Vol. 35 (2004) ACTA PHYSICA POLONICA B No 1

CHARMONIUM PRODUCTION WITH ANTIPROTON GAS-JET INTERACTIONS AT FNAL*

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(Received October 29, 2003)

Precision measurements of charmonium spectroscopy are obtained studying charmonium formed in $\overline{p}p$ annihilation. Two experiments at FNAL, E760 and E835, adopted this technique. Some of their results are briefly discussed.

PACS numbers: 13.20.Gd, 13.25.Gv, 13.40.Gp, 14.20.Dh

1. Introduction

Charmonium spectroscopy in $\overline{p}p$ annihilation is a powerful technique to perform precision measurement of charmonium spectroscopy for the narrow states with mass below the open charm threshold (3729 MeV).

The first experiment studying the charmonium spectroscopy in $\overline{p}p$ annihilation was R704 at CERN in 1984 [1, 2], that collected 3 pb^{-1} of data at the J/ψ, χ_1 and χ_2 to measure their mass and width, proving the feasibility of the experiment.

The two experiments E760 (in 1990-91) and E835 (in 1996-97 and 2000) at FNAL applied this technique installing a hydrogen Gas-Jet target on the Antiproton Accumulator, realizing a wide program of charmonium spectroscopy.

The $\overline{p}p$ center of mass energy distribution obtained in these experiments is very narrow if compared with the widths of most $\overline{c}c$ mesons and can be precisely controlled through the $\overline{p}$ beam parameters. The resonances are then scanned moving the beam energy across them. Details about the experiment and the detector can be found elsewhere [3].

* Presented at the XXXIII International Symposium on Multiparticle Dynamics, Kraków, Poland, September 5–11, 2003.

2. η_c, η_c' ($^1S_0$)

The mass and the width of the η_c were measured by all the $\overline{p}p$ experiments detecting its $\gamma\gamma$ decay, their results are summarized in Table I.

TABLE I

Mass and width measurements of charmonium states obtained by $\overline{p}p$ annihilation experiments. E835-I and E835-II are results obtained in the first (1996-97) and the second (2000) data taking period.

	Experiment	M (MeV)	Γ (MeV)
η_c	E835 [4]	$2984.1 \pm 2.1 \pm 1.0$	$20.4^{+7.7}_{-6.7} \pm 2.0$
	E760 [5]	$2988.3^{+3.3}_{-3.1}$	$23.9^{+12.6}_{-7.1}$
	R704 [6]	$2982.6^{+2.7}_{-2.3}$	$7.0^{+7.5}_{-7.0}$
J/ψ	E760 [7]	$3096.87 \pm 0.03 \pm 0.03$	$(99 \pm 12 \pm 6) \times 10^{-3}$
	R704 [1]	$3096.95 \pm 0.1 \pm 0.3$	-
ψ'	E760 [7]	$3686.02 \pm 0.09 \pm 0.27$	$(306 \pm 36 \pm 16) \times 10^{-3}$
χ_{c0}	E835-II [8]	$3415.4 \pm 0.4 \pm 0.2$	$9.8 \pm 1.0 \pm 0.1$
	E835-I [9]	$3417.4^{+1.8}_{-1.9} \pm 0.2$	$16.6^{+5.2}_{-3.7} \pm 0.1$
χ_{c1}	E835-II (Prelim.)	3510.64 ± 0.12	0.88 ± 0.09
	E760 [10]	$3510.53 \pm 0.04 \pm 0.12$	$0.88 \pm 0.11 \pm 0.08$
	R704 [2]	$3511.3 \pm 0.4 \pm 0.4$	< 1.3 (95% C.L.)
χ_{c2}	E835-II (Prelim.)	3556.10 ± 0.17	1.93 ± 0.22
	E760 [10]	$3556.15 \pm 0.07 \pm 0.12$	$1.98 \pm 0.17 \pm 0.07$
	R704 [2]	$3556.9 \pm 0.4 \pm 0.5$	$2.6^{+1.4}_{-1.0}$
h_c	E760 [11]	$3526.20 \pm 0.15 \pm 0.20$	< 1.1 (90% C.L.)
	R704 [12]	$3525.4 \pm 0.8 \pm 0.4$	-

Recently the η_c' have been observed by Belle at $M_{\eta_c'} = 3654 \pm 6 \pm 8$ MeV [13], this have been confirmed by BaBar and CLEO. E760 and E835 searched for the η_c' in the $\gamma\gamma$ decay channel in the Crystal Ball energy region ($M_{\eta_c'} = 3594 \pm 5$ MeV) without observing any signal [5, 14].

3. J/ψ, ψ' ($^3S_1$)

A clean sample of J/ψ and ψ' events is obtained looking for their decay to e^+e^-. E760 measured directly the J/ψ and ψ' mass and width [7]. The results obtained are summarized in Table I.

4. χ_{cJ} (^3P_J, $J = 0, 1, 2$)

The mass and widths of the χ_{cJ} states have been measured with the highest accuracy in $\overline{p}p$ annihilation. In particular, the E760 measurement of Γ_{χ_1} is still the only one available in the world. Preliminary results by E835 confirm these measurements, as shown in Table I.

E835 collected a large integrated luminosity on the χ_0, obtaining the most precise measurement of its mass and width [8]. The value obtained for Γ_{χ_0} is in disagreement with previous measurements; however the partial widths for the χ_{cJ} electric dipole radiative decay, obtained as $\Gamma_{\chi_J \to J/\psi\gamma} = \Gamma_{\chi_J} \mathcal{B}_{\chi_J \to J/\psi\gamma}$ are now in agreement with the theoretical expectations:

$$\Gamma_{\chi_J \to J/\psi\gamma} \propto k_J^3 |E_{if}|^2 , \tag{1}$$

where $k_J = (M_{\chi_J} - M_{J/\psi})/(2M_{\chi_J})$ and $|E_{if}| = \int R_\chi(r) r^2 R_{J/\psi}(r) dr$ where $R(r)$ are the radial wave function of the charmonium states.

The χ_{c0} have been studied also in $\pi^0\pi^0$ decay [15]. In the $\overline{p}p \to \pi^0\pi^0$ reaction, the χ_{c0} resonance is superimposed on a continuum so the differential cross section for the process can be written as:

$$\begin{aligned} \frac{d\sigma}{dz} &= \left| \frac{-A_\mathrm{R}}{x+i} + A\mathrm{e}^{i\delta_A} \right|^2 + \left| B\mathrm{e}^{i\delta_B} \right|^2 \\ &= \frac{A_\mathrm{R}^2}{x^2+1} + A^2 + 2A_\mathrm{R}A \frac{\sin\delta_A - x\cos\delta_A}{x^2+1} + B^2 , \end{aligned} \tag{2}$$

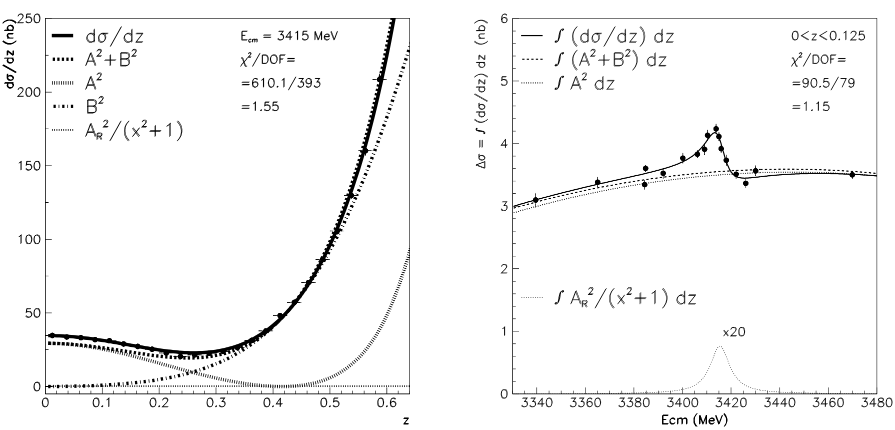

Fig. 1. Measured angular distribution (a) and cross section (b) of the reaction $\overline{p}p \to \pi^0\pi^0$ in the χ_{c0} energy region. The observed cross section enhancement due to the interference is compared with the one of the resonance if there was no interference, multiplied by a factor 20.

where $x = 2(E - M_{\chi c0})/\Gamma_{\chi c0}$, $z = |\cos\theta^*|$ and θ^* is the direction of $\pi^0\pi^0$ with respect to the $\overline{p}p$ axis in the center of mass, A_{R} is the Breit–Wigner resonant amplitude coefficient, A and δ_A are the amplitude and phase for the helicity 0 part of the continuum, that can interfere with the resonance, B and δ_B the ones for helicity 1 continuum production, which do not interfere with the resonance. The $A_{\mathrm{R}}A$ term in (2) shows that when the interfering continuum cross section is much higher than the resonant contribution, as it happens in this case, the resonance signal is enhanced by the interference. Figure 1 shows the measured angular distribution and cross section for $\overline{p}p \to \pi^0\pi^0$, fitted with the contributions in (2).

5. h_c ($^1P_1$)

A h_c candidate was observed by R704 with $M_{h_c} = 3525.4 \pm 0.9$ MeV in its J/ψ inclusive decay [12] and by E760, in the $h_c \to J/\psi\pi^0$ channel at $M_{h_c} = 3526.20 \pm 0.25$ [11] but still need confirmation.

Data for h_c confirmation have been collected by E835; the analysis of the data is still under way.

6. Proton form factor in the time-like region

By selecting exclusive $\overline{p}p \to e^+e^-$ events far from resonances E760 [16] and E835 [17, 18] performed the measurement of the proton magnetic form factor in the time-like region at large momentum transfer $8.9 < s < 14.4$ GeV^2.

The differential cross section of the process $\overline{p}p \to e^+e^-$ can be expressed in term of the magnetic and electric proton form factors G_{M} and G_{E} as:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4\beta_p s}\left[|G_{\mathrm{M}}|^2(1+\cos^2\theta^*) + \frac{4m_p^2}{s}|G_{\mathrm{E}}|^2\sin^2\theta^*\right]. \tag{3}$$

Integrating (3) over the solid angle and using one of the two approximation $|G_{\mathrm{E}}| = 0$ or $|G_{\mathrm{E}}| = |G_{\mathrm{M}}|$ respectively for high and low momentum transfer, it is possible to measure $|G_{\mathrm{M}}|$ as a function of s. The results, together with the ones at lower s^2 obtained at e^+e^- machines, are shown in figure 2.

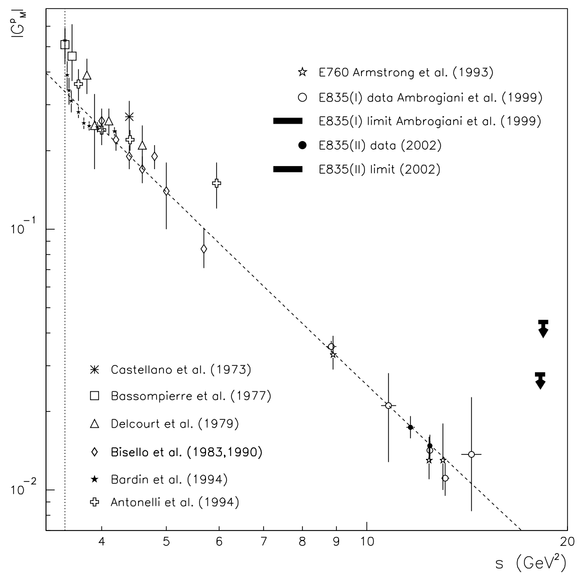

Fig. 2. Measurements of the proton magnetic form factor in the time-like region. The dashed line is the fit with the QCD asymptotic behavior prediction.

REFERENCES

[1] C. Baglin *et al.*, *Nucl. Phys.* **B286**, 592 (1987).

[2] C. Baglin *et al.* [R704 Collaboration], *Phys. Lett.* **B172**, 455 (1986).

[3] E835 Collaboration, submitted to *Nucl. Instrum. Methods.*

[4] M. Ambrogiani *et al.* [E835 Collaboration], *Phys. Lett.* **B566**, 45 (2003).

[5] T.A. Armstrong *et al.* [E760 Collaboration], *Phys. Rev.* **D52**, 4839 (1995).

[6] C. Baglin *et al.*, *Phys. Lett.* **B187**, 191 (1987).

[7] T.A. Armstrong *et al.* [E760 Collaboration], *Phys. Rev.* **D47**, 772 (1993).

[8] S. Bagnasco *et al.* [E835 Collaboration], *Phys. Lett.* **B533**, 237 (2002).

[9] M. Ambrogiani *et al.* [E835 Collaboration], *Phys. Rev. Lett.* **83**, 2902 (1999).

[10] T.A. Armstrong *et al.* [E760 Collaboration], *Nucl. Phys.* **B373**, 35 (1992).

[11] T.A. Armstrong *et al.*, *Phys. Rev. Lett.* **69**, 2337 (1992).

[12] C. Baglin *et al.* [R704 Collaboration], *Phys. Lett.* **B171**, 135 (1986).

[13] S.K. Choi *et al.* [BELLE collaboration], *Phys. Rev. Lett.* **89**, 102001 (2002) [Erratum-ibid. **89**, 129901 (2002)].

[14] M. Ambrogiani *et al.* [E835 Collaboration], *Phys. Rev.* **D64**, 052003 (2001).

[15] M. Andreotti *et al.* [E835 Collaboration], *Phys. Rev. Lett.* **91**, 091801 (2003).

[16] T.A. Armstrong *et al.* [E760 Collaboration], *Phys. Rev. Lett.* **70**, 1212 (1993).

[17] M. Ambrogiani *et al.* [E835 Collaboration], *Phys. Rev.* **D60**, 032002 (1999).

[18] M. Andreotti *et al.*, *Phys. Lett.* **B559**, 20 (2003).