Experimental Results on Charmonium from E760 (FNAL)

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Abstract

E760 is a fixed target experiment dedicated to the study of charmonium spectroscopy in $\bar{p}p$ annihilations. Results on χ_1 and χ_2 resonance parameters from 1990 data taking are presented, consisting of precise measurement of mass, total width and partial width to $\bar{p}p$. A preliminary result is presented on the first direct determination of Ψ' width from line shape analysis.

1 Introduction

Bound states of heavy quarks and antiquarks, being the simplest aggregates of strongly interacting particles, can play a fundamental role in our understanding of strong interactions.

Experiments at colliding e^+e^- beams have provided an impressive amount of data, both on Ψ and Υ families. Yet some properties of these systems are unknown or poorly known, particularly for the states with quantum numbers other than $J^{PC} = 1^{--}$ that cannot be formed in e^+e^- collisions (to first order in α), because they have 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 has been proven to be within experimental possibilities, since they decay with non-negligible branching ratios to electromagnetic final states.

2 The experiment E760 at FNAL

To perform an experiment on charm the first requirement is on the luminosity.

In experiment E760 we study charmonium states produced in the interaction of the $\bar{p}$ beam circulating in the Fermilab Antiproton Accumulator with an internal H_2 gas jet target installed in one of the low-dispersion sections of the accumulator. By this technique we obtain a luminosity of $7 \cdot 10^{30} cm^{-2} s^{-1}$ at the beginning of each $\bar{p}$ stack, with a beam lifetime of 55 h. (It was 40 h in 1990 due to vacuum problems.)

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, since the protons in the jet target can be considered at rest.

The main requirements for the beam are the possibility to have $\bar{p}$'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 been designed to identify electromagnetic final states of $(c\bar{c})$ decays, e.g.,

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

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

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

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

The main sources of background that have been taken into account in the detector design are low multiplicity hadronic final states with high energy π^o's, whose symmetric decay could be misidentified as a single electromagnetic shower, and could also be misinterpreted as a high energy electron when one of the photons undergoes a conversion in the beam pipe.

All results presented here refer to states studied in reactions 1) and 2).

2.1 Detector layout

The detector is a non-magnetic spectrometer with full azimuthal (ϕ) coverage and polar angle (θ) acceptance ranging from $2°$ to $70°$.

The central detector ($12° < \theta < 70°$) has cylindrical symmetry around the beam axis and consists of: two scintillator hodoscopes (H1 and H2); a straw-tube drift chamber, a radial projection chamber and a multiwire proportional chamber which provide the inner tracking; a multicell

Figure 1: E760 detector layout

threshold Čerenkov counter for electron/pion separation; two planes of Iarocci tubes and a planar multiwire proportional chamber which provide the outer tracking; and an electromagnetic calorimeter consisting of 1280 lead-glass blocks pointing to the interaction region, with a 20-fold segmentation in θ and a 64-fold segmentation in ϕ. 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 monitor is provided by a set of silicon detectors covering the polar angle region from $82°$ to $90°$, which measures the direction and energy of the recoil proton from forward antiproton elastic scattering. (References can be found in ref. [3].)

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.

The layout of the detector is shown in fig.1.

2.2 Beam energy calibration

A precise knowledge of the center of mass energy scale ($\sqrt{s}$) and of center-of-mass energy distribution is crucial for the success of our experiment.

The absolute momentum calibration of the $\bar{p}$ beam has been performed determining the orbit length from beam revolution frequency measurements at the formation energy of Ψ' [2], and the linearity of the calibration has been checked at the formation energy of the J/ψ, since the mass of these states has been measured to an accuracy of $\approx 100\ KeV/c^2$ [1].

As a result of this calibration the uncertainty on the absolute energy scale in the center of mass depends on the energy itself and ranges from $\approx 30\ KeV$ at $\sqrt{s} = 3.1\ GeV$ to $\approx 70\ KeV$ at $\sqrt{s} = 3.6\ GeV$.

The reproducibility of energy measurement relies on the measurement of orbit length variations with respect to the reference orbit. The precision of the beam position monitoring devices allows a reproducibility on the energy measurement with an error of 50 KeV at $\sqrt{s} = 3.1\ GeV$.

2.3 Beam momentum distribution

The knowledge of center-of-mass energy distribution must be unfolded from the observed excitation curve to extract the resonance parameters, and it becomes essential to perform a line shape analysis of very narrow resonances.

The accumulator stochastic cooling system provides excellent beam energy definition: $\Delta p/p \approx 2 \cdot 10^{-4}$, corresponding to $FWHM(\sqrt{s}) \approx 500\ KeV$, which allows for the first time the direct determination of resonance widths smaller than 1 MeV.

The beam frequency distribution is measured very precisely by the Schottky noise spectrum; to determine the momentum spread we need to know dp/df that is given by the relation:

$$\frac{\Delta p}{p} = \frac{1}{\eta}\frac{\Delta f}{f} \tag{5}$$

The parameter η (that depends on both beam energy and accumulator lattice) can be measured with a precision of 10% with standard accelerator techniques.

We adopted a new method (double scan [2]) to measure directly dp/df, based on the fact that the formation energy of the resonance itself provides a natural momentum gauge: we measure the excitation curve on the central orbit (where momentum is measured from the orbit length and revolution frequency), but we also measure the same excitation curve displacing the revolution frequency (while keeping the magnetic field constant) by a fixed amount for any point of the energy scan. We then bring back the beam on the central orbit to resume the scan, changing the magnetic field by the amount necessary in order to match the change in momentum due to the frequency shift.

The precision that can be achieved by this method on the measurement of η is 5%, which gives us enough sensitivity to measure directly the Ψ' width.

3 Event selection

In the 1990 run we took data at J/ψ,Ψ', χ_1, χ_2 and on various points far from those resonances.

The data taken in regions away from resonances allow a direct measurement of the background surviving each selection, which is a crucial parameter in a line shape analysis for narrow resonances.

In the final state of reaction (2) the J/ψ is produced almost at rest in the CM frame and the e^+ and e^- momenta are nearly coplanar. This allowed to design a single trigger for both reactions (1) and (2)

The fast trigger logic designed for these channels uses the signals from the scintillator hodoscopes H1 and H2, the Čerenkov counter and a matrix of 5×8 analogue sums from the central calorimeter. The event trigger requires two loosely coplanar ($|\Delta\phi| > 163°$) electron tracks in the central detector (an electron track being defined as the coincidence between the appropriate elements of H1, H2 and the Čerenkov) and two energy depositions in the central calorimeter above a certain threshold and separated by at least 90° in ϕ. The measured efficiency for this trigger, that takes into account misalignment among trigger elements and cracks, is $.87 \pm .02$.

At the offline level we first have a preliminary requirement of two electron candidates (defined as charged tracks with an associated cluster in the central calorimeter) with an invariant mass of at least 2 GeV/c^2, of which at least one associated to a signal in the Čerenkov counter. 96% of the events from reaction (2) pass this selection.

A first analysis chain, called *inclusive* selection, is based on the requirement of two isolated electrons with an invariant mass m_{ee} equal to that of the J/ψ. The definition of an isolated electron is based on the pulse-height information from H2 and the Čerenkov and on the lateral dimen-

Figure 2: Reconstructed e^+e^- invariant mass, χ_2 sample, inclusive selection

Figure 3: Reconstructed e^+e^- invariant mass, χ_2 final sample

sions of the central calorimeter shower, which are combined into an *electron quality index.* The cut on the electron quality index and the relative efficiency have been determined from a sample of approximately 4000 $J/\psi \rightarrow e^+e^-$ decays. Most of the remaining background (fig.2) has an invariant mass much lower than the J/ψ mass, and can be removed requiring the invariant mass to be above 2.75 GeV/c^2. The overall efficiency of this analysis, including the invariant mass cut, is $.833 \pm .007$.

For the χ_1 and χ_2 resonances we also had a parallel analysis chain performed on events passing the preliminary selection, based on the kinematic fit to the exclusive channel

$$p\overline{p} \rightarrow (c\bar{c}) \rightarrow J/\psi + \gamma \rightarrow e^+e^- + \gamma \qquad (6)$$

in which the conservation of four-momentum and the requirement $m_{ee} = m_{J/\psi}$ provide 5 constraints (2 for the case where the radiated γ escaped detection). The fit is carried out with the method of Lagrangian multipliers; events are rejected if the χ^2 probability is less than 10^{-4}. The efficiency of this selection is $.906 \pm .011$.

For χ_1 and χ_2 resonances the final sample (fig.3) is obtained requiring that events accepted by the fit have at least one of the two electron candidates confirmed as an isolated electron by the *electron quality index.* The overall selection efficiency for this final sample is $.893 \pm .013$.

4 Results

The events in the each sample are grouped into energy bins corresponding to the points of the energy scan.

The resonance parameters are determined by means of a maximum likelihood fit, in which these data points are fitted to the convolution of the Breit-Wigner cross section with the measured beam energy distribution, plus a constant background term.

The fitted parameters are, for each resonance, its mass, total width and the product

$$\Gamma(R \rightarrow p\overline{p}) \times B.R.(R \rightarrow Final)$$

The results of the fits are summarized in table 1. The excitation curve and corresponding fit for χ_1 and χ_2 scans are shown in fig.4. For χ_1 and χ_2 states the $\Gamma(\chi \rightarrow p\overline{p})$ (table 2) have been derived

Table 1: Resonance parameters

State	Mass (MeV/c^2)	Width (KeV/c^2)
χ_1	$3510.53 \pm 0.04 \pm 0.12$	$880 \pm 110 \pm 80$
χ_2	$3556.15 \pm 0.07 \pm 0.12$	$1980 \pm 170 \pm 70$
J/ψ	$3096.88 \pm 0.06 \pm 0.03$	
Ψ'	3686.0 (input)	317^{+50}_{-47} *)

*) Preliminary result

Figure 4: Measured cross section for χ_1 (a) and χ_2 (b) scans. Dashed lines represent the typical center-of-mass energy distribution.

Table 2: Partial width to $p\bar{p}$

State	$\Gamma(\chi \to p\overline{p})$ (eV)
χ_1	$69 \pm 9 \pm 10$
χ_2	$180 \pm 16 \pm 26$

using the world average of the branching ratios to the final states.

5 Conclusions

Our measurements of mass, total width and branching ratios to $p\bar{p}$ for χ_1 and χ_2 charmonium states show a substantial improvement over previously available data. In particular the χ_1 total width has been measured for the first time. We also have presented a preliminary result on the first direct measurement of the Ψ' total width. Our result differs significantly from the previously quoted value [1], that was however derived from an indirect measurement.

References

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