Fermi National Accelerator Laboratory

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# Observation of the $^1P_1$ State of Charmonium

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## Abstract

Experiment E760 at Fermilab has performed a search for the $^1P_1$ state of Charmonium resonantly formed in $\bar{p}p$ annihilations, close to the center of gravity of the $^3P_J$ states. We report results from the study of the $J/\psi+\pi^0$ and $J/\psi+2\pi$ final states. We have observed a statistically significant enhancement in the $\bar{p}+p \rightarrow J/\psi+\pi^0$ cross section at $\sqrt{s} \simeq 3526.2$ MeV. This enhancement has the characteristics of a narrow resonance of mass, total width and production cross section consistent with what is expected for the $^1P_1$ state. In our search we have found no candidates for the reactions $\bar{p}+p \rightarrow J/\psi+\pi^o+\pi^o$ and $\bar{p}+p \rightarrow J/\psi+\pi^++\pi^-$ .

The singlet states of heavy quarkonia ($\overline{Q}Q$; s=0, J=$l$, P=(-1)$^{(l+1)}$, C=(-1)$^l$) pose an unusual experimental challenge because they can be neither resonantly produced in $e^+e^-$ annihilation into a virtual photon (J$^{PC}$=1$^{--}$) nor populated by E1 decay of the $^3S_1$ states. To date only the $\eta_c$ ($1^1S_0$, $0^{-+}$) has been positively identified [1]. An early claim for the $\eta_c'$ ($2^1S_0$, $0^{-+}$) [2] remains unconfirmed, and searches by previous experiments failed to find the $h_c(1^1P_1\ (1^{+-}))$ [3].

The study of $\bar{c}c$ singlet states, resonantly formed in $\bar{p}p$ annihilations, is one of the principal objectives of experiment E760 at Fermilab. This letter describes a search for the singlet P state. The observation of this state is important since a comparison of its mass with the masses of the triplet P states provides a measurement of the deviation of the vector part of the $\bar{Q}Q$ interaction from pure one gluon exchange [4]. The branching ratios for the $^1P_1$ hadronic decays relate to the validity of QCD helicity selection rules[5], QCD multipole expansion models[6], and isospin conservation.

In $\bar{p}p$ annihilations the $^1P_1$ state can be formed through the coherent annihilation of the three quarks of the proton and the three antiquarks of the antiproton into three hard gluons (the annihilation into two gluons violates C-parity conservation). This process is forbidden by the helicity conservation rule in massless QCD[5]. However, as is well known, this rule is strongly violated, for example, in the decay $\eta_c(^1S_0) \rightarrow \bar{p}p$. The $^1P_1$ is expected to be narrow ($\leq 1.0$ MeV) with comparable decay rates to light hadrons[7] and, through an electric dipole transition, to the ($\eta_c+\gamma$) final state[8]. Several predictions of the mass of the singlet P can be found in the literature[9], most of them within a few MeV of the center of gravity of the $\chi_c(^3P_J)$ states, defined as [1],[10]:

$$m_{c.o.g.} \equiv \frac{m_{\chi_0} + 3m_{\chi_1} + 5m_{\chi_2}}{9} = 3525.27 \pm 0.12 \text{ MeV} \qquad 1)$$

The cross section at the peak of the resonance for the formation reaction $\bar{p}p \rightarrow {}^1P_1$ is expected to be $\leq 10^{-6}$ of the total cross section for $\bar{p}p \rightarrow$ hadrons at the same energy. To maximize the chances of successfully identifying this rare process in the presence of a large hadronic background we have searched for the decay of the ${}^1P_1$ into the lower lying charmonium states $\eta_c$ and $J/\psi$. With our non-magnetic spectrometer, which is optimized for the detection of electromagnetic final states, we have searched for the transitions:

$$
\begin{aligned}
{}^1P_1 &\to \eta_c + \gamma \to \quad (\gamma\gamma) + \gamma && 2) \\
{}^1P_1 &\to J/\psi + \pi^0 \to \quad (e^+e^-) + \pi^0 && 3a) \\
{}^1P_1 &\to J/\psi + 2\pi \to \quad (e^+e^-) + 2\pi && 3b)
\end{aligned}
$$

While the dominant decay mode is expected to be $\eta_c + \gamma$, the small branching ratio for $\eta_c \to \gamma\gamma$ strongly suppresses the $3\gamma$ final state and makes it comparable in rate to the (3a) and (3b) final states. The branching ratios for the decays (3a) and (3b) are expected to be small since reaction (3a) does not conserve isospin and reaction (3b) is suppressed by the limited phase space available and by angular momentum barrier effects. However, because they include a pair of electrons with large invariant mass, the final state signatures for these decays are highly distinctive and permit a sensitive search for the ${}^1P_1$.

In this letter we discuss only the decay channels (3a) and (3b). The study of (2) is in progress and the results will be reported in a forthcoming paper.

The experiment was set up in the antiproton source complex at Fermilab. An internal hydrogen jet target intersected the antiproton beam (up to $4.0 \times 10^{11}\,\bar{p}$) stored in the accumulator ring, providing a point-like source with instantaneous luminosity in the range of 3 to 9 $\times 10^{30} cm^{-2} sec^{-1}$. Typically, data for an integrated luminosity $\int \mathcal{L}\mathrm{d}t \approx 1\,pb^{-1}$ were collected with one beam-fill (stack). A high performance stochastic cooling system compensated for the effects of scattering and energy loss in multiple traversals of the target by the beam , keeping its momentum spread at $\Delta p/p \leq 2.5 \times 10^{-4}$ (r.m.s.), corresponding to a FWHM in the center of mass energy of 600-850 keV.

The search for the ${}^1P_1$ was confined to the immediate vicinity of $m_{c.o.g.}$ (eq.1) and data were taken in small energy steps ($\leq$ 500 keV ) to allow observation of a narrow resonance. A summary of the data is given in Table 1.

The detector was mounted around a straight section of the antiproton accumulator ring and has been described in detail elsewhere [10]. Two electromagnetic calorimeters covered the full azimuth($\phi$) and from 2° to 70° in the polar angle ($\theta$). The central calorimeter ($11° < \theta < 70°$) consisted of an array of 1280 lead glass counters, each pointing to the interaction region. The forward region ($2° < \theta < 11°$) was covered by a planar lead-scintillator calorimeter consisting of 144 identical towers. A set of cylindrical wire chambers inside the calorimeters provided accurate tracking of charged particles;

Table 1: Summary of data relating to the search for the ${}^1P_1$ state. The stack numbers are in the time-order in which the data were taken. Stacks 4,6,7,8,10,12 taken at higher energy, were used for studying the components of the non-resonant continuum.

| stack | $\sqrt{s}$ ( MeV) | $\int \mathcal{L}$dt (nb$^{-1}$) | candidates $J/\psi+\gamma$ | candidates $J/\psi+\pi^0$ |
|---|---|---|---|---|
| 1 | 3524.3 | 823 | 4 | 3 |
| 2 | 3524.0 | 783 | 2 | 1 |
| 3 | 3522.6 | 980 | 3 | 3 |
| 5 | 3523.5 | 490 | 5 | 0 |
| 9 | 3525.0 | 1041 | 8 | 1 |
| 11 | 3526.2 | 1337 | 2 | 9 |
| 13 | 3525.6 | 1310 | 3 | 4 |
| 14 | 3526.1 | 1364 | 7 | 7 |
| 15 | 3526.6 | 1137 | 4 | 4 |
| 16 | 3526.3 | 1017 | 4 | 9 |
| 17 | 3527.2 | 1016 | 3 | 2 |
| 18 | 3525.9 | 885 | 2 | 5 |
| 19 | 3526.2 | 940 | 4 | 6 |
| 20 | 3526.1 | 980 | 2 | 7 |
| 21 | 3526.5 | 911 | 0 | 4 |
| 22 | 3526.2 | 876 | 2 | 2 |
| 4 | 3594.5 | 827 | 0 | 3 |
| 6 | 3616.1 | 1276 | 0 | 3 |
| 7 | 3612.9 | 1167 | 0 | 3 |
| 8 | 3619.1 | 575 | 2 | 2 |
| 10 | 3621.4 | 1216 | 0 | 3 |
| 12 | 3590.9 | 917 | 0 | 5 |

among these was a radial projection chamber (RPC) giving up to 16 charge samples for a dE/dx measurement. Two scintillator-counter hodoscopes (H1 and H2) parallel to the beam pipe were used in the trigger and for an additional dE/dx measurement (H2). A threshold Čerenkov counter with two-fold polar and eight-fold azimuthal segmentation, identified electrons. A silicon detector at $86.5^0$ to the beam direction measured the yield of elastic recoil protons and provided a monitor of the absolute luminosity with errors $\leq 4\%$.

The trigger for reactions (3a) and (3b) was designed to select events with a large mass $e^+e^-$ pair within the acceptance of the central calorimeter, without restrictions on accompanying particles. It was implemented by requiring two 'electron tracks', as defined by the appropriate coincidence between the elements of the hodoscopes H1 and H2 and the corresponding cells in the Čerenkov counter, and by requiring two large energy depositions in the central calorimeter separated by more than 90° in $\phi$.

Off-line, a filtering program checked the correspondence of the two electron tracks with the two highest energy clusters in the central calorimeter and computed the invariant mass of the two electron candidates ($m_{e^+e^-}$), accepting for further analysis only events with $m_{e^+e^-} > 2.5$ GeV/c$^2$. The remaining background consisted predominantly of events with high energy $\pi^0$'s which produced two electron pairs either from Dalitz decay of a $\pi^0$ or from conversion of a photon in the 0.2 mm thick stainless steel beampipe. The selection of events with a $J/\psi$ decaying into $e^+e^-$ was then based on distinguishing single electron tracks from electron pairs, using the pulse height information from the hodoscope H2 and from the Čerenkov counter, the dE/dx information from the RPC, and the transverse shape of the energy depositions in the calorimeter. The combined efficiency of the trigger and offline selection for events of type (3a) and (3b) has been estimated to be $\epsilon = 0.81 \pm 0.03$[10]. As an example of the results achieved with this analysis, we show in Fig.1a the distribution of the invariant mass $m_{e^+e^-}$ for events collected at the $\psi'$ formation energy where the average rate is about 1 event per nb$^{-1}$ of integrated luminosity. The large peak at the left arises from inclusive decays $\psi' \rightarrow J/\psi + X \rightarrow (e^+e^-) + X$, while the smaller peak at higher mass is due to the exclusive decay $\psi' \rightarrow e^+e^-$. The shaded area represents the residual background estimated by normalizing to equal luminosity the events collected at $\sqrt{s} = 3666.7\ MeV$, outside the resonance region.

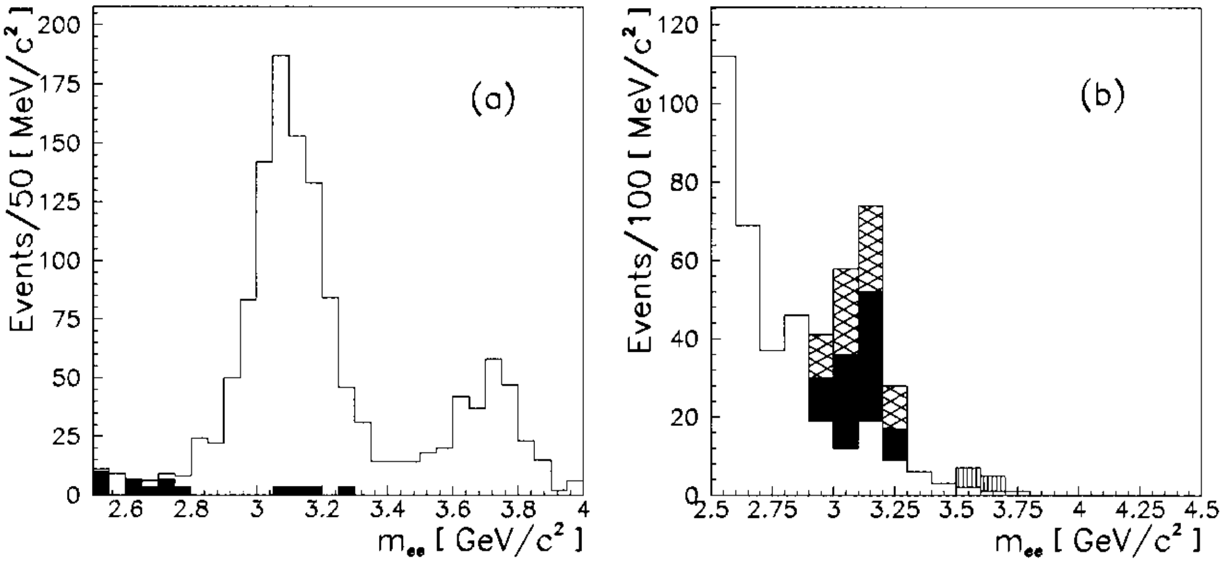

Figure 1: Distribution of events versus $(m_{e^+e^-})$, a) taken at the $\psi'(2^3S_1)(\int \mathcal{L}\mathrm{dt} \approx 1pb^{-1})$ and, b)taken near $m_{c.o.g.}(\int \mathcal{L}\mathrm{dt} \approx 16pb^{-1})$.

Fig.1b shows the invariant mass distribution for all the data taken during the ${}^1P_1$ scan. From a comparison of Fig.1a and Fig.1b it is clear that in the data from the ${}^1P_1$ scan we have events of the type: $\bar{p}p \rightarrow J/\psi + X$. It should be noted that the $J/\psi$ signal in this data is ≈ 100 times smaller than in the event sample of Fig.1a. This explains why the background component appears to be larger. Events of Fig.1b with $m_{e^+e^-} > 2.9$ GeV/c$^2$ were fit to the reactions (3a), (3b) and to $\bar{p}p \rightarrow J/\psi + \gamma \rightarrow (e^+e^-) + \gamma$ and $\bar{p}p \rightarrow e^+e^-$ whenever the event topology was compatible with the final state hypothesis. Most of the events could be fit unambiguously either to $J/\psi + \gamma$, or to $J/\psi + \pi^o$. The efficiency of the fit was estimated to be ≈ 90%. The shaded areas in Fig.1b represent events fitting $\bar{p}p \rightarrow J/\psi + \pi^o$ (black solid), $\bar{p}p \rightarrow J/\psi + \gamma$ (cross hatched) and $\bar{p}p \rightarrow e^+e^-$ (vertical stripes). The residual events in the $J/\psi$ mass region are compatible with the expected background. No events were found to fit the reactions $\bar{p}p \rightarrow J/\psi + \pi^o + \pi^o$ or $\bar{p}p \rightarrow J/\psi + \pi^+ + \pi^-$.

The results of the above analysis were checked and found consistent with the results obtained with an alternative analysis chain which relied only on the calorimeter response for identifying isolated electrons.

In columns 4 and 5 of Table 1 we list the number of $J/\psi + \gamma$ and $J/\psi + \pi^o$ candidates found for each stack. It should be pointed out that only events fully contained in the acceptance of the detector (≈ 40% of all $J/\psi + \pi^o$ and ≈ 55% of all $J/\psi + \gamma$ ) were included in this final sample while in Fig.1b events with a $\gamma$ escaping detection which fitted either $\bar{p}p \rightarrow J/\psi + \pi^o$ or $\bar{p}p \rightarrow J/\psi + \gamma$ are also shaded.

We first discuss the $J/\psi + \gamma$ channel. C-parity conservation prevents the $J^{PC} = 1^{+-}$ singlet P state from decaying into this final state. The events observed in this channel can therefore be due only to a true continuum or due to the contributions of the nearby $\chi_1(3510.6)$ and $\chi_2(3556.0)$ resonances. The measured cross section is found to be consistent with the latter hypothesis when the beam energy distribution is taken into account.

We now turn to the reaction $\bar{p}p \rightarrow J/\psi + \pi^o \rightarrow (e^+e^-) + \pi^0$. Our results for this channel are displayed in Fig.2, with the data binned in intervals of 150 keV in the center of mass energy. We note that below $m_{c.o.g.}$ (see eq.1) an apparently uniform level of ≈ 2.0 events per pb$^{-1}$ is observed. This corresponds to a cross section of $\sigma(\bar{p}p \rightarrow J/\psi + \pi^o) = (99 \pm 40)$ pb, in reasonable agreement with what is predicted for the continuum [11].[1] Above $m_{c.o.g}$ a consistently higher cross section is observed in the small region around 3526 MeV.

The data of the ${}^1P_1$ scan listed in Table 1 were analyzed using the maximum like-

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[1] The continuum level is found to increase slowly to $156 \pm 36$ pb at $\sqrt{s} \approx 3610 MeV$ and can therefore be taken to be constant within the narrow energy range of the ${}^1P_1$ scan.

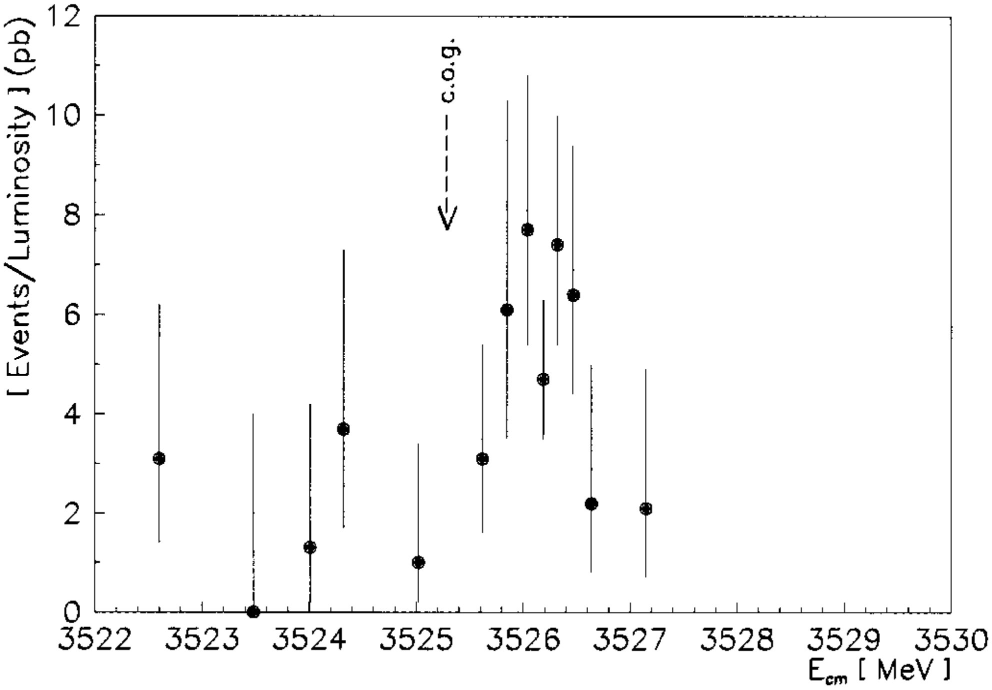

Figure 2: Number of events/[integrated luminosity] versus center of mass energy; data are binned in 150 keV intervals in the average center of mass energy.

lihood method to fit the measured cross sections to a constant continuum level plus a Breit-Wigner resonance function convoluted with the known beam momentum shape. The ratio of L($H_1$), the maximum value of the likelihood function for this hypothesis, to L($H_0$), the maximum value of the likelihood function for the null hypothesis (constant continuum cross-section) yields $\sqrt{2ln[L(H_1)/L(H_0)]} = 3.5$. We have determined the probability that a fictitious resonance may result from a fluctuation of the flat continuum by performing several thousand Monte Carlo simulations of the events distribution (our energies and luminosities) assuming a constant cross section equal to the average of all our measurements in the ${}^1P_1$ scan. By fitting the data of the Monte Carlo 'experiments' with exactly the same procedure as the data from the ${}^1P_1$ scan we found that the probability that a structure with $\sqrt{2ln[L(H_1)/L(H_0)]} \geq 3.5$ could arise anywhere in the scanned region from a statistical fluctuation is only 1 in 400.

The results of the fit can be summarized as follows. We see evidence of a resonance in the $\bar{p}p \rightarrow J/\psi + \pi^o$ channel, with a resonance mass value $M_R$=3526.2±0.15±0.2 MeV/c$^2$, where the second error comes from the uncertainty in the beam energy calibration. Because of the low statistics of our experiment and the ~ 750 keV width of the center of mass energy distribution, we can only set an upper limit on the resonance width of $\Gamma_R$ <1.1 MeV at a 90% confidence level.[2]

Since these results are consistent with what expected for the $1^1P_1$, we interpret this resonance in the $\bar{p}p \rightarrow J/\psi + \pi^0$ cross section as the first evidence for the $1^1P_1$ state of charmonium.

The value for the product $BR(R \rightarrow p\bar{p}) \times BR(R \rightarrow J/\psi + \pi^o)$ determined from the analysis of our data, depends on $\Gamma_R$. If we take as a plausible range of values 1000 keV$\geq \Gamma_R \geq$ 500 keV, we find:

$$(1.6 \pm 0.4) \times 10^{-7} \leq BR(R \rightarrow p\bar{p}) \times BR(R \rightarrow J/\psi + \pi^o) \leq (2.1 \pm 0.6) \times 10^{-7}$$

after folding in the value BR($J/\psi \rightarrow e^+e^-$)=(6.9±0.9)%[1] [3]. There is no reliable prediction of the partial width $\Gamma({}^1P_1 \rightarrow \bar{p}p)$. Kuang, Tuan and Yan[6] have related the decay (${}^1P_1 \rightarrow J/\psi + \pi^0$) to the decay ($\psi' \rightarrow J/\psi + \pi^0$) and obtained $\Gamma({}^1P_1 \rightarrow J/\psi + \pi^0) = 2$ keV. If we take this estimate at face value, we infer BR(${}^1P_1 \rightarrow \bar{p}p$) $\simeq 6 \times 10^{-5}$ (for $\Gamma_R$ = 700 keV) which is close to the corresponding measured value for the ${}^3P_1$ state[10].

Finally, we wish to take note of the fact that we have found no events of the type $\bar{p} + p \rightarrow J/\psi + 2\pi$ and set a limit BR( ${}^1P_1 \rightarrow J/\psi + 2\pi$)/BR(${}^1P_1 \rightarrow J/\psi + \pi^0$ )$\leq$ 0.18

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[2] We wish to point out that the observed excitation curve has a width $\Gamma = 900 \pm^{560}_{320}\ keV$, a value only slightly larger than what is expected from the beam contribution alone.

[3] Because of the limited statistics, the above analysis has been made ignoring possible interference between the resonance and the continuum.

at the 90% confidence level. There are two conflicting predictions[6][12] for this ratio. Our result is consistent only with the prediction of Voloshin[12].

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