Search for hidden charm states decaying into J/ψ or ψ' plus pions

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A search has been made in 300 GeV/c $\pi^{\pm}$- and proton-Li interactions for production of states that decay into J/ψ or ψ' plus one or two pions. A 2.5σ enhancement in the $J/\psi\,\pi^0$ spectrum, possibly the recently reported $^1P_1$ state of charmonium, is observed at a mass of 3.527 GeV/c^2. In the J/ψ plus two pion mass spectrum, we report, together with the expected $\psi' \to J/\psi\,\pi^+\pi^-$, the tentative observation of a structure at a mass of 3.836 GeV/c^2. No enhancements are seen in the $J/\psi\,\pi^{\pm}\pi^{\pm}$, $J/\psi\,\pi^{\pm}\pi^0$, $J/\psi\,\pi^{\pm}$, or $\psi'\,\pi^{\pm}$ mass spectra.

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I. INTRODUCTION

Since nearly all observations of hidden charm states have been made at e^+e^- colliders, most of the established states have the quantum numbers of the photon or are produced via the decay of directly produced vector states. Examples of the latter include the χ meson states, which are produced via the radiative decay of the ψ' (3685). Because of small branching ratios or unfavorable quantum numbers, many states are difficult to produce by vector meson decay. Also, above the open charm threshold, vector mesons tend to decay predominantly into $D\overline{D}$ pairs. These restrictions on e^+e^- production of heavy flavor states make it interesting to examine hadroproduction processes, where the requirement of producing charmonium states through a vector state is not present. In addition, it is conceivable that states of four or more quarks can be produced in hadronic interactions. There have been attempts [1] to interpret some of the light-quark mesons, such as the $a_0(980)$ and the $f_0(975)$, as $qq\bar{q}\,\bar{q}$ states, and it is of interest to explore this possibility in the heavy-quark meson sector.

Fermilab experiment 705 (E705) has measured the production of various charmonium states [2,3] including the $J/\psi, \psi'$ and various χ states in interactions of 300 GeV/$c\pi^{\pm}$, protons and antiprotons with a lithium target of natural isotopic composition. The polarity of the E705 secondary beam line was reversed at approximately monthly intervals during the data acquisition period. The positive polarity beam consisted of 55% protons and 45% pions, while the negative polarity beam consisted of 98% pions and 2% antiprotons. Kaons were not identified by the beam Cherenkov counters, and they are included in our definitions of "pion." We have examined events containing reconstructed $J/\psi(\psi')$ states for evidence of either heretofore undetected charmonium states or states of four quarks which decay into a $J/\psi(\psi')$ plus pions. In this paper we report the results of this search in both our pion and proton induced data samples.

II. PARTICLE IDENTIFICATION

The J/ψ and ψ' were detected in E705 through their $\mu^+\mu^-$ decay modes. The E705 spectrometer [4] incorporated a copper and steel muon filter of 27 hadron absorption lengths. Particles that generated coincidences of three planes of scintillation counters embedded in the filter were flagged by the fast trigger as muon candidates. If two or more such triple coincidences were present in an event, an on-line trigger processor [5] performed partial reconstruction of track segments downstream of the momentum-analyzing magnet. These segments, together with the coordinates of the target center, were used by the processor to estimate the muon candidate momentum and the invariant masses of all dimuon candidates in the event. The event was written to tape only if it contained a dimuon candidate with an estimated mass greater than 2.7 GeV/c^2.

Offline, all tracks including the muons were fully reconstructed using tracking information from wire chambers upstream and downstream of the analyzing magnet. The momentum (P) of each track was determined by its bend angle in the horizontal plane, in which the magnet imparted an integrated impulse of 766 MeV/c, and by the undeviated slope in the vertical plane. The dimuon mass spectra for the four beam types are shown in Fig. 1. Details on the extraction of the data of the Fig. 1 plots can be found in an earlier paper [2]. In the remainder of this paper a J/ψ is defined by $2.88 \leq M_{\mu\mu} \leq 3.28$ GeV/c^2 and a ψ' by $3.56 \leq M_{\mu\mu} \leq 3.82$ GeV/c^2.

Electrons were identified using fully reconstructed tracks together with energy (E) and position information measured by a large scintillating and lead glass electromagnetic calorimeter [6]. The horizontal and vertical profiles of showers after the first four radiation lengths of the calorimeter (the "active converter") were measured by fine grained position detectors, with single shower position resolution between 2 and 6 mm throughout the active area of the calorimeter. The energies deposited in the active converter and the rest of the calorimeter (the "main array") were measured separately. The single shower energy resolution of the calorimeter ranged between $0.05/\sqrt{E}$ and $0.13/\sqrt{E}$, depending upon the region of the calorimeter. Figure 2 shows the energy deposited in the active converter divided by the square root of the total deposited energy, plotted versus E/P, for showers associated with tracts entering the calorimeter within ± 3 cm of the horizontal and vertical shower centroids. Shower/track combinations with $0.8 \leq E/P \leq 1.2$ and an active converter energy greater than the larger of 0.2 GeV and $0.15\sqrt{E}$ GeV were identified as electrons. The requirement on active converter energy was imposed to reduce contamination further in the electron sample due to hadrons, as is suggested by Fig. 2.

Photons were defined as showers with (1) $E \geq 2$ GeV, (2) active converter energy greater than the larger of 0.2 GeV and $0.15\sqrt{E}$ GeV, (3) horizontal and vertical energy deposition profiles well matched to simulated photon shapes, and (4) the absence of charged tracks within ± 5 cm of the horizontal and vertical shower centroids. Neutral pions were reconstructed by forming diphoton invariant mass combinations. Figure 3(a) shows the diphoton mass distribution for photons meeting these criteria for events in the J/ψ mass range. The dotted line represents a polynomial fit to the background outside the π^0 mass region. In Fig. 3(b) the π^0 shape predicted by a detailed Monte Carlo simulation, incorporating the measured position and energy resolutions of the calorimeter, is superimposed on the background-subtracted diphoton mass distribution. In the following analysis neutral pions are identified as diphoton mass combinations within the mass range 110 MeV/c^2 $< M\gamma\gamma <$ 170 MeV/c^2. The measured π^0 mass centroid varied between 137.6 MeV/c^2 and 142.5 MeV/c^2, depending upon the region of the calorimeter. From this observation we infer a systematic

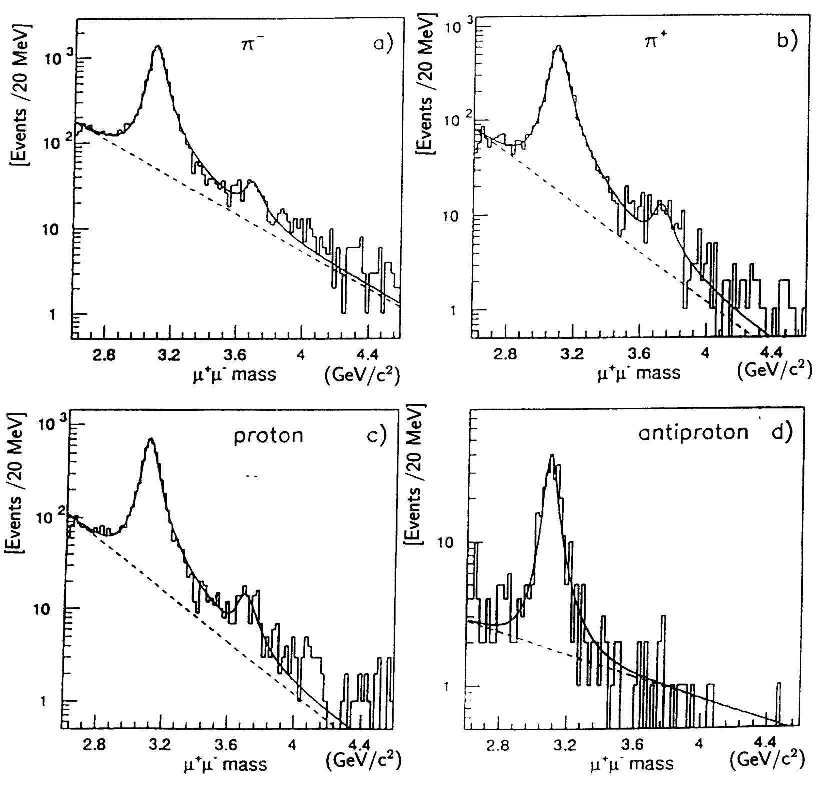

FIG. 1. Dimuon mass spectra from 300 GeV/c (a) π^-, (b) π^+, (c) proton, and (d) antiproton interactions with a lithium target.

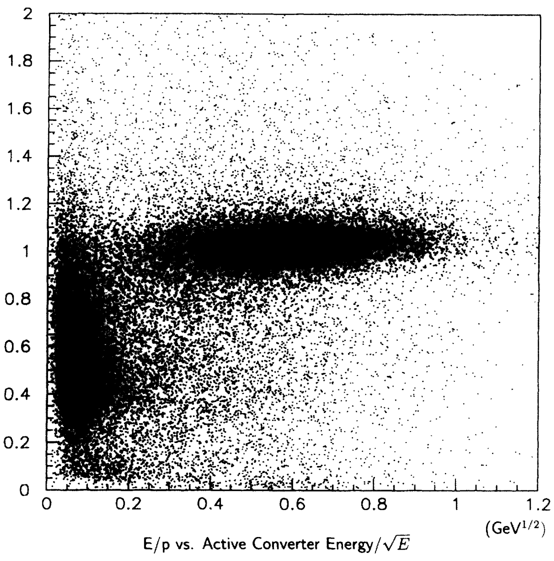

FIG. 2. Electromagnetic detector active converter energy divided by the square root of the total shower energy versus E/P for changed pion candidates.

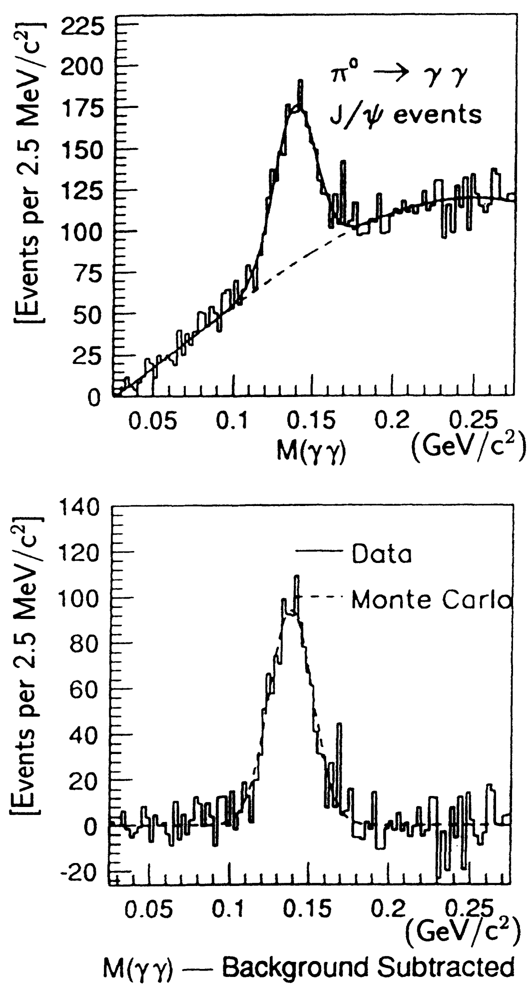

FIG. 3. Diphoton mass spectrum from J/ψ events; (b) expected π^0 mass resolution from the Monte Carlo simulation, superimposed on background-subtracted diphoton combinations in the π^0 mass region.

uncertainty of 3% in the absolute energy scale for single photons.

We have formed mass combinations of one or two charged or neutral pions with dimuons that fell within the mass of the J/ψ and ψ'. Charged pions were defined as tracks that did not satisfy the criteria for either an electron or a muon. The momentum resolution for charged tracks can be parametrized as $\sigma_P/P = 0.2 + 0.02P + 0.001P^2$($P$ in GeV/c). This parametrization is confirmed by the effective 1σ width of the J/ψ, 44 MeV/c^2, which agrees well with Monte Carlo predictions. With an approximate ±170 mr horizontal by ±85 mr vertical coverage, the E705 spectrometer was sensitive to J/ψ's in the range $-0.1 < x_F < 0.5$. Feynman-x values larger than 0.5 are typically associated with muons in the central, beam-diffraction region, in which the spectrometer wires were intentionally desensitized. It should also be noted that the spectrometer acceptance effectively set a 2 GeV/c minimum momentum threshold for the charged particles, while the hadronic filter material set a 6 GeV/c threshold for muons.

III. HIDDEN CHARM STATE DECAYING TO J/ψ PLUS ONE PION

We have investigated the $J/\psi\,\pi^0$ spectrum in a search for neutral resonant states decaying into J/ψ plus a single pion. As shown in Fig. 4(a), which combines both our proton and pion data, we observe a 2.5σ enhancement (42 ± 17 events over background and a 1σ width of 0.014 ± 0.005 GeV/c^2) at 3.527 ± 0.008 GeV/c^2 in our $J/\psi\,\pi^0$ mass spectrum. In order to estimate the combinatoric background in Fig. 4(a), J/ψ's were multiply paired with π^0's from other events. The resultant mass distribution was fit to a fourth degree polynomial which was then scaled to match the number of entries in the high mass tail (3.65–4.00 Gev/c^2). This normalized distribution is presented by the dashed line. The bold lines represent fits to the data based on the background parametrization plus a single Gaussian. There is an estimated 3% systematic uncertainty in background determination, which is considerably smaller than the quoted statistical error.

The enhancement persists even if we plot pion and proton data separately [Figs. 4(b) and 4(c)]; the number of events above background in the peak is determined from the fit to be 26 ± 12 and 16 ± 10 for the pion and proton data, respectively. For the pion sample, we determine the product of the cross section ($x_F > 0$) and branching ratio for this state to be 5.3 ± 2.5 nb/nucleon.

We have tentatively identified this enhancement as the $^1P_1$ state of charmonium. A 3.5σ enhancement in the same decay mode has been reported [7] at a mass of $3256.2 \pm 0.15 \pm 0.2$ MeV/c^2 by Fermilab experiment E760. The identification of this state with the charmonium $^1P_1$ is supported by its mass, which is near the spin-weighted centroid of the χ states. Our 8 MeV/c^2 mass uncertainty reflects the statistical uncertainty in measuring the centroid. Since we constrain the J/ψ to its well-established mass, the systematic error in the absolute mass scale is estimated to be less than 1 Mev/c^2.

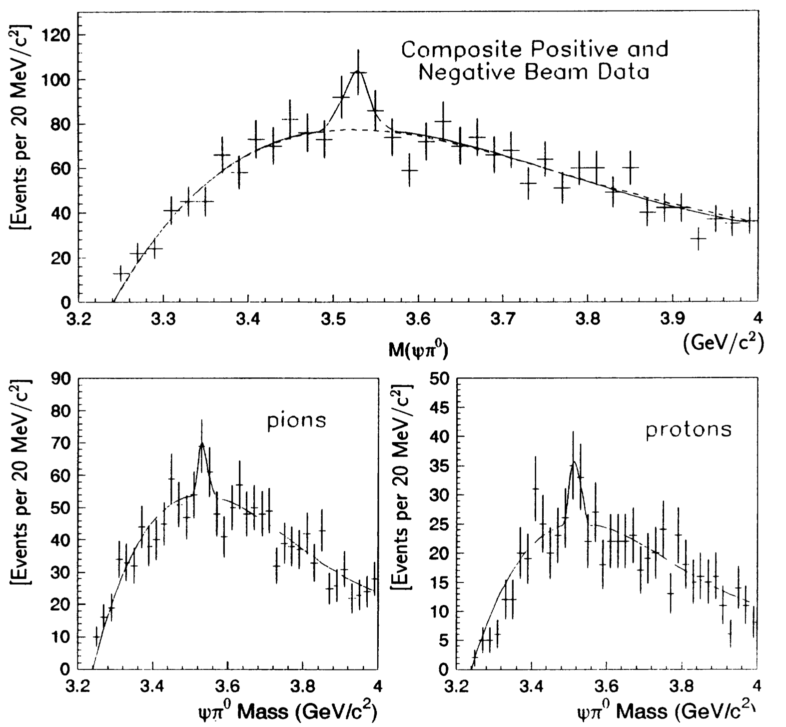

FIG. 4. (a) $J/\psi\,\pi^0$ mass spectrum from the combined pion and proton beam data; (b) $J/\psi\pi^0$ mass spectrum from the pion beam data; (c) $J/\psi\,\pi^0$ mass spectrum from the proton beam data.

We have also searched for enhancement in the $J/\psi\,\pi^{\pm}$ mass spectrum. As shown in Fig. 5(a), the $M(\mu\mu\pi^{\pm}) - M(\mu\mu)$ mass-difference spectrum obtained from the combined data set (all beam types) shows no evidence of structure. By taking the difference in invariant masses one effectively removes the error due to the J/ψ mass reconstruction. The background curve, shown superimposed on the data in Fig. 5(a), was formed by uniquely pairing J/ψ's with charged pions from other events. If the state at 3.527 GeV$/c^2$ was a $c\bar{c}q\bar{q}$ state rather than the $^1P_1c\bar{c}$, one would expect to observe isospin partners of this state. However, there is no evidence for an excess of events over background near 430 MeV$/c^2$, the region in the mass-difference histogram corresponding to 3527 MeV$/c^2$.

We have also examined the $\psi'\,\pi^{\pm}$ mass spectrum for resonance structure. Figure 5(b) shows the mass-difference spectrum $M(\mu\mu\pi^{\pm}) - M(\mu\mu)$, for the $\psi' \to \mu\mu$ events from the combined data set. The background shape, shown superimposed on the data, was generated by pairing $\psi' \to \mu\mu$ candidates with a single charged pion from other events. There is no evidence for any significant enhancements above background in this spectrum.

IV. HIDDEN CHARM STATES DECAYING TO J/ψ PLUS TWO PIONS

For the J/ψ events used in the study of $J/\psi\,\pi^+\pi^-$ final states, two additional criteria were imposed on the charged pions to increase signal-to-background ratios for resonance states. First, the J/ψ events were required to have fewer than six reconstructed charged pions per event. Only 8.7% of the J/ψ events failed to meet this requirement. Second, the dipion mass was required to be greater than 80% of its maximum kinematically possible value. This requirement was imposed since, according to Brown and Cahn [8], the phase space for a decay such as $\psi' \to J/\psi\pi\pi$ is modified by chiral symmetry such that the dipion mass is skewed toward high values. While chiral symmetry breaking and final state pion scattering would tend to diminish this effect, Mark III data [9] show that it still persists. Imposing the 80% dipion mass cut is expected to remove 62% of the uncorrelated $J/\psi\,\pi^+\pi^-$ combinations (assuming a phase space distribution for the $\pi^+\pi^-$), while retaining 69% of the $\psi' \to J/\psi\,\pi^+\pi^-$ signal. Imposing this requirement eliminated 73% of the $J/\psi\,\pi^+\pi^-$ events.

In order to increase our sensitivity for the two pion mode, we have combined data from the negative and positive pion beams. The $J/\psi\,\pi^+\pi^-$ mass spectrum from our $\pi^{\pm}$Li data, using the cuts discussed above, is shown in Fig. 6(a). The $J/\psi\,\pi^+\pi^-$ background was generated by uniquely pairing J/ψ's with dipions from other events. In an alternative approach, a background curve was generated using same-sign dipions, and this procedure gave a similar result. A clear $\psi' \to J/\psi\,\pi^+\pi^-$ signal at 3.683 ± 0.005 GeV$/c^2$ can be seen in the opposite-sign dipion mass spectrum in Fig. 6(a). In addition to the ψ' signal, an enhancement is observed at 3.836 ± 0.013 GeV$/c^2$. No such peaks are observed in the same-sign dipion mass spectra obtained using the same cuts.

The data of Fig. 6(a) are not well fit by a single Gaussian peak on a smooth background. The addition of a second peak significantly improves the fit, as shown by the curve superimposed on the data of Fig 6(a). The number of events above background in the ψ' peak and in the enhancement at 3.836 GeV/c^2 are determined to be 77 ± 21 and 58 ± 21, respectively. The widths of the ψ' peak and the enhancement at 3.836 GeV/c^2 are 0.017 ± 0.004 GeV/c^2 and 0.024 ± 0.005 GeV/c^2, respectively, in good agreement with Monte Carlo estimates of the spectrometer resolution for the $J/\psi\,\pi^+\pi^-$ mass combinations of 0.022 and 0.029 GeV/c^2, respectively. Under the assumption that the enhancement is a resonant state, we have determined its cross section times branching ratio relative to the simultaneously observed ψ' signal, and from this, a value for $B(X \to J/\psi\,\pi^+\pi^-)\sigma(\pi^- N \to X + x')$ of $5.3 \pm 1.9 \pm 1.3$ nb per nucleon, for $x_F > 0$. In determining this cross section, we have used acceptances based on Monte Carlo studies which assume that the x_F distribution for the 3.836 GeV/c^2 enhancement is the same as the one observed for the J/ψ production. The A dependence of the cross section is assumed to be $A^{0.92}$, the same as that observed in J/ψ production.

We have also searched for the ψ' and 3.836 GeV/c^2 enhancement in our 300 GeV/c^2 proton beam data. These data, shown in Fig. 6(b), have considerably lower statistics than our combined π^+ and π^- data. We do not observe significant peaks in $J/\psi\,\pi^+\pi^-$ mass spectrum either at the ψ' mass or at 3.836 GeV/c^2 in the proton data. However, there is a slight excess of events above background in the region of the ψ' mass and 3.836 GeV/c^2. Motivated by our observations in the pion data sample, we have also fit the proton beam spectrum with a pair of Gaussians where the ψ' mass was constrained to the

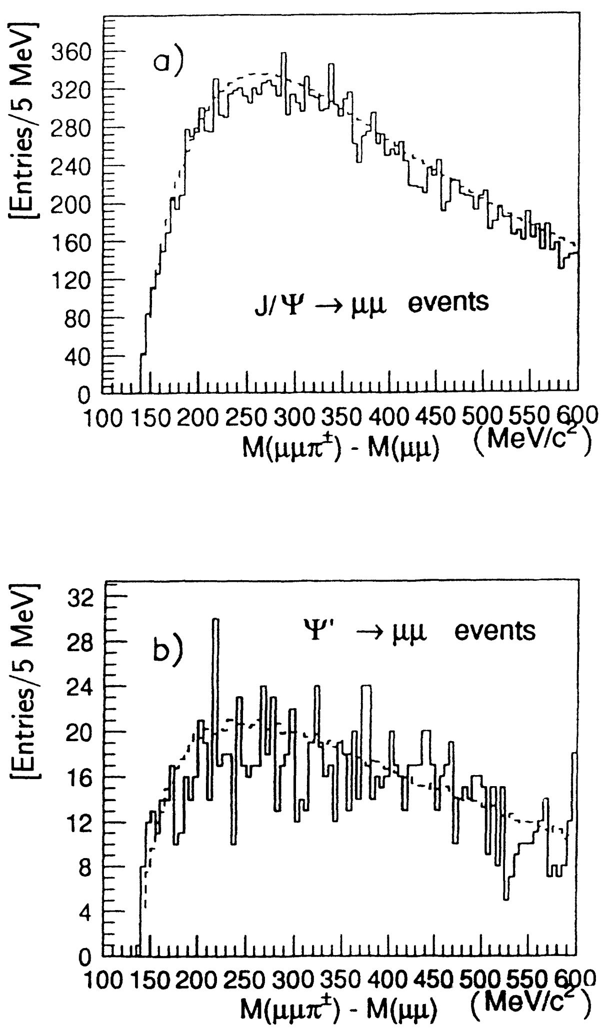

FIG. 5. (a) $M(\mu\mu\pi^{\pi}) - M(\mu\mu)$ mass difference spectrum for $J/\psi \to \mu\mu$ events from the combined pion and proton beam data; (b) $M(\mu\mu\pi^{\pm}) - M(\mu\mu)$ mass difference spectrum for $\psi' \to \mu\mu$ events from the combined pion and proton data.

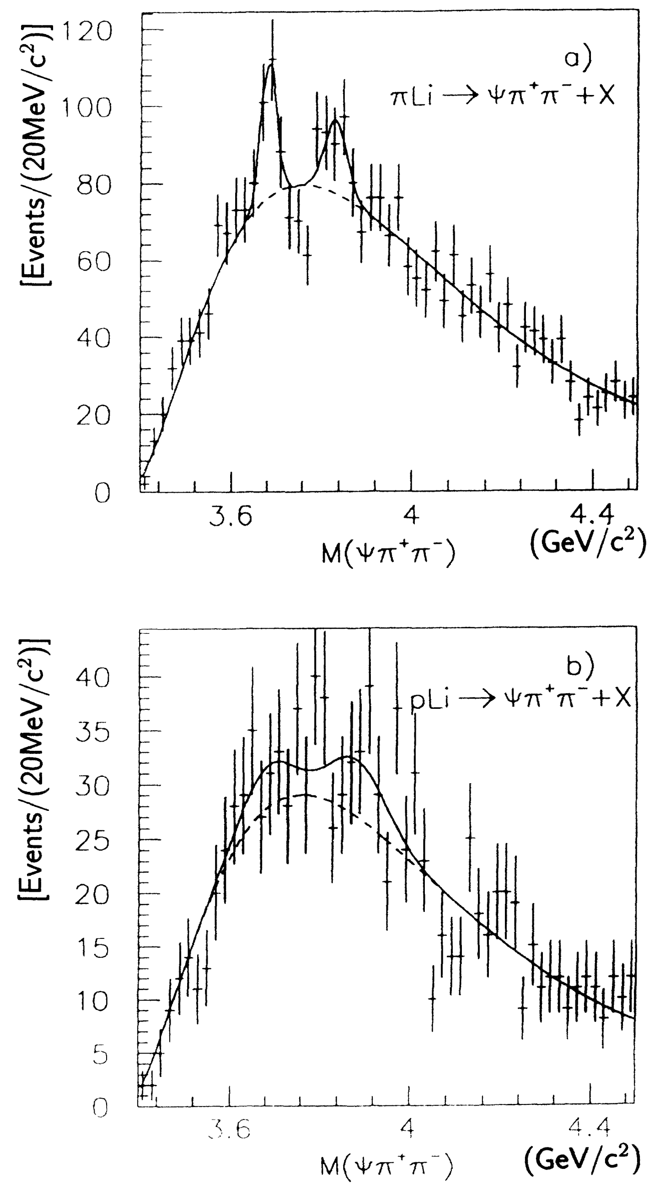

FIG. 6. $J/\psi\,\pi^+\pi^-$ mass spectra from 300 GeV/$c\pi^{\pm}$Li interactions; (b) $J/\psi\,\pi^+\pi^-$ mass spectrum from 300 GeV/c proton Li interactions.

value determined from the combined pion sample and the other parameters were allowed to vary. The number of entries in the two peaks are 27 ± 23 and 45 ± 24, respectively.

While the statistics are low for the ψ' and the enhancement at 3.836 GeV/c^2 in the pion data, they are still adequate to study the dipion mass distributions in the mass region of the two peaks. Figures 7(a) and 7(b) show the dipion mass distributions obtained, after background subtractions, to the ψ' and the 3.836 GeV/c^2 enhancement in the pion-induced $J/\psi\,\pi^+\pi^-$ spectrum. Both dipion mass spectra are peaked toward the high end of the mass distribution as suggested by the Brown and Cahn theory. The curves shown are based on the shape suggested by this theory. For this particular study, the low dipion mass cut was not imposed as this would clearly bias the results.

Possibly explanations of the 3.836 GeV/c^2 enhancement, other than a new state, have been investigated. Reconstruction of real ψ' decays at the wrong mass due to idiosyncrasies of track reconstruction is unlikely, since no spurious peaking has been produced in ψ' Monte Carlo events. These studies are based on the overlay of simulated states on real data and employ the complete reconstruction process. Furthermore, we can calculate the cross section for ψ' production, relative to the J/ψ, by using only the events in the ψ' peak. Using a branching ratio for $\psi' \to J\psi\,\pi^+\pi^-$ of 0.324 ± 0.026 [10] and a relative efficiency of 9% for accepting and reconstructing the dipion given that the dimuon is accepted and reconstructed, we obtain for the ψ' cross section relative to the J/ψ a value of $15 \pm 4 \pm 3\%$, in good agreement with the value of $14 \pm 2 \pm 2\%$ measured in our experiment [2] by direct observation of the $\psi' \to \mu\mu$ decay mode. If all of the events in the second peak were to be interpreted as mismeasured ψ', then the corresponding value of relative cross section would increase by a factor of 1.75, in clear disagreement with our independent measurement of ψ' production. Also considered as possible origins of the enhancement at 3.836 GeV/c^2 were Dalitz decays, $\chi \to J/\psi\, e^+e^-$, or conversions of the photons from $\chi \to \gamma\psi$ resulting in $J/\psi\, e^+e^-$ final states in which the e^+e^- were misidentified as $\pi^+\pi^-$. Neither the opening angles of the dipions nor the level of the observed enhancement are considered with these hypotheses.

If the enhancement at 3.836 GeV/c^2 is confirmed by future experiments, then the most likely interpretation is that it is due to a $c\bar{c}$ charmonium state. A more speculative interpretation would be that it is due to a $c\bar{c}q\bar{q}$ state. The lack of a signal in the $J/\psi\,\pi^\pm\pi^0$ mass spectrum, shown in Fig. 8, and in the $J/\psi\,\pi^\pm\pi^\pm$ spectra supports the interpretation of the enhancement seen in the $J/\psi\,\pi^+\pi^-$ spectrum as an isospin singlet. The fitted curve in Fig. 8 is generated by the same technique as in Fig. 6. The observation of a $J/\psi\,\pi^+\pi^-$ mode for the 3.836 GeV/c^2 state, which is above the threshold for decays into $D\bar{D}$ (but below $D\bar{D}^*$ threshold), argues against the $0^{++}, 1^{--}, 2^{++}$, and 3^{--} quantum number assignments for this enhancement, which would permit the otherwise kinematically allowed S, P, D, and F wave

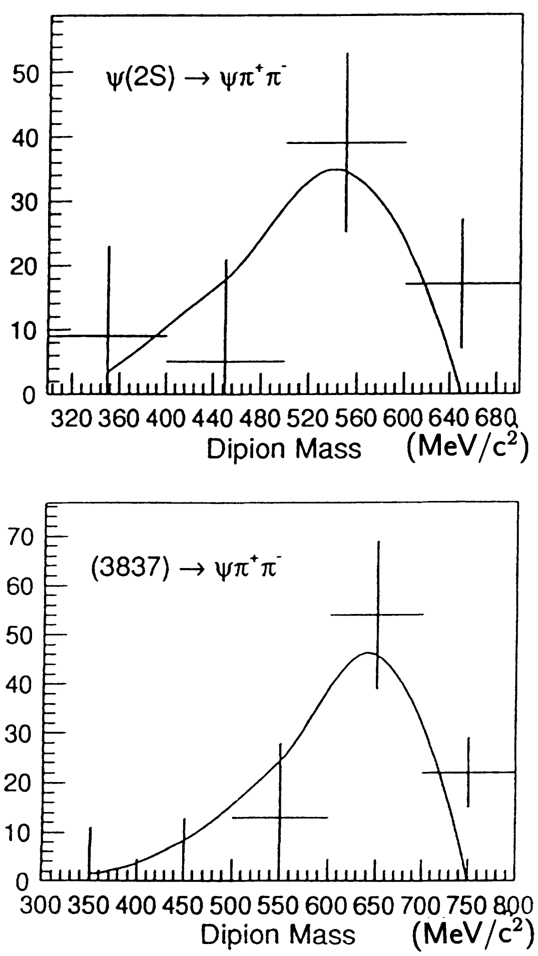

FIG. 7. (a) $\pi^+\pi^-$ mass spectrum from $J/\psi\,\pi^+\pi^-$ events in the ψ' mass region; (b) $\pi^+\pi^-$ mass spectrum from $J/\psi\,\pi^+\pi^-$ events in the 3.836 GeV/c^2 mass region.

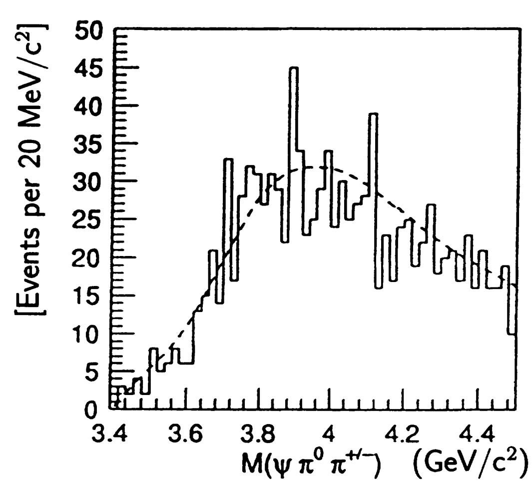

FIG. 8. $J/\psi\,\pi^0\pi^\pm$ mass spectrum from the $\pi^\pm$Li data.

decays into $D\overline{D}$. The remaining charmonium candidates for such a state are the ${}^1P_1(1^{+-}), {}^3D_2(2^{--})$, and the ${}^1F_3(3^{+-})$ states. All other charmonium states are excluded by G parity or by allowed open charm channels in $D\overline{D}$, which would dominate the decay width. Of the three charmonium states which may provide the explanation of the enhancement at 3.836 GeV/c^2, the ${}^1P_1$ state is predicted to lie near 3.525 GeV/c^2, the center of mass of the χ states. While the 3.836 GeV/c^2 enhancement could still be the first radial excitation of the ${}^1P_1$, the fact that we do not observe the lower mass ${}^1P_1$ state in the $J/\psi\,\pi^+\pi^-$ mass spectrum makes this explanation unlikely. On the other hand, the mass of the ${}^1F_3$ state is expected to be larger than 3.836 GeV/c^2. For an inverse square law potential, the F states have the same energy as the charmonium $4S$ state, which has been identified with the observed $\psi(4160)$ state [11]. Theoretical predictions [12,13] of 3.810 GeV/c^2 and 3.840 GeV/c^2 for the mass of the charmonium ${}^3D_2$ state are much closer to the observed 3.836 GeV/c^2 mass of our enhancement, and that is our preferred interpretation.

The alternative interpretation of the 3.836 GeV/c^2 enhancement as a four-quark state suggests that the decay into $J/\psi\,\pi^+\pi^-$ might proceed through an intermediate $J/\psi\,\rho$ state (since 3.836 GeV/c^2 is approximately a ρ mass above the J/ψ). However, the peaking in mass of the dipion in the 3.836 GeV/c^2 enhancement toward the ρ mass does not necessarily indicate the presence of a ρ in the decay process. Although the decay ${}^3D_2 \to J/\psi\,\pi^+\pi^-$ is D wave, the dipion mass spectrum may also be peaked toward higher values by effects similar to those discussed by Brown and Cahn for S-wave decays. Although we could, in principle, test for the presence of a ρ in the decay process by comparison of the $J/\psi\,\pi^0\pi^0$), with the $J/\psi\,\pi^+\pi^-$ decay modes (since the ρ does not decay into $\pi^0\pi^0$), the combination of small branching ratio and small acceptance for the $J/\psi\,\pi^0\pi^0$ mode makes this study difficult. The low statistics of the 3.836 GeV/c^2 enhancement do not permit a spin parity analysis, which might also distinguish between the standard charmonium decay and four quark state hypotheses.

V. CONCLUSION

We have examined the $J/\psi\,\pi^0, J/\psi\,\pi^\pm, \psi'\,\pi^\pm, J/\psi\,\pi^+\pi^-, J/\psi\,\pi^\pm\pi^0$, and $J/\psi\,\pi^\pm\pi^\pm$ mass combinations produced in 300 GeV/$c\,\pi^\pm$ and proton Li interactions in a search for $c\bar{c}$ or $c\bar{c}q\bar{q}$ states. We have observed an enhancement in the $J/\psi\,\pi^0$ mass spectrum at 3.527 GeV/c^2 in both our pion and proton beam data. The overall significance of this effect is 2.5σ in the combined pion and proton data. We conclude that the enhancement is due to the recently reported ${}^1P_1$ state of charmonium. In the $J/\psi\,\pi^+\pi^-$ mass spectrum from our pion beam data, we have observed the decay $\psi' \to J/\psi\,\pi^+\pi^-$ and a 2.8σ structure at a mass of 3.836 GeV/c^2. The $J/\psi\,\pi^+\pi^-$ mass spectrum from our proton beam data does not contradict the presence of such an enhancement, although statistics are too low to allow an independent confirmation. If the 3.836 GeV/c^2 structure is eventually confirmed by other data, an interpretation as the previously unobserved ${}^3D_2(2^{--})$ state of charmonium is favored. We find no evidence for any structure in the $J/\psi\,\pi^\pm\pi^\pm, J/\psi\,\pi^\pm\pi^0, J/\psi\,\pi^\pm$, and $\psi'\,\pi^\pm$ mass spectra. Finally, we find no effects in our data that require a four-quark explanation, although decisive tests of a four-quark hypothesis are precluded by lace of statistics.

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