Charmonium spectroscopy in $\bar{p}p$ annihilations

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The study of charmonium in $\bar{p}p$ annihilations has provided many of the most precise measurements on masses and widths for these states. The most peculiar characteristics of this kind of experiments are reviewed and perspectives for a new experiment in this field are presented.

1. INTRODUCTION

More than 20 years since the discovery of charmonium, its study remains an active field of investigation. Experiments at colliding e^+e^- beams have provided an impressive amount of data, both on ψ and Υ families. Yet properties of the states with quantum numbers other than $J^{PC} = 1^{--}$ were unknown or poorly known because they had been studied in the radiative decays of higher mass states.

In $\bar{p}p$ annihilations all states can be formed, allowing precise measurements for all states, provided that the signal for these resonances can be extracted from the huge hadronic non-resonant background. For charmonium states this task is within experimental possibilities, since they decay with non-negligible branching ratios to electromagnetic final states.

2. THE EXPERIMENTAL TECHNIQUE

An H_2 molecular cluster jet target installed in an antiproton ring, equipped with a stochastical cooling system, can provide an interaction source which has the required high instantaneous luminosity. It has also the additional advantages of an almost point-like size of the source (that allows excellent angular resolution on photons direction) and the continuous mode of operation (which allows an efficient use of the antiprotons).

A comprehensive review of this technique and of the experimental results can be found in [1].

The main requirements for the beam are the possibility to have large stacks of $\bar{p}$'s of well defined momentum anywhere in the range between $\sim 3.5\ GeV/c$ to $\sim 6.5\ GeV/c$ and the possibility to scan the resonance by changing the beam momentum in small steps.

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

$$p\overline{p} \to (c\bar{c}) \to e^+e^- \tag{1}$$

$$p\overline{p} \to (c\bar{c}) \to J/\psi + X \to e^+e^- + X \tag{2}$$

$$p\overline{p} \to (c\bar{c}) \to \gamma\gamma \tag{3}$$

$$p\overline{p} \to (c\bar{c}) \to \eta_c + X \to \gamma\gamma + X \tag{4}$$

Resonance parameters are determined from the excitation curve measured by performing an energy scan across the formation energy of the resonance. The observed excitation curve is the convolution of the Breit-Wigner cross section for the resonance ($\sigma_{BW}(E)$) with the energy distribution function for the beam ($G(E)$):

$$\sigma(E_{cm}) = \int_0^{\infty} \sigma_{BW}(E')G(E' - E_{CM})dE' \qquad (5)$$

The resonance parameters that can be extracted from a fit to the excitation curve are: the mass of the resonance (M_R), its total width (Γ_R) and the peak cross section (proportional to $BR(p\bar{p}) \times BR(final\ state)$).

The quality of the measurement depend essentially on the interaction source characteristics: the center-of-mass energy is only determined by the beam momentum, since the protons in the jet target can be considered at rest; the precision on resonance widths measurement is only determined by the beam momentum resolution. The detector is used essentially to discriminate between signal (charmonium formation) and background events.

The sensitivity to small cross sections depends equally on the detector (i.e. on its efficiency and ability to reject the background) and on the interaction source (i.e. instantaneous luminosity and source dimensions). A large acceptance and the ability to fully reconstruct the final state can improve dramatically the signal to noise ratio for the smaller cross sections.

The main sources of background that must be taken into account in the detector design are low multiplicity hadronic final states with high energy π^o's, whose asymmetric decay (if the low energy gamma is not detected) could be misidentified as a single electromagnetic shower, and could also be misinterpreted as a high energy electron when the high energy photon undergoes a conversion in the beam pipe.

Two experiments have already been performed: R704 (CERN) and E760 (FNAL); an other experiment at FNAL (E835) is planned to take data in the next fixed target program.

The main characteristics of detectors are similar: a non-magnetic spectrometer with limited (R704) or full (E760/E835) azimuthal (ϕ) coverage and polar angle (θ) acceptance ranging from $\sim 2°$ to $\sim 70°$. A set of detectors and hodoscopes provide the charged particle tracking and multiple sampling of dE/dx. A threshold Čerenkov counter is used already at the first trigger level for electron/pion separation. The energy deposit in the electromagnetic calorimeter is used at the first trigger level to select events with large invariant mass e^+e^- or $\gamma\gamma$ pairs: large acceptance, high segmentation and low energy threshold are essential for γ/π^o separation.

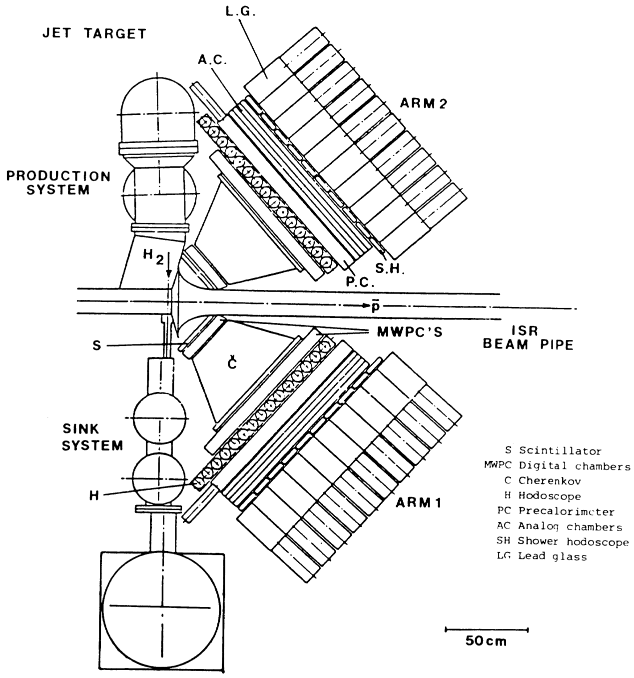

Figure 1. Top view of R704 detector

The antiproton beam is not bunched; the high, and asynchronous, interaction rate ($\sim$ MHz) poses tight requirements on the trigger and the data acquisition system.

3. MERITS OF THE TECHNIQUE

This technique cannot compete with e^+e^- experiments in the measurements of BR of charmonium states, however it is extremely good in determining just those properties that are worst determined in e^+e^- experiment.

One of the major advantages is that the masses of all states can be measured (in principle) with equally high accuracy, i.e. the spacing among $c\bar{c}$ levels can be measured with high precision.

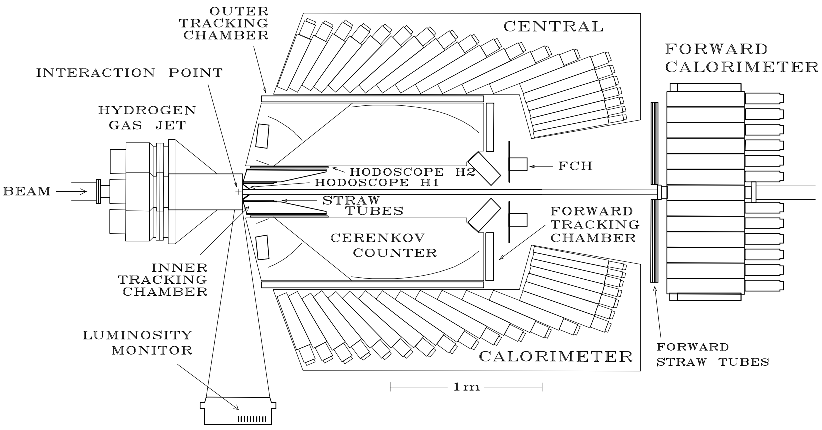

Figure 2. Side view of E760 detector

Hyperfine splittings for S and P states are predicted by numerous potential models, but also by one-loop QCD calculations [14] and the experimental results can already provide reliable measurements of α_s. The value of α_s will (hopefully) soon be measured in lattice gauge calculations from the $1S-1P$ (or the $1S-2S$) splitting at the c-quark mass-scale.

The total width of charmonium states can be directly determined with sufficiently high precision also for the narrowest state (the J/ψ); when combined with the precise measurements on BR's provided by e^+e^- (or $\bar{p}p$) experiments, these results can be used to quantitatively compare predictions on the ratio of partial widths, which is another possible way to determine α_s.

The study of angular distributions of χ_{c_1} and χ_{c_2} allows measurements of helicity amplitudes describing the formation process (B_0 and B_1) and of the contributions of electric dipole (a_1), magnetic quadrupole (a_2) and electric octupole (a_3) to the radiative decays. All of this quantities are of some theoretical interest: B_0 is expected to be zero in massless QCD, a_3 is expected to be zero in the single quark radiation hypothesis, and a_2 is related to the anomalous magnetic moment of the c-quark.

4. EXPERIMENT R704

The H_2 jet target was installed in one of the rings at the ISR. A peak luminosity of $\sim 3 \cdot 10^{30} cm^{-2}s^{-1}$ was achieved, with a minimum r.m.s. E_{cm} spread of $\sim 500\, KeV$ at $4\, GeV$. The detector (see fig.1) is described in detail in ref. [2]. Detector acceptance for events of reactions 1 to 3 was $\sim 10\%$. The total integrated luminosity was $\sim 3\, pb^{-1}$.

R704 was the first experiment to use this technique, and in spite of the short period allocated to its data taking, yielded the more precise measurements available at that time on χ_{c_1} and χ_{c_2} masses and on χ_{c_2} total width[3].

R704 made also measurements of χ_{c_1} and χ_{c_2} angular distributions [5] (based on 37 and 50 events respectively) and of χ_{c_2} and η_c partial width to $\gamma\gamma$ [4] with a precision comparable to the best measurements obtained in e^+e^- experiments.

This experiment also searched for the singlet P state of charmonium ($h_c(^1P_1)$), but found no evidence for it[6].

5. EXPERIMENT E760

All known charmonium states below open charm threshold (with the only exception of χ_{c_0}) have been studied by E760.

The H_2 jet target was installed in the Fermilab Antiproton Accumulator. A peak luminosity of $\sim 1 \cdot 10^{31} cm^{-2}s^{-1}$ was achieved, a minimum r.m.s. E_{cm} spread of $\sim 160\, KeV$ at $4\, GeV$. The detector (see fig.2) is described in detail in ref. [7]. Detector acceptance for events of reactions 1 to 4

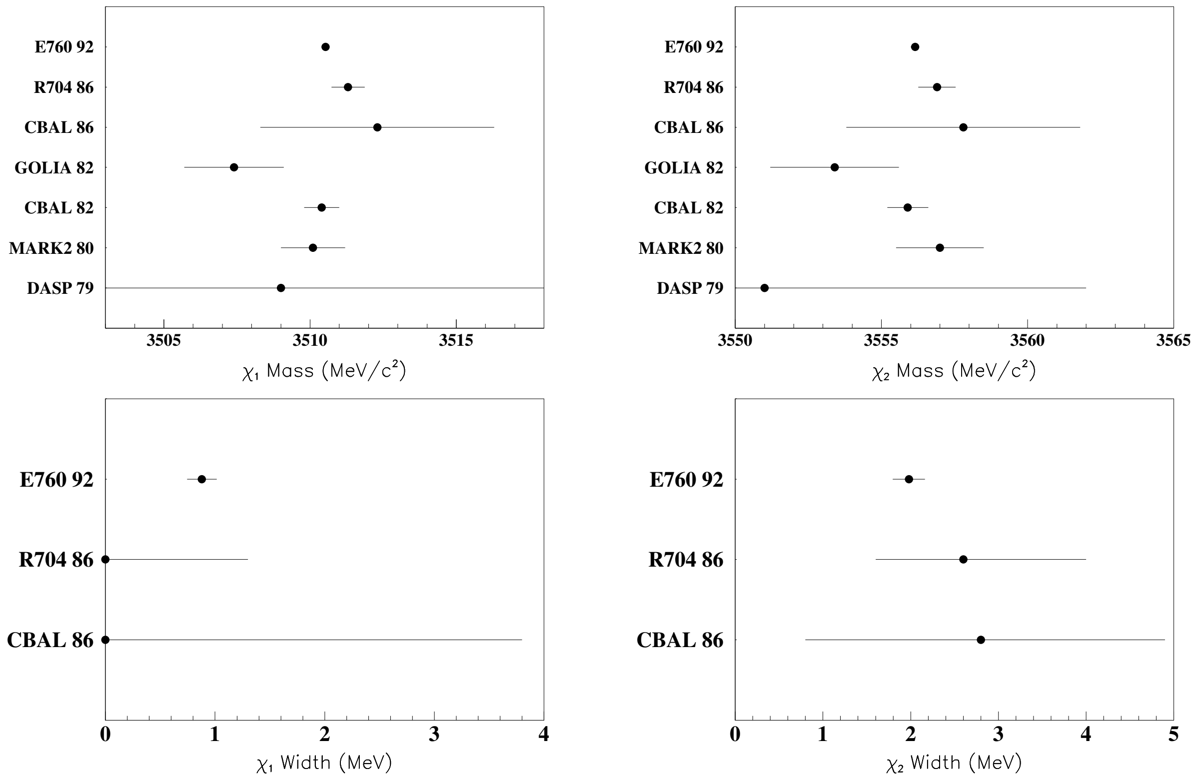

Figure 3. Results on χ_{c_1} and χ_{c_2} masses and widths from different experiments (References from PDG94)

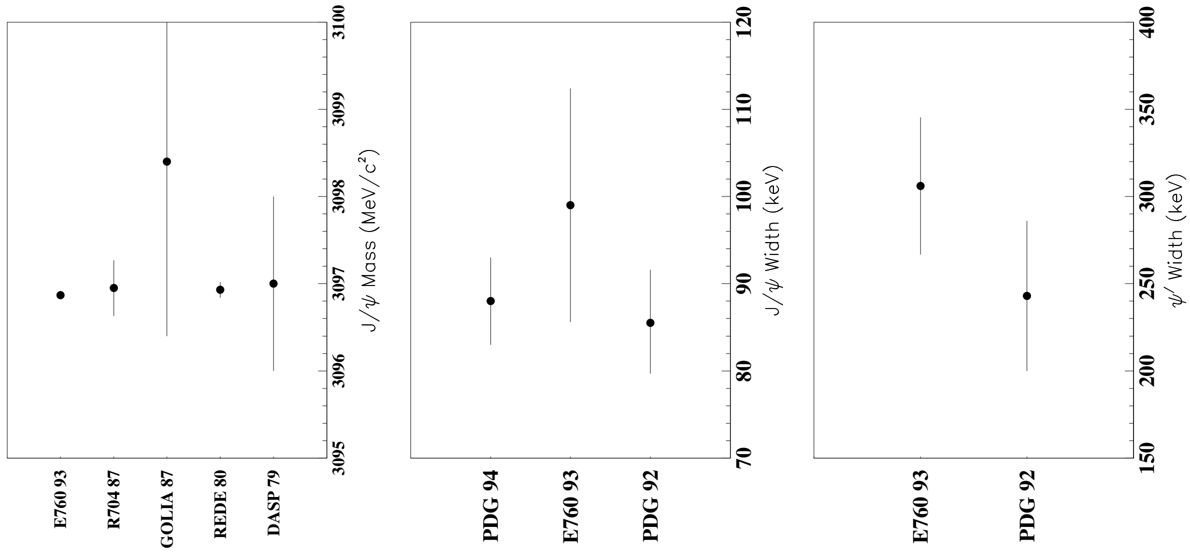

Figure 4. Results on J/ψ mass and width and ψ' width from different experiments

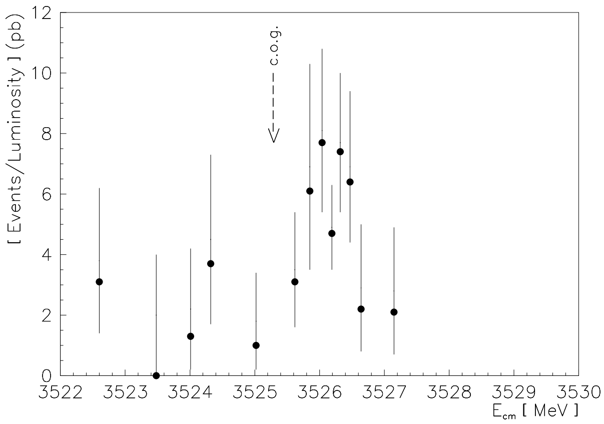

Figure 5. h_c formed in $p\bar{p} \to J/\psi\pi^o$ from E760

was $\sim 50\%$. The total integrated luminosity was $\sim 36\,pb^{-1}$.

J/ψ and ψ' total widths have been directly measured for the first time and a new measurement of J/ψ mass has been obtained [8].

Evidence for the singlet P state of charmonium has been observed in the exclusive channel $\bar{p}p \to h_c \to J/\psi\pi^o$[9]. No signal was found in the $\eta_c\gamma \to 3\gamma$ channel, but the upper limit set by this experiment for this cross section is not yet significant, even if very close to the predicted values.

E760 has given the most precise direct measurements to date of χ_{c_1} and χ_{c_2} masses and widths, and precise measurements of $BR(p\bar{p}) \times BR(J/\psi\gamma)$[7]. χ_{c_2} partial width to $\gamma\gamma$ has also been measured [10]. χ_{c_1} and χ_{c_2} angular distributions were measured with large statistics [11].

η_c mass, width and partial width to $\gamma\gamma$ have been measured [12]. No evidence was found for the η_c' observed by Crystal Ball [13], but data are not sufficient to rule it out either [12].

6. NEXT: EXPERIMENT E835

Experiment E835 at FNAL, a major upgrade of the E760 experiment, is planned to start taking data in 1996. The goal is to reach a total integrated luminosity of $160\,pb^{-1}$.

The maximum instantaneous luminosity will be increased by a factor ~ 5 increasing both the maximum $\bar{p}$ current in the ring and the H_2 jet density. Furthermore the H_2 jet density can be continuosly adjusted in order to keep the instantaneous luminosity constant at the maximum value sustainable by the detector.

The increased luminosity has forced a complete re-design of the charged particle tracking and of the data acquisition system.

More accurate measurements of the χ_{c_0}, h_c, η_c and η_c' will be performed. Angular distribution for χ_{c_1} and χ_{c_2} will be studied with large samples of events to measure (or set a significant upper limit) the contribution of the octupole transition to the radiative decay.

E835 has also the potential to observe the so far undetected $^3D_2$ and $^1D_2$ charmonium states (above the $D\bar{D}$ threshold but possibly below the $D^*\bar{D}$ threshold), extending the range of precision test of QCD.

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