Study of charmonium states formed in pp annihilations: results from Fermilab E835

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OUTLINE

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• Experimental Method.
• Results:
  – $\bar{p}p \to \chi_0 \to J/\psi + \gamma \to e^+ e^- + \gamma$
  – $\bar{p}p \to \eta_c \to \gamma + \gamma$
  – $\bar{p}p \to \chi_2 \to \gamma + \gamma$
  – $\bar{p}p \to \chi_0 \to \gamma + \gamma$
  – search for $\bar{p}p \to \eta_c' \to \gamma + \gamma$
  – proton e.m. form factors (time-like)
  – $\bar{p}p \to \eta_c \to \phi \phi \to 4K$
• Summary and outlook.
Introduction

E835 studies the direct formation of $\bar{c}c$ states in $\bar{p}p$ annihilations. It is a fixed target experiment, in which the antiproton beam circulating in the Fermilab accumulator intersects a hydrogen gas jet target.

The charmonium system has often been called the *hydrogen atom of strong interactions*.

Non relativistic potential models + relativistic corrections + Perturbative QCD make it possible to calculate masses, widths and branching ratios to be compared with experiment.
**Why $\bar{p}p$?**

In $e^+e^-$ annihilations only states with the quantum number of the photon $J^{PC} = 1^{--}$ can be formed directly via the process $e^+e^- \rightarrow \gamma^* \rightarrow \bar{c}c$. States with $J^{PC} \neq 1^{--}$ are usually studied from radiative decays, e.g.

$$e^+e^- \rightarrow \psi' \rightarrow \chi + \gamma$$

In this case the measurement accuracy (for masses and widths) is limited by the detector.

In $\bar{p}p$ annihilations all quantum numbers are directly accessible.

The resonance parameters are determined from the beam parameters and **do not depend on the detector energy and momentum resolution**.
CHARMONIUM SPECTRUM

Transitions
- E1
- M1
- Hadronic
- Electromagnetic
E835 DETECTOR

\[ \bar{p}p \rightarrow cc \rightarrow e^+e^- \]
\[ \bar{p}p \rightarrow cc \rightarrow J/\psi X \rightarrow e^+e^-X \]
\[ \bar{p}p \rightarrow cc \rightarrow \gamma\gamma \]
\[ \bar{p}p \rightarrow \text{multi } \gamma \]
\[ \bar{p}p \rightarrow \phi\phi \rightarrow K^+K^-K^+K^- \]
\[ \bar{p}p \rightarrow pp \]
$\bar{p}p \rightarrow \chi_0 \rightarrow J/\psi + \gamma \rightarrow e^+ e^- + \gamma$

PRELIMINARY

$M(\chi_0) = 3414.97 \pm 0.42 \text{ MeV}$

$\Gamma(\chi_0) = 9.78 \pm 1.15 \text{ MeV}$

$B(\chi_0 \rightarrow \bar{p}p) = (5.86 \pm 0.39) \times 10^{-4}$
\[ \eta_c(1^{1S_0}) \rightarrow \gamma \gamma \]

PRELIMINARY

\[ M(\eta_c) = 2985.4^{+2.1}_{-2.0} \, MeV \]

\[ \Gamma(\eta_c) = 21.1^{+7.5}_{-6.2} \, MeV \]

\[-\]

\[ B(\eta_c \rightarrow pp) \times B(\eta_c \rightarrow \gamma \gamma) = (21.8^{+3.4}_{-3.3}) \times 10^{-8} \]

\[ \Gamma(\eta_c \rightarrow \gamma \gamma) = 3.85^{+1.5}_{-1.2} \, KeV \]

\[ (\text{with } B(\eta_c \rightarrow \bar{pp}) = (12 \pm 4) \times 10^{-4}) \]
E835 has improved the measurement of the partial width to two photons of the $\chi_{c2}$ state:

$$\Gamma(\chi_{c2} \rightarrow \gamma\gamma) = 0.27 \pm 0.049 \pm 0.033 \text{keV}$$
\[ \chi_{c0} \rightarrow \gamma \gamma \]

The \( \chi_{c0} \) state has also been studied through the two photons decay.

Analysis of the \( \chi_{c0} \) data is in progress.
$\eta_c'$ search

- E835 searched for the $\eta_c'$ state in the region:

$$3576 < E(\text{MeV}) < 3660$$

- No evidence has been found
We fit the data (maximum likelihood) with hypothesis of a spin 0 resonance plus a power law background, for three values of the total width.

According to our result we can set the upper limits:

\[
\begin{align*}
B.R.(\eta_c^\prime \to pp) \times B.R.(\eta_c^\prime \to \gamma\gamma) &< 12 \times 10^{-8} \quad (\Gamma_{\eta_c^\prime} = 5\,\text{MeV}) \\
B.R.(\eta_c^\prime \to pp) \times B.R.(\eta_c^\prime \to \gamma\gamma) &< 6 \times 10^{-8} \quad (\Gamma_{\eta_c^\prime} = 10\,\text{MeV}) \\
B.R.(\eta_c^\prime \to pp) \times B.R.(\eta_c^\prime \to \gamma\gamma) &< 6 \times 10^{-8} \quad (\Gamma_{\eta_c^\prime} = 15\,\text{MeV})
\end{align*}
\]
$\eta_c'$ search in other channels

$J/\psi \gamma$

$E_{cm}$ MeV

$J/\psi \pi^0$

$E_{cm}$ MeV
Determination of $\alpha_s(m_c)$

$$\frac{\Gamma(\eta_c \rightarrow \gamma\gamma)}{\Gamma(\eta_c \rightarrow gg)} = \frac{8\alpha_s^2}{9} \cdot \left[ 1 - \frac{3.4}{\pi}\frac{\alpha_s}{1 + \frac{4.8}{\pi}\frac{\alpha_s}{}} \right] \Rightarrow \alpha_s(m_c) = 0.33^{+0.06}_{-0.03}$$

$$\frac{\Gamma(\chi_2 \rightarrow \gamma\gamma)}{\Gamma(\chi_2 \rightarrow gg)} = \frac{8\alpha_s^2}{9} \cdot \left[ 1 - \frac{16}{3\pi}\frac{\alpha_s}{1 - \frac{2.2}{\pi}\frac{\alpha_s}{}} \right] \Rightarrow \alpha_s(m_c) = 0.38 \pm 0.02$$
Proton e.m. form factors
in the time-like region

The proton electromagnetic form factors in the timelike region can be extracted from the measurement of the cross section for the process:

\[ \bar{p}p \rightarrow e^+e^- \]

First order QED predicts:

\[
\frac{d\sigma}{d\cos\theta^*} = \frac{\pi\alpha^2\hbar^2c^2}{2xs}\left[|G_M|^2(1+\cos^2\theta^*) + \frac{4m_p^2}{s}|G_E|^2(1-\cos^2\theta^*)\right]
\]

Background from \(\pi^0\pi^0\), \(\pi^0\gamma\gamma\) and \(\pi^+\pi^-\) has been carefully evaluated and is negligible.

The form factors are extracted from the data under two separate hypotheses:

- \(|GE| = |GM|\).
- Neglecting the term containing \(GE\).

The data are well fitted by the PQCD predicted functional form:

\[
\frac{|G_M|}{\mu_p} = \frac{C}{s^2 \ln^2\left(\frac{s}{\Lambda^2}\right)}
\]
The dashed line is the PQCD fit.
The dot-dashed line represents the dipole behaviour of the form factor in the spacelike region for the same values of $|q|^2$. 
\[ \eta_c \rightarrow \phi \phi \rightarrow 4K \]

- This channel has a peculiar kinematics, so we can extract it in the huge hadronic background.

- Special trigger (using hodoscopes and SciFi detector): 4 tracks with the right kinematics.

- Event selection:
  - 4 charged tracks
  - cuts on \( \Delta \varphi, \Delta \theta \) opening angle (<25°)
  - cuts on calculated invariant mass
  - kinematic fit probability > 60%
Analysis of the $\Phi \Phi \rightarrow 4K$ channel

Events that fit with the $\Phi \Phi \rightarrow 4K$ reaction, $\eta_c$ peak energy

Events that fit with the $\Phi \Phi \rightarrow 4K$ reaction, off-resonance energies

$\sigma_{ldt} = 280.2 \text{ nb}^{1}$

$\sigma_{ldt} = 285.1 \text{ nb}^{1}$
Analysis of the data below and above the $\eta_c$ peak energy

Events that fit the $\Phi\Phi \rightarrow 4K$ reaction for energies below the $\eta_c$ peak

Events that fit the $\Phi\Phi \rightarrow 4K$ reaction for energies above the $\eta_c$ peak
Conclusions and outlook

A lot of progress has been made in our knowledge of the charmonium spectrum.

\( \psi, \psi', \chi_1, \chi_2 \) very well measured.
\( \chi_0, \eta_c \) well measured.

Nonetheless there is still a lot to be done:

1P1 needs further investigation.
new decay modes.
Still missing: \( \eta_c', \) D states.

The hadronic decay channels look promising.