Frascati Physics Series Vol. nnn (2001), pp. 000-000
HEAVY QUARKS AT FIXED TARGET - Rio de Janeiro, Oct. 9-19, 2000

STUDY OF THE CHARMONIUM STATES IN PROTON-ANTIPROTON ANNIHILATIONS FROM E835

Flavio Marchetto *
Istituto Nazionale di Fisica Nucleare - Torino Via Pietro Giuria,1 - 10125 Torino, Italy

ABSTRACT

E835 at Fermilab studies the charmonium states formed in proton-antiproton annihilations. Data have been taken in 1996-97 and in 2000. The technique and the detector of the experiment are presented. Preliminary determination of the masses and widths of the η_c (1^1S_0) and χ_{c0} (1^3P_0) and of the branching ratios of the η_c and $\chi_{c0,2}$ to $\gamma\gamma$ decay are reported.

* on behalf of the E835 Collaboration: G. Garzoglio, A. Hahn, W. Marsh, J. Peoples Jr., S. Pordes, G. Stancari, J. Streets, S. Werkema (Fermi National Accelerator Laboratory), M. Ambrogiani, W. Baldini, D. Bettoni, R. Calabrese, P.Dalpiaz, E. Luppi, R. Mussa, M. Savrie' (INFN and University of Ferrara), A. Buzzo, M. Lo Vetere, M. Macri', M. Marinelli, M. Pallavicini, C. Patrignani, E. Robutti, A. Santroni (INFN and University of Genova), K. E. Gollwitzer, G. Lasio, M. Mandelkern, J. Schultz, M. Stancari, G. Zioulas (University of California at Irvine), M. Graham, R. Rusack, S. Seo, T. Vidnovic (University of Minnesota), X. Fan, S. Jin, J. Kasper, P. Maas, T. Pedlar, J. Rosen, K. K. Seth, A. Tomaradze (Northwestern University), S. Argiro', S. Bagnasco, G. Borreani, R. Cester, F. Marchetto, E. Menichetti, M. M. Obertino, N. Pastrone, P. Rumerio (INFN and University of Torino)

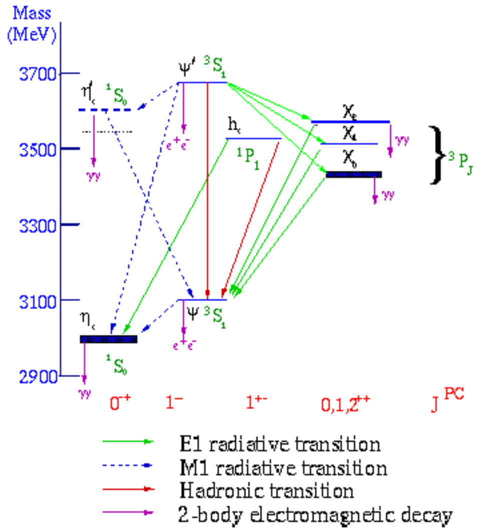

Figure 1: Charmonium spectrum

1 Introduction

Charmonium states have been a rich source of tests of QCD and the precision measurements of masses and widths have provided constraints for the potential models and the benchmark to verify the predictions. Most of the $\bar{c}c$ measurements has been obtained in e^+e^- annihilation, but because such annihilation goes through a virtual photon, $J^{PC} = 1^{--}$ are the only directly accessible quantum numbers. The access to the other states, $J^{PC} \neq 1^{--}$, is then via radiative decays. In this case the measurement has to rely on the photon energy resolution of the detector. On the contrary, in $\bar{p}p$ annihilation all the states can be formed directly through two and three gluons exchange. The technique, which requires *almost* monochromatic antiprotons, has been first applied at CERN in the experiment R704 [1].

However, beside all the experimental efforts, out of the eight states lying below the open charm threshold (see fig. 1), precise measurements of mass and width of two states (η_c' and $^1P_1$) are still not available or need confirmation [2].

In this paper we summarize the results obtained from experiment 835 at

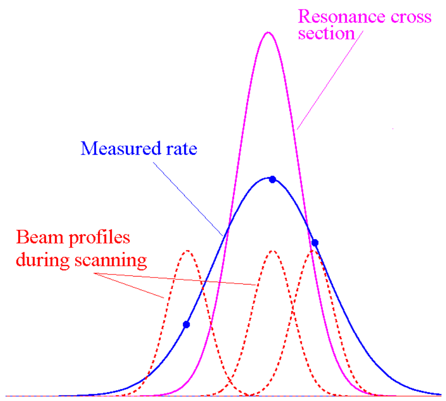

Figure 2: Sketch of a resonance scan

Fermilab, which studied the $(\bar{c}c)$ states in $\bar{p}p$ annihilations. The data taking spanned over two period: 1996-97 (E835-96-97) and 2000 (E835-2000)

2 Technique of the experiment

The convolution of the beam intensity and the resonance Breit-Wigner cross-section gives the event yield as a function of the $\bar{p}p$ center of mass energy (see fig. 2).

The relation is the following:

$$\frac{N_{ev}}{Luminosity} \propto \int I_{beam}(E)\sigma_{BW}(E)dE$$

where:

$I_{beam}(E)$ is the beam intensity as a function of the energy and:

$$\sigma_{BW}(E) = \frac{(2J+1)\pi}{k_{cm}^2}\frac{BR(\bar{p}p \to R) \times BR(R \to f)}{1 + 4(E^2 - M_R)^2 + \Gamma_R^2}$$

From the shape of $\frac{N_{ev}}{Luminosity}$ as a function of E, and by measuring $I_{beam}(E)$, with standard minimization technique, one can extract M_R, Γ_R, and $BR(\bar{p}p \to R) \times BR(R \to f)$.

In the next three subsections I'll briefly summarize the performances of the E835 main components: the antiproton accumulator, the target and the detector.

2.1 Antiproton Accumulator

E835 is located in the Fermilab Antiproton Accumulator , which can store a continuous beam up to $\simeq 8 \times 10^{11} \bar{p}$ [3].

The stochastics cooling allows to reduce the beam center of mass energy spread down to $\simeq$ 400 keV. The beam spectrum ($I_{beam}(E)$) can be precisely determined by analysing the beam current Schottky noise which provides the beam intensity as a function of the revolution frequency. The relative frequency uncertainty is $\simeq 10^{-7}$. The length of a beam reference orbit, which enters in the energy computation, has been derived by constraining the ψ' mass. Finally, actual deviations from the reference orbit are measured by a set of Beam Position Monitors displaced along the Accumulator straight sections. The error on the orbit length is ± 1 mm (out of $\simeq$ 474 m total length).

The combined error on the center of mass energy is in the range from 50 to 150 keV.

2.2 Jet Target

A jet of clusterized molecular hydrogen intersects at 90^o the $\bar{p}$ [4]. The atom density, controlled via pressure and temperature upstream the nozzle, can be increased up to $\simeq 3 \times 10^{14}$ $atoms/cm^3$.

The interaction volume is $\simeq (5 \times 5 \times 7)$ mm^3.

A data taking cycle started with the filling of the Antiproton Accumulator up to several units of $10^{11}\bar{p}$. Due to $\bar{p}p$ interactions the beam current was dropping as a function of time and to substain a *quasi* constant instantaneous luminosity ($\simeq 2.5 \times 10^{31} cm^{-2} sec^{-1}$) the jet density was consequently increased.

2.3 The detector

The detector (see fig. 3) has been optimized for the charmonium decays to electromagnetic final states such as $J/\psi \ + \ X \rightarrow e^+e^- + X$, and $\gamma\gamma$.

The acceptance covers 2π in the azimuthal angle and between 3^o and 65^o in the polar angle (θ). The main components are:

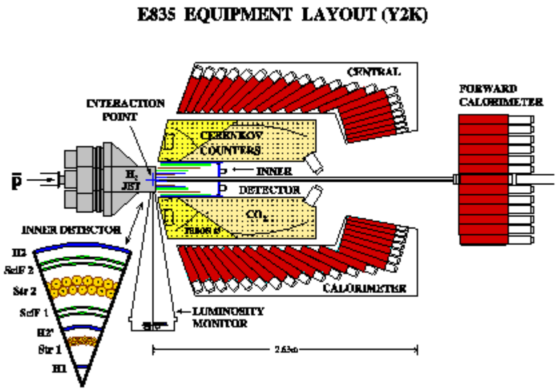

Figure 3: Schematic layout of the E835 detector

- a threshold gas Cherenkov counter to tag electrons and three barrels of scintillator hodoscopes to trigger on event multiplicity and topology [5]
- a lead-glass Central Calorimeter [6] which covers the region $11^o < \theta < 70^o$. The energy resolution is $\sigma_E/E \simeq 0.06/\sqrt{E} + 0.014$, and the angular resolution is $\sigma_\theta \simeq 6$ mrad and $\sigma_\phi \simeq 11$ mrad
- a lead-glass Forward Calorimeter having an acceptance between 3^o and 11^o in θ. The energy resolution is similar to the Central Calorimeter with a larger constant term. The position resolution is $\simeq 5$ cm.
- the Charged Tracking is made of two components: a) four layers of Straws for the ϕ measurement with a resolution of $\simeq 8$ mrad; b) two layers of Scintillating Fibers to measure θ between 15^o and 65^o with a resolution of $\simeq 4$ mrad.

All the elements of the detector are instrumented with Time to Digital Converter (few ns resolution) to reject accidental pile-up due to close in time interactions.

State	Mass (MeV/c^2	Width (keV)
J/ψ	$3096.87 \pm 0.03 \pm 0.03$	$99 \pm 12 \pm 6$
χ_{c1}	$3510.53 \pm 0.04 \pm 0.12$	$880 \pm 110 \pm 80$
χ_{c2}	$3556.15 \pm 0.07 \pm 0.12$	$1980 \pm 170 \pm 70$

Table 1: Mass and width results from E760

The luminosity is measured from the $\bar{p}p$ recoil at $\simeq 86.5^o$ with a $\simeq 3\%$ precision [7].

3 Historical review

I'll briefly summarize the results obtained with this technique [8].

- R704 at CERN ISR (1984) proved the feasibility of the experiment and detected a clear sample of J/ψ and $\chi_{c1,2}$ with and integrated luminosity of 3 pb^{-1}.
- E760 at the Antiproton Accumulator of Fermilab with an integrated luminosity of 30 pb^{-1} performed a precise measurement of mass and width of J/ψ and $\chi_{c1,2}$, which are reported in table 1.

  The list of E760 measurements includes: a) ψ' width: $(306 \pm 36 \pm 16)$ keV [9]; b) coupling to $\bar{p}p$ of $J/\psi, \chi_{c1}, \chi_{c2}$, and ψ'; c) $\chi_{c2} \to \gamma\gamma$ partial width [10]; d) η_c mass [12]. Furthermore it was observed a signal at 3526.2 MeV/c^2 interpreted as $h_c(^1P_1)$ candidate [11].

4 Results

E835 took data in the years 1996-97 for a total integrated luminosity of 145 pb^{-1} and $\simeq 100$ pb^{-1} in 2000. The results discussed in this report, which are mostly preliminary, are the following:

- measurement of χ_{c0} mass and width;
- measurement of η_c mass and width and of the coupling $\eta_c \to \gamma\gamma$;
- determination of the $\chi_{c0,2} \to \gamma\gamma$ partial width;
- η_c' search.

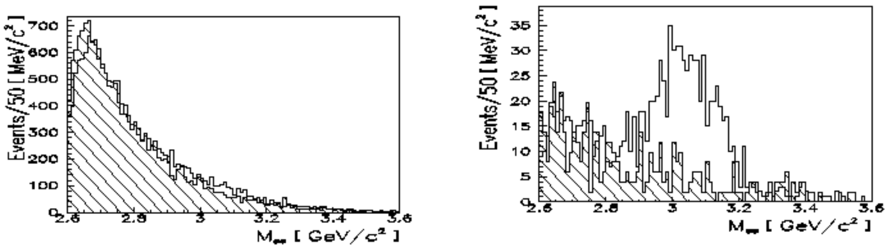

Figure 4: e^+e^- invariant mass distribution: no cut (left) and after the *single electron* selection (right)

- analysis of the angular distributions of the $\chi_{c1,2}$ radiative decays.

5 Measurement of χ_{c0} mass and width

Data at the χ_{c0} energy were collected either in 1996-97 ($\simeq$ 5.8 pb $^{-1}$ of which 3.5 pb $^{-1}$ on the resonance) either during 2000 data taking ($\simeq$ 30 pb $^{-1}$ of which 20 pb $^{-1}$ on the resonance)

χ_{c0} has been detected via the process $\bar{p}p \to \chi_{c0} \to J/\psi + \gamma \to e^+e^- + \gamma$.

The hardware trigger selected events having a e^+e^- pair with a large invariant mass by requiring a Cherenkov signal, to reject the large background due to pions, together to two almost back to back large energy clusters in the Central Calorimeter. The e^+e^- invariant mass distribution for all the triggers passing the hardware selection is shown in fig. 4 (left).

The unshaded (shaded) histogram refers to energies on (off) resonance and the areas have been normalized to the same luminosity.

The software selection isolates the triggers with both charged tracks (e^+ and e^-) recognized as single ionizing particle. The identification is based upon the dE/dx measured with the hodoscopes and on the Cherenkov pulse heights. The rejection is mainly background due to γ converted in the beam pipe. The e^+e^- invariant mass distribution after this selection is shown in fig. 4 (right).

Finally, to the events surviving the previous selection, it is applied a kinematical fit (5C) requiring a probability greater than 10^{-4}. The e^+e^- invariant mass distribution of the selected events is shown in fig. 5. After the above straightforward requirements, the background left (shaded histogram) is of the

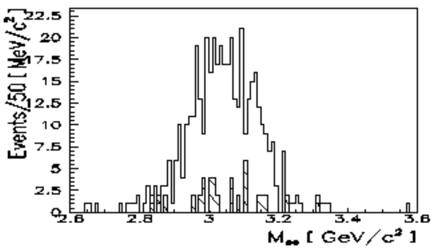

Figure 5: e^+e^- invariant mass distribution of the $\chi_{c0} \to J/\psi\gamma$ events

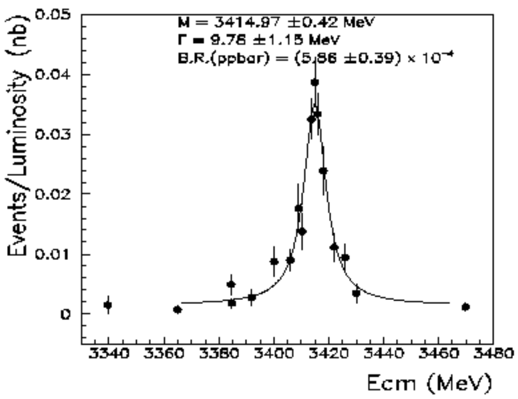

Figure 6: Measured cross section of $\bar{p}p \to J/\psi\gamma$ in the χ_{c0} region

order of a few pb.

Events are then grouped as a function of energy, and divided by the luminosity for each energy point to obtain the excitation curve (see fig. 6).

The continuous line on fig. 6 is the result of a fit of the measured cross section to a constant background plus a Breit-Wigner resonance. The fit is performed with the Maximum Likelihood method to extract the resonance parameters: mass, total width, and the product $BR(\chi_{c0} \to \bar{p}p) \times BR(\chi_{c0} \to J/\psi\gamma) \times BR(J/\psi \to e^+e^-)$, and the background cross section.

The relative point to point corrections are typically within a few percent. In fact the acceptance does not considerably change by changing the value

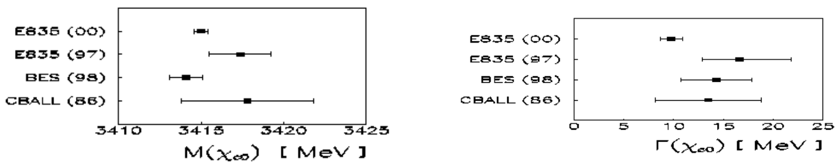

Figure 7: χ_{c0} mass and width: comparison of the experimental results

of the center of mass energy by a few MeV. Furthermore the trigger and the analysis efficiency are quite stable being the data taken at almost constant luminosity and *constant detector performances* [1].

Preliminary analysis of the data taken by E835-2000 gave the following results:

$Mass = 3414.97 \pm 0.42 \pm 0.2\ MeV$, $\Gamma = 9.78^{+1.22}_{-1.1}\ MeV$, $BR(\chi_{c0} \to \bar{p}p) \times BR(\chi_{c0} \to J/\psi\gamma) \times BR(J/\psi \to e^+e^-) = 2.11^{+0.14}_{-0.13} \pm 0.11 \times 10^{-7}$.

In figure 7 we show a comparison of these results with the previous published data.

While the mass is in good agreement with previous results, the total width, Γ, is smaller. We remark that our E835-96-97 result [13)], though statistically compatible with the present one, was based on a poorer statistics and furthermore the scan of the resonance was limited to four energy points only.

5.1 Some comparison to Perturbative QCD predictions

We remark some striking discrepancies between the obtained results and PQCD predictions, namely:

a) the measured ratio $\Gamma(\chi_{c0} \to hadrons)/\Gamma(\chi_{c2} \to hadrons)$ gives $5.72^{+0.70}_{-0.64}$, while PQCD at first order predicts 9.7 [14)];

b) the measurement of $\Gamma(\chi_{c0} \to \bar{p}p)/\Gamma(\chi_{c0} \to hadrons) \simeq BR(\chi_{c0} \to \bar{p}p)$, which is forbidden by massless QCD, gives $5.86^{+2.6}_{-1.1} \times 10^{-4}$. The $\bar{p}p$ coupling is in fact ~ 6 times larger than the $\chi_{c1,2}$ coupling.

[1] A whole resonance scan takes only a few weeks

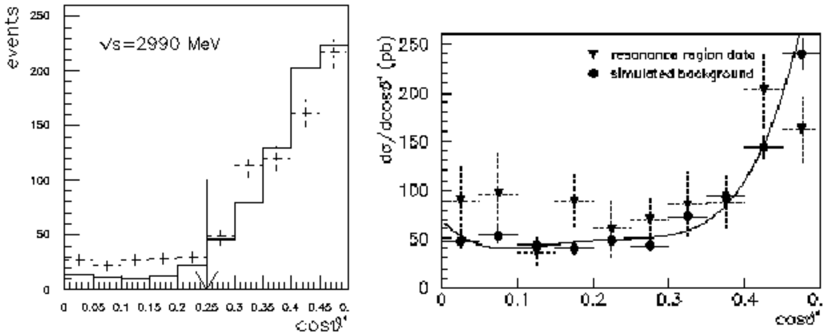

Figure 8: Measured cross section of $\bar{p}p \rightarrow \gamma\gamma$ vs. $|cos\theta^*|$ at the η_c region (left) and at the χ's region (right)

6 $\gamma\gamma$ final state

Let us examine the event selection for the process $\bar{p}p \rightarrow \bar{c}c \rightarrow \gamma\gamma$, where $\bar{c}c$ here stands for $\eta_c, \chi_{c0,2}$ or η_c'.

The selection allows for two clusters on time. At most one *undetermined* cluster [2] is allowed if the invariant mass with any of the above clusters is outside the π^o region (100 -170 MeV/c^2). The two-body kinematical fit probability has to be greater than 5%.

The background is due to $\pi^o\pi^o$ and $\pi^o\gamma$ final states where two γ ($\pi^o\pi^o$ case) or one γ ($\pi^o\gamma$ case) from the π^o decay is undetected either because is out of the detector acceptance either below detection threshold ($\sim 20\ MeV$).

The distributions of the $\gamma\gamma$ candidates as a function of cosθ^* where θ^* is the decay angle in the center of mass of the reaction are shown for $\sqrt{s} = 2990$ MeV (η_c energy) (fig. 8 (left)) and for $\sqrt{s} \sim 3550$ MeV (fig. 8 (right)).

The continuous line in fig. 8 (left) and the full dots in fig. 8 (right) are the predictions of the expected background due to $\pi^o\pi^o$ and $\pi^o\gamma$ (feeddown calculation). The distribution of the ($\bar{c}c$) decays vs. $|$ cosθ^* $|$ should be flat, on the contrary the distribution due to the background is expected to be peaked

[2]Cluster are classified according to three categories: a) on time: in a few ns range from the event time; b) out of time; c) undetermined: no TDC information, typically because the signal is below the energy threshold $\sim 40\ MeV$.

at larger $|\cos\theta^*|$, in the the forward direction. For this reason a further cut set at $|cos\theta^*| < 0.25$ at the η_c region and $|cos\theta^*| < 0.40$ at the χ's and η_c' region has been applied.

6.1 η_c mass and width

These data refer to E835-96-97 and are still preliminary.

The event yields in each energy point normalized with the luminosity are shown as full dots in fig 9.

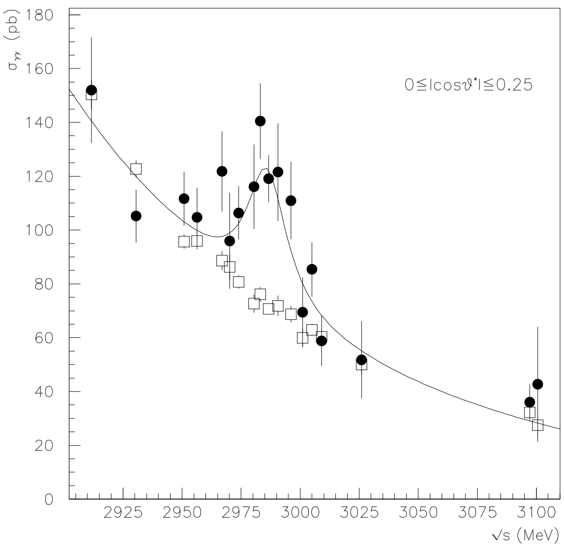

Figure 9: Measured cross of $\bar{p}p \to \gamma\gamma$ for $|\cos\theta^*| < 0.25$ as a function of the center of mass energy

Corrections due to limited differences in the trigger and analysis efficiencies have been already applied. The empty squares are the feeddown calculation results. The agreement between the background calculation and the data points is remarkably good.

A Maximum Likelihood fit to a resonance plus a continuum obtained from the feeddown gives the following results:

Mass $= 2985.4 \pm 2.1$ MeV/c^2, Width $= 21.1^{+7.5}_{-6.2}$ MeV, $\Gamma_{\gamma\gamma} = 3.9^{+1.5+1.8}_{-1.3-1.1}$ keV for which we have taken from PDG the $BR(\eta_c \to \bar{p}p) = (1.2 \pm 0.4) \times 10^{-3}$.

The η_c mass measured by E835-96-97 is in good agreement with recent measurement beside BES [16] which found a mass substantially lower. The total width, larger than previous measurements, agrees well with the value recently published by CLEO [17].

Using PQCD first order approximation one can derive from the ratio $\Gamma(\eta_c \to gluon\ gluon)/\Gamma(\eta_c \to \gamma\gamma) \simeq \Gamma(\eta_c)/\Gamma(\eta_c \to \gamma\gamma) \simeq \frac{9\alpha_s^2}{8\alpha^2} \times \frac{(1+4.8\alpha_s/\pi)}{(1-3.4\alpha_s/\pi)}$, the value of $\alpha_s(m_c)$ which is found equal to 0.33 ± 0.02.

6.2 $\chi_{c0,2} \to \gamma\gamma$ results

I'll summarize the results, which have been recently published [15], after noticing that E835-2000 collected a six times larger statistics at the χ_{c0}.

For each data point on the resonance, we constructed the following ratio:

$$R = \frac{(N^{res}_{\gamma\gamma} - N^{bckd}_{\gamma\gamma})/\epsilon_{\gamma\gamma}}{(N^{res}_{J/\psi\gamma} - N^{bckd}_{J/\psi\gamma})/\epsilon_{J/\psi\gamma}} \frac{BR(\gamma\gamma)}{BR(J/\psi\gamma)}$$

where $N^{res}_{\gamma\gamma}(N^{res}_{J/\psi\gamma})$ is the number of $\gamma\gamma$ $(J/\psi\gamma)$ candidates; $N^{bckg}_{\gamma\gamma}(N^{bckg}_{J/\psi\gamma})$ is the expected number of background events; $\epsilon_{\gamma\gamma}$ $(\epsilon_{J/\psi\gamma})$ is the acceptance $\times$ efficiency of the $\gamma\gamma$ $(J/\psi\gamma)$ selection.

Averaging R over the data points around the resonances, we found:

$< R >= (0.244 \pm 0.125) \times 10^{-4}$ for χ_{c0} and $(1.67 \pm 0.30) \times 10^{-4}$ for χ_{c2}.

Replacing the $BR(J/\psi\gamma)$ taken from the PDG, we quoted: $BR(\gamma\gamma) = (0.97 \pm 0.50 \pm 0.28) \times 10^{-4}$ for χ_{c0} and $(1.35 \pm 0.25 \pm 0.12) \times 10^{-4}$ for χ_{c2}. Finally the $\gamma\gamma$ partial width that has been quoted is: $\Gamma_{\gamma\gamma} = (1.61 \pm 0.83 \pm 0.65)$ keV for χ_{c0} [3] and $\Gamma_{\gamma\gamma} = (270 \pm 49 \pm 33)$ eV for χ_{c2}.

Our result of $\Gamma(\chi_{c2} \to \gamma\gamma)$, substantially smaller than other measurements, is only compatible with the E760 previous measurement [2].

[3] Here, to be consistent with the published result I used $\Gamma(\chi_{c0}) = 16.6 MeV$ instead of the preliminary result quoted in this paper.

7 η_c' search

E835-96-97 performed a search of the η_c' decaying via $\gamma\gamma$. Data were taken for $\sqrt{s}$ between 3576 and 3660 MeV, in 20 energy points almost equally spaced by 5 MeV and with an average luminosity of 1.5 pb^{-1} per point.

Preliminary results of the data analysis gave an upper limit (90% CL) of the product $BR(\bar{p}p \to \eta_c') \times BR(\eta_c' \to \gamma\gamma)$ at a few units of 10^{-8} depending on the center of mass energy and the resonance width which has been assumed for the calculation.

8 $\chi_{c1,2}$ angular distributions

The angular distribution can be described, from the formation channel, in terms of the helicity components $B_{|\lambda\bar{p}-\lambda p|}$, where $|\lambda\bar{p}-\lambda p|$ is the $\chi_{c1,2}$ along the $\bar{p}$ direction. Furthermore, from the decay channel, the angular distribution can be described in terms of the multipole contributions: electric dipole E1, magnetic quadrupole M2, electric octupole E3. The parameter to describe the decay process are: $A_{|\lambda\psi-\lambda\gamma|}$, where $|\lambda\psi-\lambda\gamma|$ is the $\chi_{c1,2}$ spin projection along the J/ψ direction. Finally, the parameter A_i (i=0,1,2) can be expressed in terms of multipole expansion parameters a_{i+1}. The formalism requires: $B_0^2+B_1^2=1$ and $a_1^2+a_2^2+a_3^2=1$. From a sample of 2144 χ_{c1} and 6028 χ_{c2} with an unbinned Maximum Likelihood analysis we obtained as preliminary results:

χ_{c1} : $a_2 = 0.011^{+0.032}_{-0.031}$

χ_{c2} : $a_2 = -0.107^{+0.049}_{-0.047}$; $a_3 = 0.014^{+0.046}_{-0.038}$; $B_0^2 = 0.097^{+0.090}_{-0.093}$

These results are not fully explained by the current predictions: in example the predicted theoretical value of the ratio $a_2(\chi_{c1})/a_2(\chi_{c2})$ is +0.67, while we derived -0.10 $\pm$ 0.31.

9 Conclusions

The experiment E835 has studied the charmonium states in $\bar{p}p$ formation and the data taking has recently finished. In this paper are presented some results, most of which still preliminary. The list includes: mass and width of χ_{c0} and η_c; $\gamma\gamma$ partial widths of $\chi_{c0,2}$ and η_c. Analyses of other states and decay channels are still underway.

10 Acknowledgements

It is a pleasure for the author to acknowledge the organizers for the excellent Conference. The E835 Collaboration wishes to acknowledge the Fermilab Beams Division for the successful beam manipulation. Finally, the E835 Collaboration acknowledges the support of the U.S. Department of Energy (DOE), the U.S. National Science Foundation (NSF), and the Italian Istituto Nazionale di Fisica Nucleare (INFN).

References

1. C. Baglin *et al.*, Nucl. Phys.**B286**, 592 (1987).
2. C. Caso *et al.*, The Eur. Phys. Jour. C**15**, 664 (2000)
3. M. Church and J. Marriner, Ann. Rev. Part. Sci. **43**, 253 (1993).
4. D. Allspach *et al.*, Nucl. Instr. Meth. **A410**, 195 (1998).
5. S. Bagnasco *et al.*, Nucl. Instr. Meth. **A424**, 304 (1999).
6. L. Bartoszek *et al.*, Nucl. Instr. Meth. **A301**, 47 (1991).
7. S. Trokenheim *et al.*, Nucl. Instr. Meth. **A355**, 308 (1995).
8. R. Cester and P.A. Rapidis, Ann. Rev. Part. Sci. **44**, 329 (1994).
9. T.A. Armstrong *et al.*, Phys. Rev. **D47**, 772 (1993).
10. T.A. Armstrong *et al.*, Phys. Rev. Lett. **70**, 2983 (1993).
11. T.A. Armstrong *et al.*, Phys. Rev. Lett. **69**, 2337 (1992).
12. T.A. Armstrong *et al.*, Phys. Rev. **D52**, 4839 (1995).
13. M. Ambrogiani *et al.*, Phys. Rev. Lett. **83** (1999) 2902
14. W. Kwong *et al.*, Phys. Rev. **D37**, 3210 (1988)
15. M. Ambrogiani *et al.*, Phys. Rev. **D62**, 052002 (2000).
16. J.Z. Bai *et al.*, Phys.Rev. **D62**, 072001 (2000).
17. G. Brandenburg *et al.*, Phys. Rev. Lett. **85**, 3095 (2000).