Precision Charmonium Spectroscopy at the Fermilab Antiproton Accumulator

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1. Introduction

The study of quarkonia, the bound states of quark-antiquark where both the quark and the antiquark carry the same flavor, is of fundamental importance to the study of Quantum Chromodynamics (QCD). Such states provide the simplest system of QCD, and were it not for the complications arising from the fact that in these systems non-perturbative effects are large, they would have been the ideal ground for confronting the theory with experiment. Even with this caveat, the quarkonia have been a rich source of information for QCD. Precision measurements of the properties of quarkonia should still

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still be pursued, either as a means of determining accurately the parameters of the theory (e.g., α_s) or as test of the validity of the theory itself. [2]

Charmonium and bottomonium share the characteristic that they have a rich spectrum of bound states with relatively small spacing between them, which implies that a non-relativistic description can be attempted. Indeed simple minded calculations[2] show that the relative velocity in the quark-antiquark system is $\beta^2 \approx 0.25$ in the charmonium system and $\beta^2 \approx 0.08$ in the bottomonium system, which should be contrasted with $\beta^2 \approx 0.6$ for the lighter mesons. Thus one can describe the spectrum by solving a Schrödinger equation with a central potential of a functional form that incorporates the asymptotic behavior of QCD and a few free parameters that are adjusted to give a best fit to the data. The states can be classified, just as in the case of the hydrogen atom or of positronium, by the usual spectroscopic notation $n^{2S+1}L_J$, where n is the principal quantum number and L, S, J are the orbital, spin, and total angular momentum. As in the case of positronium we have for these fermion-antifermion states that the parity is given by $P = (-)^{L+1}$, and the charge conjugation parity by $C = (-)^{L+S}$.

Despite the fact that charmonium is now 18 years old, the study of its spectrum is not complete yet. The major limitation arises from the fact that almost all of the results up to now were obtained in e^+e^- collisions where one can readily form only the $^3S_1$ states of charmonium (i.e., the J/ψ and the ψ'), states that carry the quantum numbers of the intermediate photon ($J^{PC} = 1^{--}$). All of the other states have been studied through the radiative decays of the ψ's, in which case the precision of the measurements has been limited by the resolution of the detection equipment. Thus to this date the following states have been positively identified in e^+e^- collisions: $\eta_c(1^1S_0)$, $J/\psi(1^3S_1)$, $\chi_{c0}(2^3P_0)$, $\chi_{c1}(2^3P_1)$, $\chi_{c2}(2^3P_2)$, and the $\psi'(2^3S_1)$. The $\eta_c'(2^1S_0)$ has been seen only by the Crystal Ball experiment[3], and the $h_c(2^1P_1)$ has remained unobserved. A somewhat similar situation exists in the case of bottomonium.

2. Charmonium Production in $p\bar{p}$ Collisions

The program of $p\bar{p}$ collisions at high energies pursued at CERN and at Fermilab required intense antiproton beams with small momentum spread. This availability of such antiproton beams, made possible by the use of stochastic cooling[4], circulating in modest sized storage rings with energies of a few GeV allowed for a breakthrough in the study of charmonium[5]. With the introduction of an internal hydrogen gas target in a storage ring filled with circulating antiprotons one can have $p\bar{p}$ collisions at a center-of-mass energy equal to the mass of the charmonium states (2.9 to 3.8 GeV). In such collisions all of the charmonium states can be formed directly, and one can measure their masses and widths by measuring and varying the energy of the circulating antiprotons. This creates a rather unique situation in high energy physics, in the sense that one measures the energy of the *initial* state rather than the final state. As a result one can achieve extremely good energy resolution since the storage ring is intrinsically a superb spectrometer and one is no longer limited by detector resolution. Nevertheless there is a price to be paid, the cross section for charmonium production lies in the nano-barn to picobarn range, while the total cross section for $p\bar{p}$ is approximately 70 millibarns. An elaborate detector is still required in order to identify the charmonium states in the presence of this enormous background. Fortunately these states can be easily detected by their characteristic decays into high mass e^+e^- or $\gamma\gamma$ pairs.

The first experiment to study charmonium in such a way was carried out at the CERN ISR[6]. A second generation experiment has been carried out at Fermilab during 1990 and 1991. It is the results from the latter experiment (E760) that are being reported here. In this experiment antiprotons circulating inside the Fermilab Antiproton Accumulator with a momentum in the range[3] of 3.5 to 5.9 GeV/c collide with an internal hydrogen gas jet target of thickness $\approx 5 \times 10^{13}$atoms/cm^2. The maximum number of circulating antiprotons used was 4×10^{11} and this led to a peak luminosity of 10^{31} cm^{-1}s^{-1}. The small beam and gas jet sizes led to a small point-like annihilation source of approximately .6 cm diameter. More significantly, the antiproton beam had a momentum spread $\Delta p/p \approx 2 \times 10^{-4}$ (r.m.s.) which implies a FWHM resolution of 0.5 MeV in the center-of-mass energy.

A study of a resonance is carried out by decreasing the beam energy in small steps over the region of interest. The number of observed events with

[2]It is interesting to note, that the similar system of QED, i.e., positronium, is the system in which there still exists a significant discrepancy between theory and measurement in the width of orthopositronium (1^3S_1)[1].

[3]A similar experiment to study bottomonium would require a stored antiproton beam at 45 to 65 GeV/c. Such a facility does not exist. In addition, the lower cross sections for bottomonium production make such an experiment virtually impossible.

a high mass e^+e^- or $\gamma\gamma$ pair as a function of energy is used to extract the mass and width of the resonance[7]. The detector, shown in Figure 1, covers the polar angle range of 2 to 70 degrees, and has full azimuthal coverage. It has been designed to efficiently detect the electromagnetic final states of charmonium decays. Its major component is the central calorimeter (CCAL), a cylindrical arrangement of 1280 lead glass counter s. A lead-scintillator sandwich calorimeter covers the forward range of 2 to 11 degrees. A threshold gas Cherenkov counter tags electron tracks, and two scintillator hodoscopes (H1 and H2) identify charged particles. Cylindrical wire and drift chambers complete the detector. We record events with two 'electrons,' defined as the proper coincidence of the Cherenkov counter and the hodoscopes and by requiring two large energy depositions in the CCAL separated by more than 90 degrees in azimuth. The trigger identifies high mass objects decaying into e^+e^- by calculating, using a fast online processor, the invariant mass of the two energy deposition clusters in the CCAL. Objects decaying into a high mass $\gamma\gamma$ pair are identified in a similar fashion, except that the electron track requirement is replaced by requirement of no hits in the first hodoscope (H1) and no hits in an array of forward scintillators (the veto counters). A luminosity monitor, consisting of solid state total absorption detectors, measures the recoil protons at 90 degrees in the lab. These protons are due to low momentum transfer forward elastic $p\bar{p}$ scattering; we use the known cross section for this process to normalize our data.

The center-of-mass energy is deduced from the beam energy. The beam energy is in turn calculated from the beam velocity which is derived from the revolution frequency of the circulating beam. That is, we use the relation

$$E_{cm}^2 = 2m_p^2c^4(1 + 1/\sqrt{1-(Lf/c)^2})$$

where f is the revolution frequency of the beam and L is the circumference of the storage ring. L was not determined to sufficient precision by the usual surveying techniques, so we had to find its value by running at a resonance with a precisely measured mass. We used the ψ' as our reference since its mass is known to $\Delta M_{\psi'} = \pm 100$ keV/c^2[8]. Using the known mass of the ψ' we are able to determine the orbit length to an accuracy given by $\Delta L = (M_{\psi'}L/\gamma^3\beta^2m_p^2)\Delta M_{\psi'}$, which is $\Delta L = \pm 0.67$ mm for the Accumulator that has a total length $L \approx 474$ m. By inverting this equation we find that the 0.67 mm uncertainty in orbit length contributes a systematic error of 33 keV/c^2 to the measurement of the J/ψ mass. The revolution frequency can be measured to an accuracy of 1 part in 10^7. It is important to keep the orbit itself constant as we change energies, we were able to keep the orbit length constant to within ± 1 mm, which in turn implies a statistical error of 50 keV/c^2 in the determination of the mass of the J/ψ.

The observed excitation curve is a convolution of the Breit-Wigner cross section for the resonance with a distribution function that characterizes the energy spread of the circulating beam. We can easily measure the revolution frequency spectrum of the beam, which can then be used to determine the beam energy distribution through the relation

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

where η is a parameter of the Accumulator that can be very accurately measured[7]. From the measurement of the excitation curve we can then extract the mass of the resonance M_R, and the width of the resonance Γ_R. Moreover, if the detector acceptance and efficiency are known, we can determine the product $B_{p\bar{p}}B_{out}$ of the branching of the resonance to $p\bar{p}$ (i.e., the formation process) times the branching ratio of the resonance to the specific decay channel we are studying.

3. Measurements of the Parameters of the J/ψ, ψ', χ_{c1}, and χ_{c2}

We have used in E760 the method outlined above to study the charmonium states J/ψ, ψ', χ_{c1}, and χ_{c2}. We detected these states by the following decays:

$$J/\psi \rightarrow e^+e^-$$
$$\psi' \rightarrow e^+e^- \text{ and } \psi' \rightarrow J/\psi\, X \rightarrow e^+e^-\, X$$
$$\chi_{c1,c2} \rightarrow J/\psi\, \gamma \rightarrow e^+e^-\, \gamma\ .$$

These decay channels have sizeable branching ratios and have a large mass e^+e^- pair in the final state.

Figure 2 shows the invariant mass distribution for e^+e^- for events collected at the region of the ψ', where one can see both a peak at 3.7 GeV due to the direct decay $\psi' \rightarrow e^+e^-$ and a peak at 3.1 GeV due to the inclusive decay $\psi' \rightarrow J/\psi X \rightarrow e^+e^-X$. The shaded area in the figure shows the

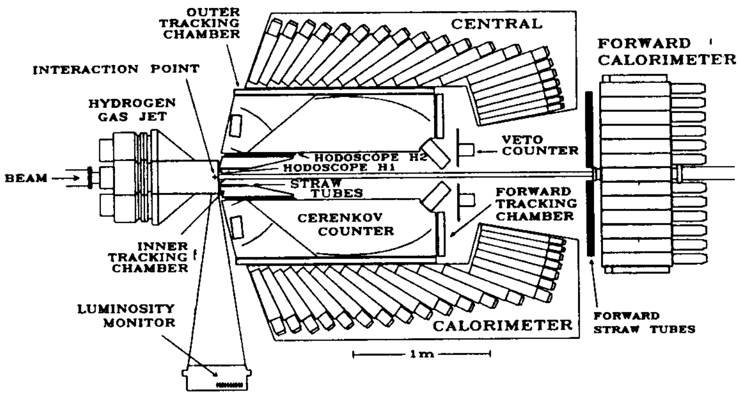

Figure 1: The E760 detector.

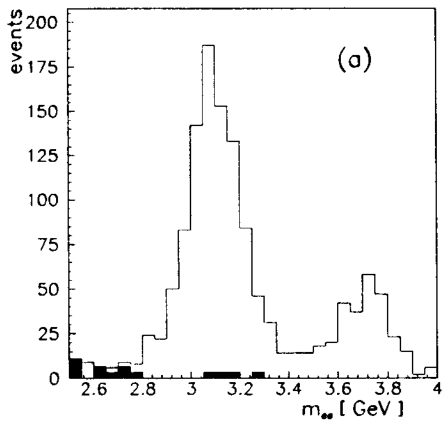

Figure 2: Invariant mass distribution for the e^+e^- pair for events taken at the ψ'. The integrated luminosity for the data shown is $\approx 1\text{pb}^{-1}$.

expected background determined from events collected at a center-of-mass energy $\sqrt{s} = 3.6667$ GeV, far away from any resonances, normalized to the same luminosity. It is clear that we can indeed detect charmonium decays amidst a large hadronic background.

The measured excitation curves for the J/ψ, and the ψ' are shown in Figure 3, and the excitation curves for the χ_{c1}, and the χ_{c2} are shown in Figure 4. As mentioned earlier, from a shape analysis we can extract the values of M_R and Γ_R. If we also use the acceptance and efficiency of our detector, we can also extract a value for $B_{p\bar{p}}B_{out}$. If we use the values for B_{out} found in the literature[9] we can derive values for $B_{p\bar{p}}B_{out}$ and for the partial widths $\Gamma_{out} = \Gamma_R B_{out}$ and $\Gamma_{p\bar{p}} = \Gamma_R B_{p\bar{p}}$.

Table I shows the measured parameters for the J/ψ and the ψ' and compares them with the earlier measurements. Similarly Table II shows the results obtained for the χ_{c1} and the χ_{c2}. The results from the χ's are in good agreement with theoretical predictions based on perturbative QCD[10].

4. The $h_c(2^1P_1)$ State of Charmonium

Roughly 50% of the luminosity accumulated by E760 (i.e., 30 pb^{-1}) was spent in a search for the $h_c(2^1P_1)$ state of charmonium[11]. The search was centered in the vicinity of the center of gravity of the χ states, i.e., at

$$E_{cog} = \frac{\sum_J (2J+1) M_{\chi_{cJ}}}{\sum_J (2J+1)},$$

and data were taken at least every 0.5 MeV. The search focused on the

Table I: Parameters of the J/ψ and ψ' charmonium states.†

Parameter	J/ψ	ψ'
M_R(MeV/c^2) (this expt.)	$3096.87 \pm 0.03 \pm 0.03$	(input)
M_R(MeV/c^2) (PDG[9])	3096.93 ± 0.09	3686.00 ± 0.10
Γ_R(keV) (this expt.)	$99 \pm 12 \pm 6$	$306 \pm 36 \pm 16$
Γ_R(keV) (PDG[9])	$85.5^{+6.1}_{-5.8}$	278 ± 32
$B(R \to p\bar{p})$ (this expt.)	$(1.82^{+0.31}_{-0.26}) \times 10^{-3}$	$(2.61^{+0.39}_{-0.36}) \times 10^{-4}$
$B(R \to p\bar{p})$ (PDG[9])	$(2.16 \pm 0.11) \times 10^{-3}$	$(1.9 \pm 0.5) \times 10^{-4}$

†Errors, in the order shown, are statistical and systematic.

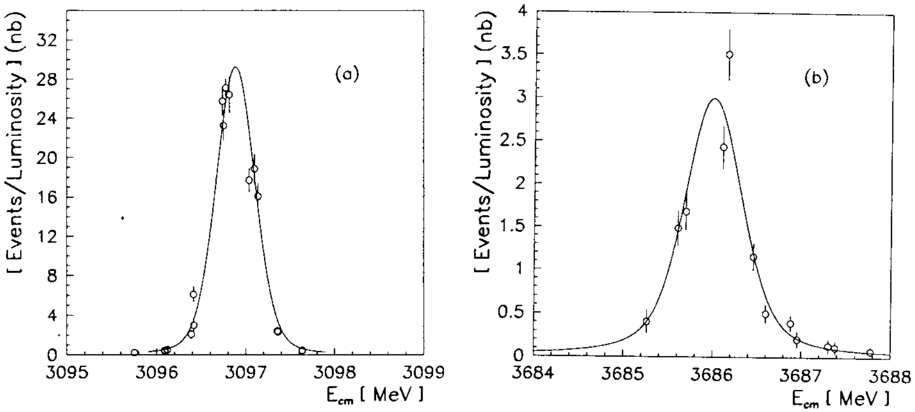

Figure 3: Excitation curves at the J/ψ (a) and at the ψ' (b).

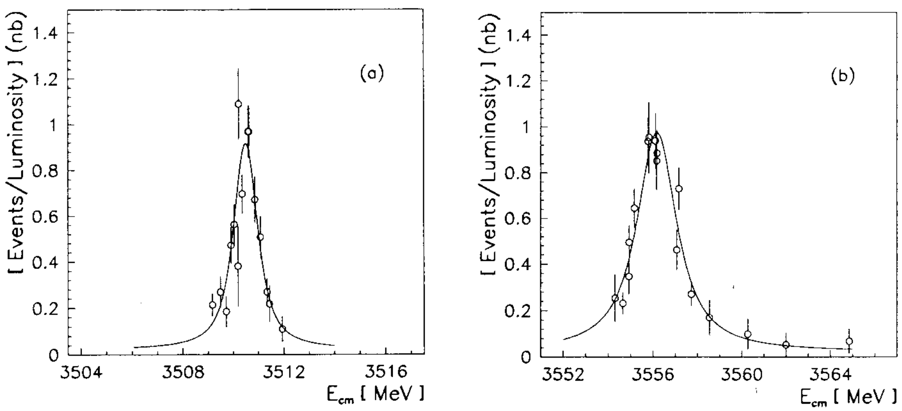

Figure 4: Excitation curves at the χ_{c1} (a) and at the χ_{c2} (b).

Table II: Parameters of the χ_{c1} and χ_{c2} charmonium states.‡

Parameter	χ_{c1}	χ_{c2}
M_R(MeV/c^2)	$3510.53 \pm 0.04 \pm 0.12$	$3556.15 \pm 0.07 \pm 0.12$
Γ_R(keV)	$880 \pm 110 \pm 80$	$1980 \pm 170 \pm 70$
$\Gamma(R \to p\overline{p})B(R \to J/\psi\gamma)$ $\times B(J/\psi \to e^+e^-)$ (eV)	$1.29 \pm 0.09 \pm 0.13$	$1.67 \pm 0.09 \pm 0.12$
$\Gamma(R \to p\overline{p})$ (eV)	$75 \pm 9 \pm 5$	$196 \pm 18 \pm 16$
$B(R \to p\overline{p}) \times 10^4$	$0.85 \pm 0.10 \pm 0.11$	$0.99 \pm 0.09 \pm 0.08$
$\Gamma(R \to hadrons)$(keV)	640 ± 110	1710 ± 210

‡Errors, in the order shown, are statistical and systematic for the M_R, Γ_R, and $\Gamma(R \to p\overline{p})B(r \to J/\psi\gamma)B(J/\psi \to e^+e^-)$. For the derived quantities $\Gamma(R \to p\overline{p})$ and $B(R \to p\overline{p})$ the errors, in the order shown, are due to our measurements and from the final state branching ratio uncertainty from the literature[9].

following decay channels:

$$h_c \to \eta_c + \gamma \to (\gamma\gamma) + \gamma$$

$$h_c \to J/\psi + \pi^0 \to (e^+e^-) + \pi^0$$

$$h_c \to J/\psi + 2\pi \to (e^+e^-) + 2\pi \quad .$$

The branching ratio to $\eta_c + \gamma$ is expected to be the dominant mode ($\sim$ 50%), but the three γ final state is very hard to detect due to the very small branching ratio of the decay $\eta_c \to \gamma\gamma$. No significant signal was seen in this mode. The other two decay channels are expected to have small branching ratios, but the J/ψ in the final state provides a very powerful signature. Figure 5 shows the invariant mass distribution for e^+e^- pairs for all the data taken during the h_c scan. A very clear peak at the J/ψ mass shows that we observe events of the type $p\overline{p} \to J/\psi + X$. It should be noted that the level of the J/ψ signal in this data is 100 times smaller than the signal in the sample of Figure 2; the background level is therefore the same for the two samples.

Events with $m_{e^+e^-}$ larger than 2.9 GeV/c^2 were fitted to the reactions $p\overline{p} \to J/\psi\ \pi^0$, $p\overline{p} \to J/\psi\ 2\pi$, $p\overline{p} \to J/\psi\ \gamma$, and $p\overline{p} \to e^+e^-$ whenever the event topology was compatible with the final state hypothesis. Most of the events could be unambiguously identified as either $J/\psi\ \gamma$ (cross hatched area in Figure 5), or $J/\psi\ \pi^0$ (solid area in Figure 5), while a few events were identified as $p\bar{p} \rightarrow e^+e^-$ (vertical striped area in Figure 5). No events were found that could fit the final states $J/\psi\ \pi^0\ \pi^0$, or $J/\psi\ \pi^+\ \pi^-$. The remainder of the events are compatible with the expected background. The $J/\psi\ \gamma$ events are compatible with the background expected from the tails of the nearby $\chi_{c1}(3510.53)$ and $\chi_{c2}(3556.15)$ resonances, given the fact that the beam energy distribution has a low level tail that extends into these regions.

Figure 6 shows the distribution of events per unit luminosity as a function of center-of-mass energy for the reaction $p\bar{p} \rightarrow J/\psi\ \pi^0\ \rightarrow (e^+e^-)\ \pi^0$. The data, binned in intervals of 150 keV in the center-of-mass energy, show for energies below E_{cog} a uniform level of ~ 2 events per pb^{-1}. This corresponds to a cross section of $\sigma(p\bar{p} \rightarrow J/\psi\pi^0) = 99 \pm 40$ pb, which is in reasonable agreement with the prediction for this continuum process[12]. Above E_{cog} we see an enhancement around 3526 MeV. We fit this enhancement to the sum of a constant continuum cross section an a Breit-Wigner resonance. We find that the data can be fit to a resonance with mass $M = 3526.2 \pm 0.15 \pm 0.20\ \mathrm{MeV/c^2}$, and with a width that can be compatible with our beam energy resolution. We can set an upper limit to the width of $\Gamma < 1.1$ MeV at the 90% confidence level. The statistical significance of the peak was evaluated by Monte-Carlo simulations of our data, and we find that the probability of this peak to be a fluctuation of the flat continuum is 1/400. We interpret this structure to be the $h_c(2^1P_1)$ state of charmonium.

If we let the width Γ_{h_c} vary in the range 0.5-1.0 MeV, we find that the branching ratio product $B(h_c \rightarrow p\bar{p})B(h_c \rightarrow J/\psi\pi^0)$ ranges from $(1.7\pm0.4)\times 10^{-7}$ to $(2.3 \pm 0.6) \times 10^{-7}$. The lack of any events of the class $p\bar{p} \rightarrow J/\psi\ 2\pi$ allows us to set a limit to the ratio $B(h_c \rightarrow J/\psi\ 2\pi)/B(h_c \rightarrow J/\psi\ \pi^0) < 0.18$ at the 90% confidence level.

5. Measurement of the Partial Width for $\chi_{c2} \rightarrow \gamma\gamma$

The measurement of the $\gamma\gamma$ decay of the $\chi_{c2}(2^3P_0)$ is of significant interest since the ratio of partial widths $\Gamma(\chi_{c2} \rightarrow gg)/\Gamma(\chi_{c2} \rightarrow \gamma\gamma)$ can be reliably calculated within the framework of perturbative QCD[13]. The measurement of such a neutral final state poses severe experimental difficulties. There are large backgrounds from hadronic processes, in particular $p\bar{p} \rightarrow \pi^0\pi^0$,

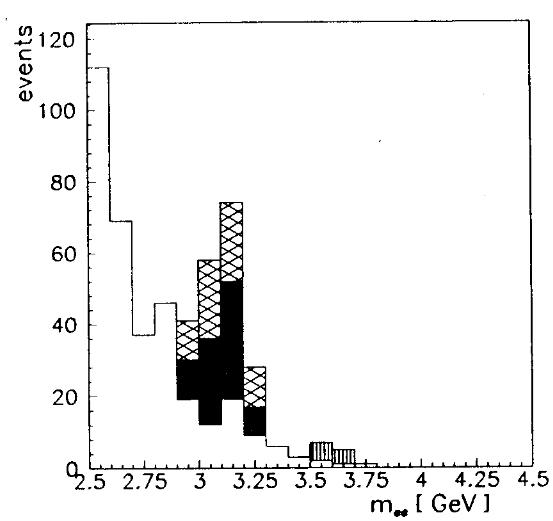

Figure 5: Invariant mass distribution for e^+e^- pairs for data taken near the center of gravity of the χ's E_{cog} ($\int \mathcal{L}dt \approx 16\mathrm{pb}^{-1}$).

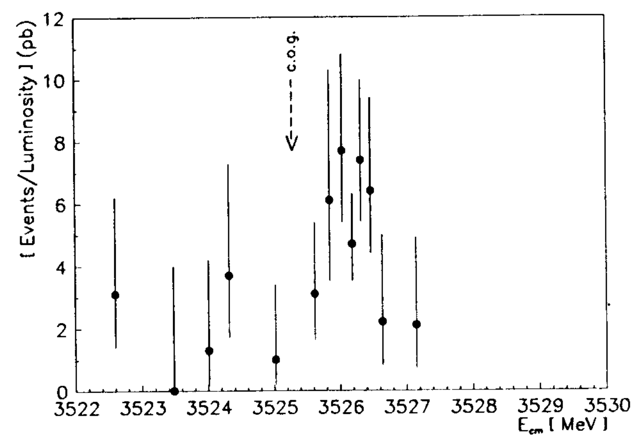

Figure 6: Events/luminosity vs. the center-of-mass energy for the h_c scan.

$p\overline{p} \to \pi^0\gamma$, and $p\overline{p} \to \pi^0\eta$, which have cross sections up to one thousand times larger than that of the $\gamma\gamma$ channel.

The crucial step in the off-line analysis is the rejection of events with π^0's where the two photons from the π^0 have a small opening angle. Such symmetric pion decays are eliminated on the basis of the cluster mass

$$m = \sqrt{(\sum_i E_i)^2 - (\sum_i \vec{p}_i)^2} \quad ,$$

where E_i is the energy deposited in the i$^{\text{th}}$ block of the CCAL, and $\vec{p}_i = E_i\hat{x}_i$ with $\hat{x}_i$ the unit vector from the interaction point to the i$^{\text{th}}$ block. Showers from symmetric π^0 decays have a large cluster mass, in contrast to showers from photons that have a low cluster mass. Events with two showers in the CCAL that have an invariant mass larger than 2.5 GeV/c^2, with no charged particles are fit to a $\gamma\gamma$ hypothesis. Any additional lower energy deposition in the CCAL is paired with both the high energy showers and if the pair have a mass consistent with a π^0 or an η the event is rejected. In addition, since the background is peaked in the forward direction, we accept only events where $|\cos\theta^*| < 0.4$, where θ^* is the angle between the γ's and the beam direction.

We collected a luminosity of 2.58 pb^{-1} at the χ_{c2} formation energy of 3556 MeV. The background is measured by using 23.3 pb^{-1} of data at center-of-mass energies from 3523 MeV to 3686 MeV where resonant $\gamma\gamma$ production is not expected.[4] The data are shown in Figure 7, together with a superposed fit that includes a slowly varying background and a Breit-Wigner shape with the known mass and width for the χ_{c2}. The only significant point above the background is at the χ_{c2} mass. After correcting for efficiency and geometrical acceptance, which includes an estimation of the uncertainties introduced by assumptions about the angular distribution of the radiative decay of the χ_{c2}, we obtain that

$$B(\chi_{c2} \to p\overline{p})B(\chi_{c2} \to \gamma\gamma) = (1.54 \pm 0.38 \pm 0.14) \times 10^{-8}$$

$$B(\chi_{c2} \to \gamma\gamma) = (1.54 \pm 0.40 \pm 0.24) \times 10^{-4}$$

$$\Gamma(\chi_{c2} \to \gamma\gamma) = (304 \pm 84 \pm 49)\text{eV} \quad ,$$

[4]Most of this data used in the background calculation comprises of the data taken during the search for the h_c.

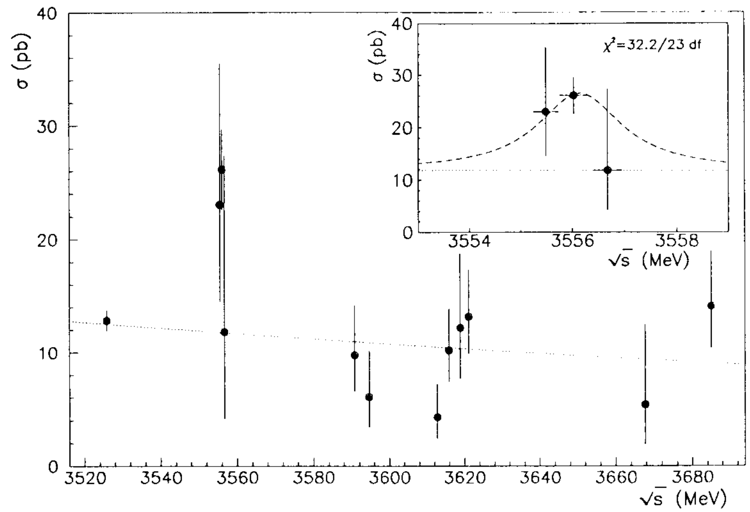

Figure 7: Measured $\gamma\gamma$ cross section, not corrected for efficiency and acceptance.

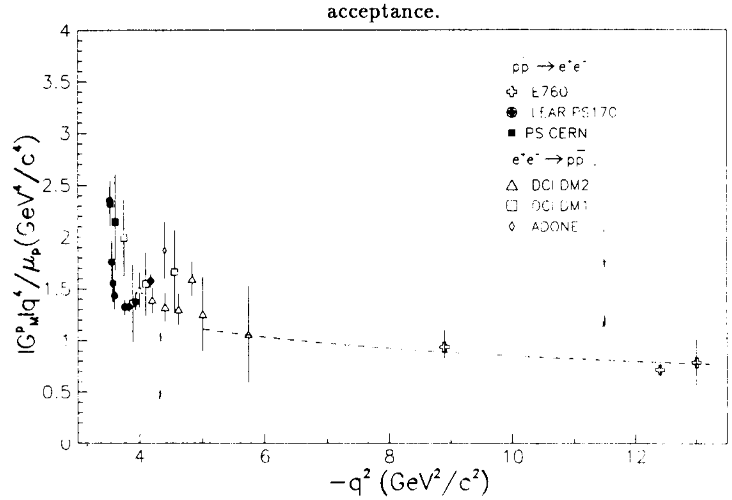

Figure 8: Variation of $q^4|G_M|/\mu_p$ versus $s = -q^2$.

where we have used our values for $B(\chi_{c2} \to p\bar{p})$, and $\Gamma_{\chi_{c2}}$. Our measurements are not in good agreement with theoretical expectations (see ref. [14] for details) which probably indicates that potentially large relativistic corrections have not been taken into account in the QCD calculations.

6. Study of the η_c

E760 collected a total of 3.56 pb^{-1} in the $\eta_c(1^1S_0)$ energy region, $\sqrt{s} =$ 2975 – 3005 MeV, at seven different energy settings. In addition, four more data points away from the η_c, but in the energy region 2910 – 3100 MeV, were collected to serve as background measurements. The analysis for the η_c is the same as the analysis used for the $\chi_{c2} \to \gamma\gamma$, since the η_c also decays into $\gamma\gamma$. The data analysis is still in progress, thus we can only report preliminary results at this time. We find that $M_{\eta_c} = 2989 \pm 3$ MeV, and that $B(\eta_c \to \gamma\gamma) = (4 \pm 2) \times 10^{-4}$. Our data do not seem to allow for an accurate determination of the total width of the η_c.

7. Measurement of the Proton Electromagnetic Form Factor in the Time-Like Region

As was noted earlier in Section 4, during the running of E760 we were able to measure the cross section for the process $p\bar{p} \to e^+e^-$. We have sufficient data, after grouping some of our runs at nearby energies, to measure this cross section at $\sqrt{s} = 3.0$ GeV, 3.5 GeV, and 3.6 GeV. The differential cross section for this process can be expressed in terms of the proton magnetic and electric form factors as:

$$\frac{d\sigma}{d(\cos\theta^*)} = \frac{\pi\alpha^2(\hbar c)^2}{8EP}[|G_M|^2(1+\cos^2\theta^*) + \frac{4m_p^2}{s}|G_E|^2\sin^2\theta^*] \quad ,$$

where E and P are the center-of-mass energy and momentum of the antiproton, and θ^* is the angle between the e^- and the $\bar{p}$ in the center-of-mass system. Our data were analyzed[15] in order to determine G_M. Due to the limited statistics we could not derive G_E and G_M separately. The values of $|G_M|$ were derived under the assumptions that either $|G_E| = |G_M|$ or that $|G_E| = 0$; the values of $|G_M|$ derived under these two approximations differ by less than 15%.

The data are shown in Figure 8 in the form $q^4|G_M|/\mu_p$ versus $s = -q^2$, where $\mu_p = 2.79$ is the proton magnetic moment. Earlier lower energy data[16] are also shown in the figure. The curve in the figure corresponds to $G_M(q^2) \propto q^{-4}\alpha_s^2(q^2)$, where the strong interaction coupling constant $\alpha_s(q^2)$ is proportional to $1/\ln(q^2/\Lambda^2)$ with $\Lambda = 0.2$ GeV. This dependence on q^2 is consistent with what was found for comparable space-like momentum transfers and agrees well with the q^4 scaling predicted by perturbative QCD[17].

8. Conclusions

E760 has opened a new chapter in the study of charmonium by providing high precision measurements of its parameters. These measurements provide a stringent test of QCD calculations. Comparisons with the calculated values show various degrees of agreement, a situation that points to the need for more accurate solutions.

In addition, in the opinion of the author, the precise nature of these measurements can provide the required input to the recently developed accurate calculations of charmonium levels in lattice QCD[18]. It should be noted that with the input of the splitting between the 1S and 2P states, i.e., $M_{h_c} - (3M_{J/\psi} + M_{\eta_c})/4$, these lattice gauge calculations give $\alpha_{\overline{MS}}(5GeV) =$ 0.174 ± 0.012. This value can be extrapolated to the mass of the Z to obtain $\alpha_{\overline{MS}}(M_Z) = 0.105 \pm 0.004$, which is of comparable accuracy as the value reported by the LEP experiments at this conference.

E760 stopped running with some questions left yet unresolved. We expect to run during the next fixed target running period at Fermilab, at which time we expect to visit or revisit, and measure more accurately, the $\eta_c(1^1S_0)$, $\eta_c'(2^1S_0)$, $h_c(2^1P_1)$, $\chi_{c0}(2^3P_0)$ and also to search for other as yet unobserved states of charmonium.

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