Observation of the $^1P_1$ State of Charmonium

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We have 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 $\bar{p}+p\to J/\psi+\pi^0$ 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 $\bar{p}+p\to J/\psi+\pi^0+\pi^0$ and $\bar{p}+p\to J/\psi+\pi^++\pi^-$.

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The singlet states of heavy quarkonia [$\bar{Q}Q$; $s=0$, $J=l$, $P=(-1)^{l+1}$, $C=(-1)^l$] 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 $\eta_c(^1S_0)\to\bar{p}p$. The $^1P_1$ is expected to be narrow (≤ 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]

$$m_{\mathrm{c.o.g.}}\equiv\frac{m_{\chi 0}+3m_{\chi 1}+5m_{\chi 2}}{9}=3525.27\pm 0.12\ \mathrm{MeV}\,. \quad (1)$$

The cross section at the peak of the resonance for the formation reaction $\bar{p}p\to\,^1P_1$ is expected to be $\le 10^{-6}$ of the total cross section for $\bar{p}p\to$ hadrons at the same energy. To maximize the chances of identifying this rare process in the presence of a large hadronic background we have searched for the decays

$$^1P_1\to\eta_c+\gamma\to(\gamma\gamma)+\gamma\,, \quad (2)$$

$$^1P_1\to J/\psi+\pi^0\to(e^+e^-)+\pi^0\,, \quad (3a)$$

$$^1P_1\to J/\psi+2\pi\to(e^+e^-)+2\pi\,, \quad (3b)$$

with our nonmagnetic spectrometer, which is optimized for the detection of electromagnetic final states. 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 3γ 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 $4.0\times10^{11}\bar{p}$) stored in the accumulator ring, providing a pointlike source with instantaneous luminosity in the range of $(3\text{-}9)\times10^{30}$ cm^{-2}sec^{-1}. Typically, data for an integrated luminosity $\int\mathcal{L}\,dt\approx1$ 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 $\Delta p/p\leq2.5\times10^{-4}$ (rms), 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 $m_{\rm c.o.g.}$ [Eq. (1)] and data were taken in small energy steps (≤500 keV) to allow observation of a narrow resonance. A summary of the data is given in Table I.

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 (ϕ) and from 2° to 70° in the polar angle (θ). A set of cylindrical wire chambers inside the calorimeters provided accurate tracking of charged particles; among these was a radial projection chamber (RPC) giving up to sixteen 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 multicell Čerenkov counter identified electrons. A silicon detector at 86.5° to the beam direction measured the yield of elastic recoil protons and provided a monitor of the absolute luminosity with errors $\leq4\%$.

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 ϕ.

TABLE I. 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 nonresonant 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

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 π^0's which produced two electron pairs either from Dalitz decay of a π^0 or from conversion of a photon in the 0.2-mm-thick stainless-steel beam pipe. The selection of events with a J/ψ 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 off-line selection for events of type (3a) and (3b) has been estimated to be $\epsilon=0.81\pm0.03$ [10]. As an example of the results achieved with this analysis, we show in Fig. 1(a) the distribution of the invariant mass $m_{e^+e^-}$ for events collected at the ψ' 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 $\psi'\to J/\psi+X\to(e^+e^-)+X$, while the smaller peak at higher mass is due to the ex-

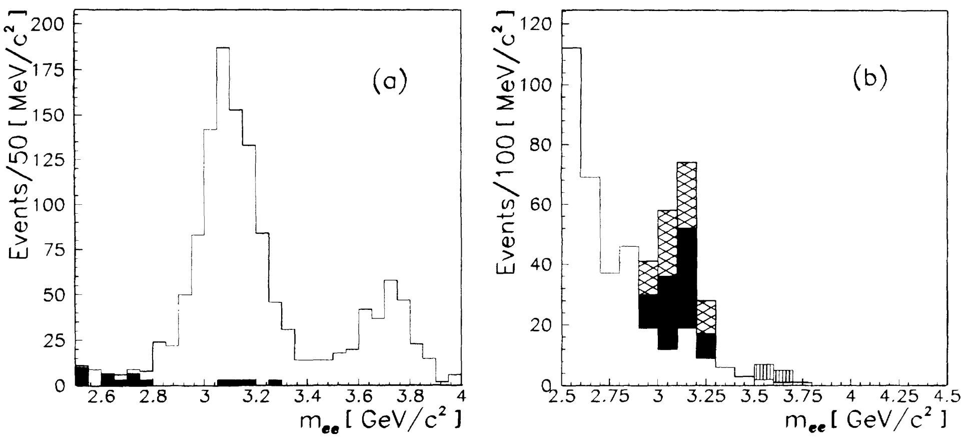

FIG. 1. Distribution of events vs $(m_{e^+e^-})$ (a) taken at the $\psi'(2\,{}^3S_1)$ ($\int \mathcal{L}\,dt \approx 1$ pb^{-1}) and (b) taken near $m_{\text{c.o.g.}}$ ($\int \mathcal{L}\,dt \approx 16$ pb^{-1}).

clusive decay $\psi' \to e^+e^-$. 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(b) shows the invariant mass distribution for all the data taken during the ${}^1P_1$ scan. From a comparison of Figs. 1(a) and (1b) it is clear that in the data from the ${}^1P_1$ scan we have events of the type $\bar{p}p \to J/\psi + X$. It should be noted that the J/ψ signal in these data is ≈ 100 times smaller than in the event sample of Fig. 1(a). This explains why the residual background component, from γ conversions and Dalitz decays, appears to be larger.

Events of Fig. 1(b) with $m_{e^+e^-} > 2.9$ GeV/c^2 were fitted by the reactions (3a), (3b) and by $\bar{p}p \to J/\psi + \gamma \to (e^+e^-) + \gamma$ and $\bar{p}p \to e^+e^-$ whenever the event topology was compatible with the final-state hypothesis. Most of the events could be fitted unambiguously either to $J/\psi + \gamma$ or to $J/\psi + \pi^0$. The efficiency of the fit was estimated to be $\approx 90\%$. The shaded areas in Fig. 1(b) represent events fitting $\bar{p}p \to J/\psi + \pi^0$ (black solid), $\bar{p}p \to J/\psi + \gamma$ (cross hatched), and $\bar{p}p \to e^+e^-$ (vertical stripes). No events were found to fit the reactions $\bar{p}p \to J/\psi + \pi^0 + \pi^0$ or $\bar{p}p \to J/\psi + \pi^+ + \pi^-$.

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 I we list the number of $J/\psi + \gamma$ and $J/\psi + \pi^0$ candidates found for each stack. It should be pointed out that only events fully contained in the acceptance of the detector ($\approx 40\%$ of all $J/\psi + \pi^0$ and $\approx 55\%$ of all $J/\psi + \gamma$) were included in this final sample while in Fig. 1(b) events with a γ escaping detection which fitted either $\bar{p}p \to J/\psi + \pi^0$ or $\bar{p}p \to J/\psi + \gamma$ area 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 $\bar{p}p \to J/\psi + \pi^0 \to (e^+e^-) + \pi^0$. In this case the tails of the χ's cannot contribute, since $\chi \to J/\psi + \pi^0$ violates C conservation. 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 $m_{\text{c.o.g.}}$ [see Eq. (1)] an apparently uniform level of ≈ 2.0 events per pb^{-1} is observed. This corresponds to a cross section of $\sigma(\bar{p}p \to J/\psi + \pi^0) = 99 \pm 40$ pb, in reasonable agreement with what is predicted for the continuum [11]. (The continuum level is found to increase slowly to 156 ± 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.)

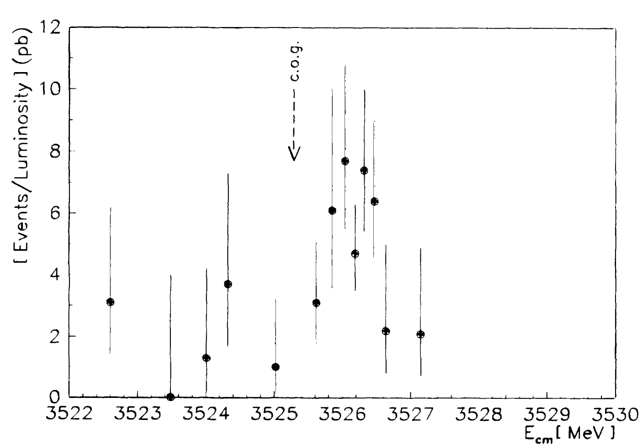

FIG. 2. Number of events per integrated luminosity vs center-of-mass energy; data are binned in 150-keV intervals in the average center-of-mass energy.

Above $m_{\rm c.o.g.}$ a consistently higher cross section is observed in the small region around 3526 MeV.

The data of the $^1P_1$ scan listed in Table I were analyzed using the maximum likelihood method to fit the measured cross sections with 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) yielded $\lambda = 2\ln[L(H_1)/L(H_0)] = 12.3$. In the limit where the distribution of λ approaches the χ^2 distribution (1 degree of freedom), the value $\lambda = 12.3$ implies a probability of 7×10^{-4} that the structure observed in the measured cross section is due to a fluctuation of the flat continuum. Since, however, this limit may not apply to our specific data sample, we have evaluated the statistical significance of our result 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 $\lambda = 2\ln[L(H_1)/L(H_0)] \geq 12.3$ could arise anywhere in the scanned region from a statistical fluctuation is 1 in 400.

The results of the fit can be summarized as follows. We see evidence of a resonance in the $\bar{p}p \to J/\psi + \pi^0$ channel, with a resonance mass value $M_R = 3526.2 \pm 0.15 \pm 0.2$ 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 $\Gamma_R \leq 1.1$ MeV at a 90% confidence level. (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.)

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

The value for the product $B(R \to p\bar{p})B(R \to J/\psi + \pi^0)$ determined from the analysis of our data depends on Γ_R. If we take as a plausible range of values 1000 keV $\geq \Gamma_R \geq$ 500 keV, we find the following:

$$(1.7 \pm 0.4)\times10^{-7} \leq B(R \to p\bar{p})B(R \to J/\psi + \pi^0) \leq (2.3 \pm 0.6)\times10^{-7}$$

after folding in the value $B(J/\psi \to e^+e^-) = (6.3 \pm 0.2)\%$ [1]. [Because of the limited statistics, the above analysis has been made ignoring possible interference between the resonance and the continuum. Such interference may affect the quoted mass and branching ratio results. In particular, in the hypothesis of interference with the full (or half) background, the maximum shift of the mass would be $\sim \pm 0.4$ MeV/c^2 (or $\sim \pm 0.3$ MeV/c^2) for a resonance width in the 0.5- to 1.0-MeV range.]

There is no reliable prediction of the partial width $\Gamma(^1P_1 \to \bar{p}p)$. Kuang, Tuan, and Yan [6] have related the decay $(^1P_1 \to J/\psi + \pi^0)$ to the decay $(\psi' \to J/\psi + \pi^0)$ and obtained $\Gamma(^1P_1 \to J/\psi + \pi^0) = 2$ keV. If we take this estimate at face value, we infer $B(^1P_1 \to \bar{p}p) \simeq 6.5 \times 10^{-5}$ (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 $\bar{p} + p \to J/\psi + 2\pi$ and set a limit $B(^1P_1 \to J/\psi + 2\pi)/B(^1P_1 \to J/\psi + \pi^0) \leq 0.18$ 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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[1] Particle Data Group, K. Hikasa *et al.*, Phys. Rev. D **45**, S1 (1992).

[2] C. Edwards *et al.*, Phys. Rev. Lett. **48**, 70 (1982).

[3] E. D. Bloom and C. W. Peck, Annu. Rev. Nucl. Part. Sci. **33**, 143 (1983); C. Baglin *et al.*, Phys. Lett. B **171**, 135 (1986).

[4] H. J. Schnitzer, Phys. Rev. Lett. **35**, 1540 (1975).

[5] A. Andrikopoulou, Z. Phys. C **22**, 63 (1984), and references therein.

[6] Y-P. Kuang, S-F. Taun, and T-M. Yan, Phys. Rev. D **37**, 1210 (1988), and references therein.

[7] W. Kwong *et al.*, Phys. Rev. D **37**, 3210 (1988).

[8] R. McClary and N. Byers, Phys. Rev. D **28**, 1692 (1983); V. O. Galkin *et al.*, Yad. Fiz. **51**, 1101 (1990) [Sov. J. Nucl. Phys. **51**, 705 (1990)]; K-T. Chao *et al.*, University of Minnesota Report No. TPI-MINN-92/12-T (to be published).

[9] J. Pantaleone and S-H. Tye, Phys. Rev. D **37**, 3337 (1988); S. N. Gupta *et al.*, Phys. Rev. D **39**, 974 (1989); V. V. Dixit *et al.*, Phys. Rev. D **42**, 166 (1990); A. M. Badalyan and V. P. Yurov, Phys. Rev. D **42**, 3138 (1990); L. P. Fulcher, Phys. Rev. D **44**, 2079 (1991); J. Stubbe and A. Martin, Phys. Lett. B **271**, 208 (1991); Y. Q. Chen and Y. P. Kuang, Phys. Rev. D **46**, 1165 (1992); F. Halzen *et al.*, University of Wisconsin Report No. MAD/PH/706 (to be published); D. B. Lichtenberg and R. Potting, Phys. Rev. D **46**, 2150 (1992), and references therein.

[10] T. A. Armstrong *et al.*, Phys. Rev. Lett. **68**, 1468 (1992); T. A. Armstrong *et al.*, Nucl. Phys. **B373**, 35 (1992).

[11] M. K. Gaillard *et al.*, Phys. Lett. **110B**, 489 (1982).

[12] M. B. Voloshin, Yad. Fiz. **43**, 1571 (1986) [Sov. J. Nucl. Phys. **43**, 1011 (1986)]; (private communication).