$J/\psi\pi^o$ AND e^+e^- EXCLUSIVE PRODUCTION IN PROTON ANTIPROTON ANNIHILATIONS

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ABSTRACT

We have measured the non resonant production cross section for the processes $\bar{p}p \to J/\psi\pi^o$ and $\bar{p}p \to e^+e^-$ at center of mass energies around $E_{cm} \approx 3.5\,GeV$. We found evidence for a resonance decaying to $J/\psi\pi^o$ of mass $M_R = 3525.2 \pm 0.15 \pm 0.2\,MeV/c^2$ and width $\Gamma_R \leq 1.1\,MeV$ (90% CL) that we identify with the state $h_c(1^1P_1)$ of charmonium. The cross section $\bar{p}p \to e^+e^-$ is analized in terms of the proton electromagnetic form factors, providing their measurements at the highest momentum transfer values available up to now in the time-like region.

THE EXPERIMENT E760 AT FNAL

Experiment E760 is devoted to the study of charmonium states produced in $\bar{p}p$ annihilations. This tecnique, as compared to the production in e^+e^- annihilations, has the advantage that also states with quantum numbers J^{PC} other than 1^{--} can be studied in formation.

The $\bar{p}$ beam circulating in the Fermilab Antiproton Accumulator intersects an internal H_2 gas jet target installed in one of the low-dispersion sections of the accumulator, providing an initial luminosity of $\sim 1 \cdot 10^{31} cm^{-2} s^{-1}$ with a beam lifetime of 90 to 50 h, depending on the beam momentum.

Resonance parameters are determined from the excitation curve measured by performing an energy scan across the resonance. The center-of-mass energy is only determined by the beam momentum, and a very precise knowledge of beam energy distribution allows a direct measurement of resonance width even for the J/ψ [3].

Since the $(c\bar{c})$ cross section in this energy range is an extremely low fraction ($\approx 10^{-6}$) of the total $p\bar{p}$ cross section, the detector has been designed to identify electromagnetic final states of $(c\bar{c})$ decays, e.g.:

$$p\bar{p} \to (c\bar{c}) \to e^+e^- \quad \text{and} \quad p\bar{p} \to (c\bar{c}) \to J/\psi + X \to e^+e^- + X \tag{1}$$

$$p\bar{p} \to (c\bar{c}) \to \gamma\gamma \quad \text{and} \quad p\bar{p} \to (c\bar{c}) \to \eta_c + X \to \gamma\gamma + X \tag{2}$$

The results on parameters of J/ψ, χ_{c1}, χ_{c2} and ψ' resonances, are described in ref.[1],[2], [3] and will not be reported here. Here we focus on the analysis of the exclusive processes:

$$p\bar{p} \to J/\psi\pi^o \to e^+e^-\gamma\gamma \tag{3}$$

$$p\bar{p} \to e^+e^- \qquad \text{(non resonant)} \tag{4}$$

which are characterized by an extremely low cross section, but can nevertheless be cleanly identified in our experiment.

DETECTOR LAYOUT

The detector (see ref. in [2]) is a non-magnetic spectrometer with full azimuthal (ϕ) coverage and polar angle (θ) acceptance ranging from 2° to 70°. The layout of the detector is shown in fig.1. The central detector ($12° < \theta < 70°$) has cylindrical symmetry around the beam axis and consists of: two scintillator hodoscopes (H1 and H2); a set of proportional and drift chambers, which identify and measure the direction of the charged tracks; a multicell threshold Čerenkov counter for electron/pion separation; and a lead glass electromagnetic calorimeter with pointing geometry. The forward detector, extending the θ acceptance down to 2°, consists of a veto hodoscope, a three-layer straw-tube drift chamber and a Pb/scintillator calorimeter. The luminosity is provided by a set of silicon detectors

Figure 1: E760 detector layout

($82^\circ < \theta < 90^\circ$) which measure direction and energy of the recoil proton from forward antiproton elastic scattering.

With this arrangement we achieve an angular resolution of 4 mrad in θ and 7 mrad in ϕ. The energy resolution $\Delta E/E$ is $0.06/\sqrt{E(GeV)}$ and $0.11/\sqrt{E(GeV)}$ for the central and forward calorimeter respectively.

INCLUSIVE EVENT SELECTION

In the final state of reactions (1) the J/ψ is always produced almost at rest in the CM frame and the e^+e^- momenta are nearly coplanar. The fast trigger logic designed for these channels requires two loosely coplanar ($|\Delta\phi| > 163^\circ$) electron tracks in the central detector (being defined as the coincidence between elements of H1, H2 and the Čerenkov) and two large energy depositions in the central calorimeter ($|\Delta\phi| > 90^\circ$) The efficiency of this trigger has been measured as $\epsilon_{trig} = 0.93 \pm 0.02$.

A preliminary offline selection requires at least two isolated showers in the central calorimeter associated with good electron track candidates.

The inclusive selection relies upon electron identification, based on the pulse height information in the Čerenkov counter, dE/dx measurements and the transverse shape of the energy distribution in the central calorimeter. A likelihood function is defined for both genuine electrons (using a clean sample from J/ψ scans) and background events (using the whole sample of events from the $^1P_1$ scan), the choice between these hypotesis is done based on the value of the likelihood ratio. The efficiency of the inclusive selection, determined from a clean sample of χ_{c2} events, is $\epsilon_{inc} = 0.88 \pm 0.02$

OBSERVATION OF 1^1P_1 STATE OF CHARMONIUM

We have searched for the 1^1P_1 state of charmonium performing a high luminosity scan ($\mathcal{L} \sim 16\,pb^{-1}$) in the vicinity of the center of gravity of the $\chi_c(^3P_J)$ states $m_{c.o.g.} = 3525.7 \pm 0.12\,MeV$[4].

All events surviving the inclusive selection are plotted in fig.2. A clear J/ψ signal can be seen also in the inclusive sample. Kinematical fits to all topologically compatible hypoteses were attempted for events in the inclusive sample. Shaded area in fig.2 represent events fitting $\bar{p}p \to J/\psi\pi^o$ (black solid), $\bar{p}p \to J/\psi\gamma$ (cross hatched) and $\bar{p}p \to e^+e^-$ (vertical stripes). No events were found to fit the reaction $\bar{p}p \to J/\psi\pi^o\pi^o$ or $\bar{p}p \to J/\psi\pi^+\pi^-$.

The subsequent analysis was restricted to events fully contained in the detector acceptance ($\epsilon_{geom} \approx 55\%$ for $J/\psi\gamma$, $\approx 40\%$ for $J/\psi\pi^o$, $\approx 55\%$ for e^+e^-).

The events observed in the $J/\psi\gamma$ channel cannot be ascribed to the decay of singlet P-state because of C-parity conservation, and are compatible with the hypotesis of χ_{c1} and χ_{c2} contribution, when taking into account the long tails of the beam energy distribution.

C-parity conservation prevents χ_c's to contribute to the events observed in the reaction $\bar{p}p \to J/\psi\pi^o$, that can only be due to a continuum or to $h_c(1^1P_1)$ resonant production.

Our results for this channel are displayed in Fig.3, with the data binned in intervals of $150\,keV$ in the center-of-mass energy. An apparenlty uniform cross section of $\sim 2\,pb$ can be noticed below the $m_{c.o.g.}$, while a consistenlty higher cross section can be observed in a small region above $m_{c.o.g.}$. The measured cross section has been fitted with the maximum likelihood method to a constant continuum level plus a Breit-Wigner resonance function convoluted with the beam energy distribution.

The non resonant reaction $\bar{p}p \to J/\Psi\pi^o$ has a cross section of $100 \pm 40\,pb$ (slowly increasing to $156 \pm 36\,pb$ at $\sqrt{s} \sim 3610\,MeV$), and the resonance parameters are $M_R =$

$3525.2 \pm 0.15 \pm 0.2\, MeV/c^2$, $\Gamma_R \leq 1.1\, MeV$ (90% CL). The value of the product $B.R.(R \rightarrow p\bar{p}) \times B.R.(R \rightarrow J/\psi\pi^o)$ depends on Γ_R, but assuming a plausible range of values ($1.0\, MeV \leq \Gamma_R \leq 0.5\, MeV$), we find $(1.7 \pm 0.4)10^{-7} \leq B.R.(R \rightarrow p\bar{p}) \times B.R.(R \rightarrow J/\psi\pi^o) \leq (2.3 \pm 0.6)10^{-7}$

We interpret this resonance as the first evidence for the $h_c(1^1P_1)$ state of charmonium. The probability that a statistical fluctuation of the continuum $J/\psi\pi^o$ could simulate a resonance with equal or higher significance anywhere in the scanned region is $1/400$.

ELECTROMAGNETIC FORM FACTORS IN THE TIME-LIKE REGION

Events in the $\bar{p}p \rightarrow e^+e^-$ channel, at center-of-mass energies far from the formation energies of J/ψ and Ψ', can only be due to non resonant production.

The differential cross section for process (4) can be expressed in terms of the proton magnetic and electric form factors as[7]:

$$\frac{d\sigma}{d(cos\theta_{cm})} = \frac{\pi\alpha^2(\hbar c)^2}{8\ E\ P}\left[|G_M|^2(1 + cos^2\theta_{cm}) + \frac{4m_p^2}{s}|G_E|^2 sin^2\theta_{cm}\right], \qquad (5)$$

where E and P are the center of mass energy and momentum of the antiproton, and θ_{cm} is the angle between the e^- and the $\bar{p}$ in the center of mass.

Candidate events are selected from the inclusive sample (adding the data taken at $\sqrt{(s)} = 2.99\, GeV and 3.61\, GeV$) by further requiring only two clusters in the central calorimeter having azimuthal opening angle $\phi_{ee} < 180 \pm 1.7°$ and polar opening angle $\theta_{ee} < 180 \pm 3°$. We also required the two electron invariant mass to be greater than $\geq 2.74, 3.30$, and $3.38\, GeV/c^2$ for data taken at $\sqrt{s} = 2.99$, 3.52, and $3.61\, GeV$, respectively. The number of events in the final sample are listed in Table 1, together with the integrated luminosity accumulated at each energy. The overall efficiency, including trigger and inclusive selection efficiency, is $\epsilon = (0.73 \pm 0.03)$.

The main sources of experimental background for the reaction (4) are two-pion final states and the large π^o yield in $\bar{p}p$ annihilation.

The cross section, $\sigma(p\bar{p} \rightarrow \pi^+\pi^-)$ is known[8] to be $\leq 10\mu b$ for $2.9 \leq \sqrt{s} \leq 3.6\, GeV$. The hadron rejection for two-track events is determined to be better than $1/10^9$, therefore the background contribution from this source is negligible ($\leq 0.01\ pb$).

The neutral events which give only two clusters in the central calorimeter, and satisfy two-body kinematics have an effective production cross section of $800\, pb$ for $\sqrt{s} \approx 2.9\, GeV$ and of $100\, pb$ for $\sqrt{s} \approx 3.5\, GeV$. The conversion probability in the beam pipe is $\leq 2\%$ and only 5% of these unresolved electron pairs survive inclusive selection. The contribution to the background from this source is also negligible ($\leq 0.016\, pb$ at $\sqrt{s} \approx 2.9\, GeV$ and $\leq 0.002\, pb$ at $\sqrt{s} \approx 3.5\, GeV$).

We have analyzed our cross sections (taking into account that the fiducial range of the apparatus is limited to $15° < \theta < 60°$) under the approximations: (a) $|G_E| = |G_M|$ [6], and

(b) neglecting the term containing G_E. Results are presented in Table 1; the values of G_M obtained under the approximation (a) are plotted in fig.4, together with other available data in the time-like region.

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