Precision Measurements of Charmonium States formed in $\bar{p}p$ Annihilation

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Abstract

Fermilab experiment E-760 studies the resonant formation of Charmonium states in proton-antiproton interactions using a hydrogen gas-jet target in the antiproton Accumulator ring at Fermilab. Precision measurements of the mass and width of the Charmonium states, χ_1 , χ_2 and a new measurement of the ψ mass are presented.

We report the first results from Fermilab experiment E-760, a study of charmonium states formed directly in proton-antiproton annihilation. We present the first measurement of the total width of the 3P_1 , (χ_1) and improved measurements of the 3P_2 , (χ_2) total width and of the masses of both resonances. We also report a new measurement of the mass of the J/ψ .

The experiment uses a beam of antiprotons circulating in the Fermilab Antiproton-Accumulator and an internal hydrogen gas-jet target to study charmonium states formed in the exclusive reaction $\bar{p} + p \rightarrow (\bar{c}c)$. States of all allowed J^{PC} are formed directly in $\bar{p}p$ annihilation while only states of $J^{PC} = 1^{--}$ are made directly in e^+e^- annihilation. The masses and widths of the $(\bar{c}c)$ states are determined directly from the antiproton beam energy by observing the excitation curves of the resonances as the energy of the antiproton beam is changed in small steps. This technique was first exploited at the CERN ISR ⁽¹⁾. In the present experiment, the antiproton beam was cooled to $(\Delta p/p)_{rms} \approx 2 \times 10^{-4}$ allowing the first direct measurement of sub-MeV widths for the charmonium states.

The Breit-Wigner cross section for resonant formation of a $\bar{c}c$ state in the reaction $\bar{p} + p \rightarrow (\bar{c}c)$ is

$$\sigma = \frac{4\pi(\hbar c)^2}{(W^2 - 4(m_p c^2)^2)} \times \frac{(2J_R + 1)}{(2s + 1) * (2s + 1)} \times \frac{\Gamma(R \rightarrow \bar{p}p) * \Gamma_R}{[(W - M_R c^2)^2 + \Gamma_R^2/4]}$$

where m_p and s are the proton mass and spin, W is the $\bar{p}p$ invariant mass, J_R, M_R, Γ_R are respectively the spin, mass and total width of the resonance and $\Gamma(R \rightarrow \bar{p}p)$ is the partial width of the resonance to $\bar{p}p$. For the charmonium states, the formation cross sections are as small as one part in 10^6 of

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the total hadronic $\bar{p}p$ cross section at these energies. Thus it is not feasible to detect these states in the total cross section or through their hadronic decays. However, by selecting the decay modes:

$$\bar{c}c \rightarrow J/\psi + X, J/\psi \rightarrow e^+e^-$$

an almost background free sample can be obtained.

The Fermilab antiproton source was primarily designed to provide antiprotons for the Tevatron collider and to operate at a fixed energy of 8.9 GeV to match the injection energy of the Fermilab main ring. The extensive modifications required to enable it to be used for the present experiment are described in the references ⁽²⁾. The results presented here depend on our knowledge of two parameters of the antiproton beam: the absolute value of the beam momentum and the beam momentum spread. The beam momentum is most precisely derived from a knowledge of the beam velocity measured from the revolution frequency, f_r , and the orbit length, L_o . The uncertainty in the center of mass energy, W , is then given by :

$$\Delta W = \frac{m_p^2}{W} (\gamma_{beam})^3 (\beta_{beam})^2 [(\Delta f_r/f_r)^2 + (\Delta L_o/L_o)^2]^{1/2}$$

Since the revolution frequency is measured with a precision of $\Delta f_r/f_r \approx 2 \times 10^{-7}$, the major uncertainty comes from the knowledge of the orbit length. Conventional surveying techniques proved not sufficiently precise and so a reference orbit length was determined by performing a scan at the ψ' . The 0.1 MeV/c² uncertainty in the known mass of the ψ' ⁽³⁾ produces a 0.7 mm systematic uncertainty in L_{ref} . Repeated energy scans at the J/ψ showed a reproducibility of the center of mass energy setting to better than 0.05 MeV/c² which corresponds to a further uncertainty of 1mm in the total orbit length of 474.046 meters. This figure is consistent with the intrinsic resolution of the beam position monitors which are used to correct for changes between the reference orbit and the orbits used in the various data scans of the resonances.

To determine the actual resonance widths, the beam momentum distribution must be unfolded from the observed excitation curves. This distribution is found from the beam revolution frequency spectrum using the relation $\Delta f_r/f_r = \eta * \Delta p/p$; the beam revolution frequency spectrum itself is obtained by Fourier analysis of the beam current Schottky noise. The quantity η ($= 1/\gamma_{beam}^2 - 1/\gamma_{transition}^2$) depends on the value of the Accumulator transition energy. Several methods have been used to determine η including a "double-scan" technique in which two excitation curves for the ψ' were measured in a single energy scan, centering the beam on two distinct orbits; this method provides a direct measurement and has the advantage of not depending on any knowledge of the accumulator lattice setting ⁽⁴⁾. We estimate a $\pm 10\%$ uncertainty in the value of η . The typical beam energy spread, $(\Delta E_{lab})_{rms}$, was 1 MeV corresponding to a spread in the center of mass energy, $(\Delta W) = \Delta E_{lab} \times m_p/M_R$, of 300 keV.

Figure 1 shows a cut through the E-760 detector. The intersection of the gas-jet ⁽⁵⁾ and the antiproton beam produces an interaction region about 0.5 cm on a side. The detector has a large acceptance and is optimized for the identification of electromagnetic final states from charmonium decay. It covers the complete azimuth, (ϕ), and from 2° to 70° in polar angle (θ). The central and forward calorimeters identify electrons and photons and measure their energies and directions. The central calorimeter covers the region $12^\circ < \theta < 70^\circ$. The apparatus inside it consists from the beam-pipe out of: an inner scintillation-counter hodoscope, two layers of longitudinal straw-tubes ⁽⁶⁾ which provide information in both ϕ and θ , a radial projection chamber and an MWPC with cathode readout to provide θ information ⁽⁷⁾, a second scintillation-counter hodoscope and a multi-cell threshold Cerenkov counter ⁽⁸⁾ for electron identification. The outermost tracking devices in the central region are two layers of larocci tubes with cathode read-out for θ and ϕ information ($68^\circ > \theta > 22^\circ$), and a planar MWPC ⁽⁹⁾ ($18^\circ > \theta > 10^\circ$). The central electromagnetic calorimeter ⁽¹⁰⁾ itself is made of 1280 lead-glass Cerenkov counters pointing to the interaction region, arranged in 64 wedges

in ϕ and 20 rings in θ . The forward region ($2^\circ < \theta < 12^\circ$) is instrumented with an 8 element hodoscope, and a 144 channel Pb/Scintillator calorimeter⁽¹¹⁾ preceded by three planes of straw-tubes. An array of silicon detectors⁽¹²⁾ covering the polar angle region from 82° to 90° measures the yield of elastic recoil protons and provides the luminosity monitor.

For this first data run, the antiproton accumulation rate was about 0.5 milliamp/hour ($1 \text{ ma} = 10^{10} \bar{p}$) and the typical cycle consisted of 40 hours stacking, some hours of deceleration from the accumulation energy to an energy just above the state of interest and then some 50 hours of data-taking while decelerating in steps of between 70 keV and 170 keV (center of mass energy) through the resonance. The beam lifetime was 40 hours and the experiment ran at a peak luminosity of $8 \times 10^{30} \text{ cm}^{-2}/\text{sec}$.

The experiment trigger for this data was designed to select all ($c\bar{c}$) decays to a final state with a J/ψ (or ψ') decaying to e^+e^- in the acceptance of the central calorimeter. This was implemented by requiring two electron "tracks" as defined by the hodoscopes and signals from the appropriate cell in the Cerenkov counters and two localized energy depositions in the central electromagnetic calorimeter above a certain threshold⁽¹³⁾. To ensure a high mass, the energy clusters were required to have an azimuthal opening angle greater than 90° . The trigger had a measured efficiency of $87 \pm 2\%$ and a rate of $< 10 \text{ Hz}$ thus allowing the experiment to operate with minimal deadtime.

Figure 2(a) shows the distribution of the invariant mass of candidate electron-positron pairs, m_{ee} , as measured with the central calorimeter for events found at the J/ψ formation energy. The J/ψ cross section is so large that a background free sample can be identified simply by requiring two energy clusters in the lead-glass calorimeter associated with appropriate signals from the Cerenkov counters. These events are then used as reference. For the χ states remarkably clean signals are found in the exclusive channel $\chi \rightarrow J/\psi + \gamma$, $J/\psi \rightarrow e^+ + e^-$ by performing a standard kinematic fit on events with two tracks pointing to energy depositions in the central calorimeter and an associated photon if it was within the acceptance of the calorimeters.

The open area in Figure 2(b) shows the m_{ee} distribution found for events which satisfy the kinematic fit (probability $> 10^{-4}$) in the χ_2 energy scan. The background is determined by taking data off-resonance and applying the same analysis as for the on-resonance data; the hatched area on fig 2b shows the background event distribution normalized to the on-resonance luminosity.

Table 1 lists the luminosity taken at each resonance, the total number of events found and the estimated number of background events under the resonance as determined by the off-resonance data. The mass and width of each state are calculated by a maximum likelihood fit of the number of events found at each point of the energy scan to the Breit-Wigner cross section convoluted with the measured beam energy distribution plus a constant background. Figures 3(a)→(d) show the excitation cross-sections measured with energy scans at the J/ψ , χ_1 , χ_2 and ψ' respectively. The full curve is the convolution of the resonance Breit-Wigner with the beam energy distribution; the dashed lines on figures 3(b) and 3(c) show the typical beam energy distribution.

The results of the fits are given in table 2. For the mass measurements, the first uncertainty given is the statistical error from the fit, the second is an estimate of the systematic error which arises from the uncertainty in the reference orbit-length due to the uncertainty in the mass of the ψ' . Since the two χ masses are so close to each other, the mass difference $M_{\chi_2} - M_{\chi_1}$ is hardly affected by the systematic uncertainty in the absolute energy and so has a smaller systematic error than the individual states. At the J/ψ mass, the systematic uncertainty in the orbit length produces a 30 keV/c² systematic uncertainty. For the width measurements, the first error given is the statistical uncertainty from the fit, the second is the systematic error due to the uncertainty in our knowledge of the beam momentum spread.

Inspection of table 2 shows that the results given here represent a significant improvement in our knowledge of the χ charmonium states parameters. For the masses of the χ_2 and χ_1 the new values agree well with previous ones and the errors are reduced by a factor > 2 . The width of the χ_1 has

been measured for the first time and the uncertainty on the χ_2 width has been reduced from $\sim 40\%$ to $\sim 10\%$. The measurements of total widths can be used to obtain the partial widths for radiative and hadronic decays given the known branching ratios ⁽³⁾. The comparisons of the partial widths with theoretical predictions will be presented elsewhere ⁽¹⁴⁾.

These first results show the power of the present technique to provide data to test models of the charmonium system and we gratefully acknowledge the technical support from our collaborating institutions and the outstanding contribution of the Fermilab Accelerator Division Antiproton department. This work was funded by the U.S. Department of Energy and the National Science Foundation and by the Italian Istituto Nazionale di Fisica Nucleare.

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Table 1: Luminosity for each resonance scan

Resonance	P_{beam} (MeV/c)	Integrated Luminosity nb ⁻¹	Total No. of Events	Background Events
J/ψ	4063.	360	~ 4000	8 ± 3
χ_1	5550.	1030	503	19 ± 3
χ_2	5724.	1160	569	22 ± 4
ψ'	6232.	500	465	6 ± 4

Table 2: Resonance parameters

Resonance	Mass (MeV/c ²)	Width (keV)
J/ψ (this expt.)	$3096.88 \pm 0.06 \pm 0.03$	
J/ψ (ref 3)	3096.93 ± 0.09	0.063 ± 0.009
χ_1 (this expt.)	$3510.53 \pm 0.04 \pm 0.12$	$880 \pm 110 \pm 80$
χ_1 (ref 3)	3510.6 ± 0.5	< 1300
χ_2 (this expt.)	$3556.15 \pm 0.07 \pm 0.12$	$1980 \pm 170 \pm 70$
χ_2 (ref 3)	3556.3 ± 0.4	2600^{+1200}_{-900}
ψ' (this expt.)	3686.0 (input)	
ψ' (ref 3)	3686.0 ± 0.1	243 ± 40
$\chi_2 - \chi_1$ (this expt.)	$45.62 \pm 0.08 \pm 0.07$	

Figure Captions

1. FIG. 1 A cut through the E-760 Apparatus.
2. FIG. 2a The reconstructed invariant mass of candidate electron pairs for events at the J/ψ formation energy
3. FIG. 2b The reconstructed invariant mass of candidate electron pairs for events at the χ_2 formation energy (open) and off-resonance normalized to the same luminosity (shaded).
4. FIG. 3a The excitation curve observed for the J/ψ .
5. FIG. 3b The excitation curve observed for the χ_1 .
6. FIG. 3c The excitation curve observed for the χ_2 .
7. FIG. 3d The excitation curve observed for the ψ' .

Fig. 1: E760 equipment layout.

Fig. 2a: The reconstructed invariant mass of candidate electron-pairs for events at J/ψ formation energy.

Fig. 2b: The reconstructed invariant mass of candidate electron-pairs for events at χ_2 formation energy (open) and for events off-resonance normalized to the same luminosity (shaded).

Fig. 3a: The excitation curve observed for the J/ψ .

Fig. 3b: The excitation curve observed for the χ_1 .