select events with a $J/\psi \rightarrow e^+e^-$ decay and accepted all events with a candidate e^+e^- pair of mass above 1900 MeV/c^2 in the central detector system. The trigger was implemented by requiring two "electron" tracks as defined by the appropriate coincidence between the elements of the inner and outermost hodoscopes and the corresponding cells in the Čerenkov counter. Independently, two large energy deposits, separated by more than 90° in azimuth, were required in the CCAL. The efficiency of this trigger, $\epsilon_{trigger} = 0.90 \pm 0.01_{stat} \pm 0.01_{sys}$, was determined by selecting a clean sample of $\bar{p}p \rightarrow J/\psi \rightarrow e^+e^-$ events in a dedicated run taken with relaxed trigger conditions.

Data were taken at several $\bar{p}$ momenta corresponding to center-of-mass energies in the range 3405 to 3430 MeV. Data taken at energies well away from the χ_{c0} and other resonances were used to establish the background level.

We require the decay of χ_{c0} per eq. (1) to produce three on-time energy deposits $(e^{\pm}, e^{\mp}, \gamma)$

in the CCAL. In order to accept events with external bremsstrahlung from one electron, as well as events with radiative J/ψ decays, the off-line analysis allowed one extra on-time cluster, provided the invariant mass of this (photon) cluster and the closest electron was $M_{e\gamma} < 100$ MeV/c^2. (The off-line cluster energy threshold was 50 MeV.)

Events were accepted in a region of uniform efficiency with electrons in the Čerenkov fiducial region of $15^\circ < \theta < 60^\circ$ and photons in the CCAL fiducial region of $12^\circ < \theta < 68^\circ$. This gave a geometrical acceptance for the present analysis of $\alpha_{geom} = 0.35 \pm 0.01$.

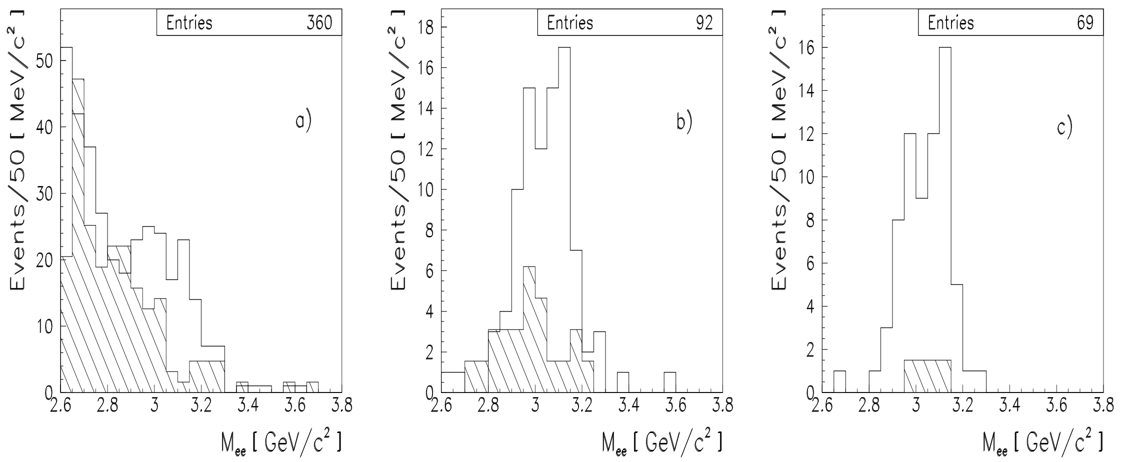

FIG. 1. e^+e^- invariant mass distribution for the events in the resonance region(unshaded), and events in off–resonance region(shaded). (a) all candidate events, (b) events after kinematic fit, (c) final selected events.

In Fig. 1(a) the unshaded histogram shows the e^+e^- invariant mass distribution for events taken at the χ_{c0} resonance signal region ($3405 < \sqrt{s}(\text{MeV}) < 3430$). The shaded histogram corresponds to the invariant mass distribution for data taken outside the resonance region, normalized to the integrated luminosity of the signal region. An excess of events in the J/ψ mass region signals the presence of the parent charmonium state.

To extract the events corresponding to reaction (1), a five constraint kinematical fit, using the known energy and momentum of the $\bar{p}p$ annihilation and the mass of the J/ψ, was applied to the events in Fig. 1(a) and only events with χ^2 probability greater than 10^{-4} were

TABLE I. Summary of data. The errors in column 4 are statistical and correspond to the 68.3% confidence interval [5]. Asterisks denote beam energy below transition energy of the Antiproton Accumulator. N refers to total events including possible background.

<table>
<tr><th>$\sqrt{s}$ (MeV)</th><th>$\mathcal{L}(\mathrm{nb}^{-1})$</th><th colspan="2">Events,N</th><th>$\sigma(\mathrm{pb}) = N/(\mathcal{L} \times \epsilon_{tot})$</th></tr>
<tr><td>3215.7*</td><td>420</td><td colspan="2">0</td><td>$0.0^{+11.4}_{-0.0}$</td></tr>
<tr><td>3269.4*</td><td>412</td><td colspan="2">1</td><td>$9.0^{+15.8}_{-5.7}$</td></tr>
<tr><td>3318.8*</td><td>951</td><td colspan="2">1</td><td>$3.9^{+6.8}_{-2.5}$</td></tr>
<tr><td>3405.8*</td><td>81</td><td>0</td><td rowspan="2">14</td><td rowspan="2">$51.7^{+16.0}_{-13.7}$</td></tr>
<tr><td>3406.8*</td><td>926</td><td>14</td></tr>
<tr><td>3414.8*</td><td>585</td><td>13</td><td rowspan="2">21</td><td rowspan="2">$83.2^{+20.0}_{-17.8}$</td></tr>
<tr><td>3414.8*</td><td>353</td><td>8</td></tr>
<tr><td>3418.1*</td><td>146</td><td>7</td><td rowspan="2">28</td><td rowspan="2">$124.2^{+24.4}_{-22.1}$</td></tr>
<tr><td>3418.5</td><td>692</td><td>21</td></tr>
<tr><td>3429.5</td><td>349</td><td>4</td><td rowspan="2">6</td><td rowspan="2">$30.2^{+16.5}_{-11.0}$</td></tr>
<tr><td>3429.9</td><td>390</td><td>2</td></tr>
<tr><td>3494.4</td><td>503</td><td colspan="2">2</td><td>$14.8^{+16.7}_{-9.3}$</td></tr>
<tr><td>3600–3660</td><td>26823</td><td colspan="2">37</td><td>5.1±0.8</td></tr>
</table>

kept. The e^+e^- invariant mass distribution of the events so selected is plotted in Fig. 1(b); the improvement in the signal to background ratio is obvious.

At this stage, the remaining background comes from events with two energetic π^0s, each of which has a resulting e^+e^- pair (from Dalitz decay, or photon conversion in the beam pipe) with essentially all of the parent π^0 energy. This background manifests itself in electron candidates with larger pulse-height in the hodoscopes and the Čerenkov counter, and in clusters with broader transverse energy distribution in the CCAL. We exploited these differences to remove this residual background. Fig. 1(c) shows the e^+e^- invariant mass distribution for the final sample.

The efficiency for this analysis was determined using clean samples of $\bar{p}p \rightarrow \chi_{(c1,c2)} \rightarrow \gamma J/\psi \rightarrow \gamma(e^+e^-)$ events and is $\epsilon_{analysis} = 0.85 \pm 0.02$. This results in an overall efficiency of $\epsilon_{tot} = \epsilon_{trigger} \times \alpha_{geom} \times \epsilon_{analysis} = 0.27 \pm 0.01$.

The integrated luminosity, $\mathcal{L}_i$, and total number of events, N_i(including the residual background), for each energy point are given in Table I. The resulting cross sections for each data point

$$\sigma(\sqrt{s_i}) = N_i(\sqrt{s_i})/(\mathcal{L}_i \times \epsilon_{tot}) \tag{2}$$

are presented in Table I and shown in Fig. 2. The cross sections for close data points ($\Delta\sqrt{s} < 1$ MeV) have been combined.

The cross sections have been fit by the maximum likelihood method [1] to a Breit–Wigner resonance plus a constant background with the form

$$\sigma(\sqrt{s_i}) = \sigma_{bckg} + \int f_i(\sqrt{s_i} - \sqrt{s'})\ \sigma_{BW}(\sqrt{s'})\ d\sqrt{s'}$$

where $\sigma(\sqrt{s_i})$ is the observed cross section at the center-of-mass energy $\sqrt{s_i}$, and σ_{bckg} is the background. $f_i(\sqrt{s_i} - \sqrt{s'})$ is the center-of-mass energy distribution function (fitted with a double Gaussian with full width < 0.7 MeV) for each point, and $\sigma_{BW}(\sqrt{s'})$ is the Breit–Wigner resonance cross section,

$$\sigma_{BW}(\sqrt{s'}) = \frac{4\pi(\hbar\ c)^2}{s' - 4m_p^2c^4} \frac{\Gamma(\chi_{c0})^2 \times \mathcal{B}_{in} \times \mathcal{B}_{out}}{4(\sqrt{s'} - M(\chi_{c0})c^2)^2 + \Gamma(\chi_{c0})^2} .$$

The χ^2 calculated using the best fit values was 8.7 for 9 degrees of freedom. The fit is shown superimposed on the data in Fig. 2.

The best fit values of the parameters $M(\chi_{c0})$, $\Gamma(\chi_{c0})$, $(\mathcal{B}_{in} \times \mathcal{B}_{out})$, $(\Gamma_{\bar{p}p} \times \mathcal{B}_{out})$ and the background level are shown as the first five entries of Table II.

As a check on the sensitivity of the results to the electron identification requirements, an alternative analysis was performed using tighter kinematic cuts and nominal fit probability $> 10^{-3}$, but making no cuts on electron identification beyond the trigger. This yielded a sample with somewhat larger background but gave resonance parameters essentially identical in both central values and errors to those presented in Table II.

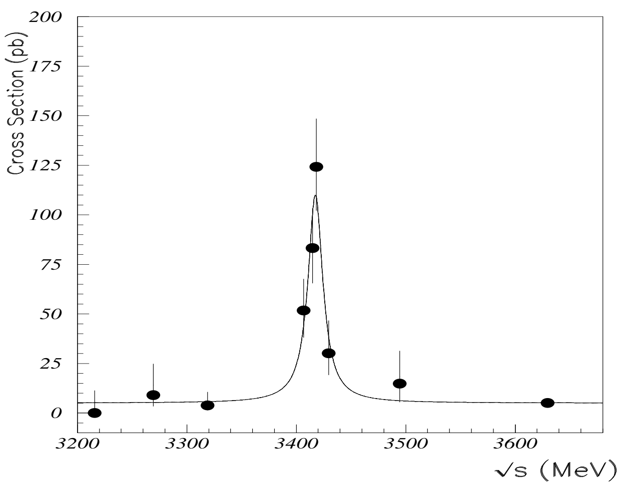

FIG. 2. Measured cross sections and resonance fit as described in the text.

Our result for the χ_{c0} mass is $M(\chi_{c0})$=3417.4$^{+1.8}_{-1.9}$±0.2 MeV/c^2 where the systematic error comes from the estimated uncertainty on the beam momentum [3]. Our value is in good agreement with the Crystal Ball result [6] of 3417.8±0.4±4.0 MeV/c^2. A recent measurement by BES [7] gives a value 3414.1±0.6±0.8 MeV/c^2.

Our result for the χ_{c0} total width is $\Gamma(\chi_{c0}) = 16.6^{+5.2}_{-3.7}$ MeV. The errors are completely dom-

TABLE II. Results for χ_{c0} resonance parameters. The first errors are statistical and the second are systematic.

M [MeV/c^2]	$3417.4^{+1.8}_{-1.9}\pm0.2$
$\Gamma(\chi_{c0})$ [MeV]	$16.6^{+5.2}_{-3.7}\pm0.1$
$\mathcal{B}_{in} \times \mathcal{B}_{out} \times 10^7$	$1.74^{+0.34}_{-0.28}\pm0.09$
$\Gamma_{\bar{p}p} \times \mathcal{B}_{out}$ [eV]	$2.89^{+0.67}_{-0.53}\pm0.14$
σ_{bckg} [pb]	$5.02^{+0.86}_{-0.78}$
$\mathcal{B}_{out}$ (literature) $\times 10^4$	3.6 ± 1.1
$\mathcal{B}_{\bar{p}p} \times 10^4$	$4.8^{+0.9+2.1}_{-0.8-1.1}$
$\Gamma_{\bar{p}p}$ [keV]	$8.0^{+1.9+3.5}_{-1.5-1.9}$

inated by statistics. Systematic errors from the uncertainty in the beam energy distribution or from our knowledge of the mean beam energy are negligible. This value for the width is consistent with Gaiser et al. [6], $\Gamma(\chi_{c0}) = 13.5\pm3.3\pm4.2$ MeV, and with the result from BES [8] which reports $\Gamma(\chi_{c0}) = 14.3\pm2.0\pm3.0$ MeV. We note that the results of both Gaiser et al. and BES depend on the knowledge of the energy resolution of the respective detectors in contrast to our result.

The third quantity which results directly from the fit to our data is the product of branching ratios, $\mathcal{B}(\chi_{c0} \to \bar{p}p) \times \mathcal{B}_{out}$, or alternatively, (depending on the choice of fit parameters) $\Gamma_{\bar{p}p} \times \mathcal{B}_{out}$. The values are given in Table II.

To determine $\mathcal{B}(\chi_{c0} \to \bar{p}p)$, we take the value of $\mathcal{B}_{out}$, the product $\mathcal{B}(\chi_{c0} \to \gamma J/\psi) \times \mathcal{B}(J/\psi \to e^+e^-)$, from the literature. We take the first factor to be $(6.0\pm1.8)\times10^{-3}$ [6] and the second as $(6.02\pm0.19)\times10^{-2}$ [9]. This leads to $\mathcal{B}(\chi_{c0} \to \bar{p}p) = (4.8^{+0.9+2.1}_{-0.8-1.1})\times10^{-4}$ and $\Gamma(\chi_{c0} \to \bar{p}p) = 8.0^{+1.9+3.5}_{-1.5-1.9}$ keV, as given in Table II. The statistical uncertainties in these last two quantities are from our measurements while the systematic errors are mainly due to the uncertainty in the value of $\mathcal{B}_{out}$. BES [8] has reported $\mathcal{B}(\chi_0 \to \bar{p}p) = (1.59\pm0.43\pm0.53) \times 10^{-4}$.

These data allow a comparison of both the hadronic widths and $\bar{p}p$ branching fractions of the χ_{cJ} states. For the hadronic widths, a comparison between the χ_{c0} and the χ_{c2} may be useful since both states decay hadronically via two gluons. The hadronic width of the χ_{c2} has been measured [1] to be $\Gamma(\chi_{c2} \to h) = 1.71 \pm 0.21$ MeV. The hadronic width of the χ_{c0} is close to its total width, the difference being essentially the partial width to $J/\psi\gamma$ which is ≈ 0.1 MeV. This gives us

$$R(expt) \equiv \frac{\Gamma(\chi_{c0} \to h)}{\Gamma(\chi_{c2} \to h)} = 9.7^{+3.3}_{-2.5}.$$

Barbieri et al. [10] and others have calculated this quantity to first order with the result [11],

$$R(theory) = (15/4)\frac{(1\ +\ 3.0\alpha_s)}{(1\ -\ 0.7\alpha_s)} = 9.7$$

where we take $\alpha_s = 0.33$ according to the compilation of ref. [9]. The prediction is consistent with our result, although, as the authors point out, the first order correction is so large as to call into question the validity of perturbation theory here. Our value is also consistent with the model of Godfrey and Isgur [12] who considered relativistic effects in a potential model calculation and obtained $R = 8.07$. Bodwin, Braaten and Lepage [13] have proposed an approach that accounts for non-perturbative effects in the calculation of the relative decay widths of the P states. However, their prediction, $R = (2.75 \pm 0.48) \pm 36\%$, is inconsistent with the experimental result.

Our data also allow us to compare the $\bar{p}p$ fractions of the hadronic decays of the χ_{cJ} states. We note that massless QCD predicts helicity conservation and thus forbids formation of J=0 states in $\bar{p}p$ annihilation [14]. This clearly fails for the χ_{c0} as it does for the η_c. An interesting feature of our result is that while $\Gamma(\bar{p}p)/\Gamma(\text{hadrons}) \approx 1 \times 10^{-4}$ for both the χ_{c1} and χ_{c2} states, this ratio is significantly larger for the χ_{c0}, being $(4.8^{+0.9+2.1}_{-0.8-1.1}) \times 10^{-4}$. Predictions for $\Gamma(\chi_{c0} \to \bar{p}p)$ based on a diquark model of the proton have been given by Anselmino et al.

[15]. Their model is not fully constrained by the existing $\chi_{c1,c2}$ data and can accomodate a wide range of values for $\Gamma(\chi_{c0} \to \bar{p}p)$, from 0.2 keV to 4 keV, to be compared with our result of $8.0^{+1.9+3.5}_{-1.5-1.9}$ keV.

To summarize, we have measured the mass, total width, and the $\bar{p}p$ decay width of the χ_{c0} resonance of charmonium by direct observation of the resonance excitation. Our results on the mass and the width agree with previous data from experiments at e^+e^- machines [9]. Our value for the $\bar{p}p$ fraction of the total hadronic width of the χ_{c0} is large compared to those for χ_{c1} and χ_{c2}, and differs from the value reported by BES.

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