Observation of the Narrow State $X(3872) \to J/\psi\pi^+\pi^-$ in $\bar{p}p$ Collisions at $\sqrt{s} = 1.96$ TeV

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 0031-9007/04/93(7)/072001(6)$22.50

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We report the observation of a narrow state decaying into $J/\psi\pi^+\pi^-$ and produced in 220 pb^{-1} of $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV in the CDF II experiment. We observe 730 ± 90 decays. The mass is measured to be $3871.3 \pm 0.7(\text{stat}) \pm 0.4(\text{syst})$ MeV$/c^2$, with an observed width consistent with the detector resolution. This is in agreement with the recent observation by the Belle Collaboration of the $X(3872)$ meson.

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The study of bound states of charm-anticharm quarks revolutionized our understanding of hadrons beginning with the discovery of the J/ψ meson in 1974 [1]. Although numerous charmonium ($c\bar{c}$) states are now known, others should be observable. Recently, the Belle Collaboration reported a new particle $X(3872)$ observed in exclusive decays of B mesons produced in e^+e^- collisions [2]. This particle has a mass of 3872 MeV$/c^2$ and decays into $J/\psi\pi^+\pi^-$. A natural interpretation of this particle would be a previously unobserved charmonium state, but there are no such states predicted to lie at or near the observed mass with the right quantum numbers to decay into $J/\psi\pi^+\pi^-$ [3,4]. Within the framework of QCD, mesons may also arise from more complex systems than the conventional quark-antiquark bound state [5]. The proximity of the $X(3872)$ mass to the sum of the D^0 and D^{*0} masses suggests that $X(3872)$ may be a weakly bound deuteronlike "molecule" composed of a D and $\overline{D}^*$. Another possibility is that $X(3872)$ is a $c\bar{c}g$ hybrid meson—a $c\bar{c}$ system possessing a valence gluon. These novel interpretations have excited great interest in $X(3872)$ [6]. Whether it is a new form of hadronic matter or a conventional $c\bar{c}$ state in conflict with theoretical models, $X(3872)$ is an important object of study. Here we report the observation of a $J/\psi\pi^+\pi^-$ resonance produced inclusively in $\bar{p}p$ collisions and which is consistent with $X(3872)$.

The analysis uses a data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV with an integrated luminosity of 220 pb^{-1} collected with the upgraded collider detector (CDF II) at the Fermilab Tevatron between February 2002 and August 2003. The important components of the CDF II detector for this analysis include a tracking system composed of a silicon-strip vertex detector (SVX II) [7] surrounded by an open-cell drift chamber system called the central outer tracker (COT) [8]. The

SVX II detector comprises five concentric layers of double-sided sensors located at radii between 2.5 and 10.6 cm. On one side of the sensors, axial strips measure positions in the plane transverse to the beam line. Strips on the other side are used for stereo measurements. The latter strips are tilted with respect to the axial strips: on one layer by $+1.2°$, another by $-1.2°$, and three by $90°$. The active volume of the COT is a 3.1 m long cylinder covering radii from 43 to 132 cm with 8 superlayers of 12 wires each. In order to provide three-dimensional tracking, superlayers of axial wires alternate with superlayers of $+2°$ stereo angle wires and superlayers of $-2°$ stereo angle wires. The central tracking system is immersed in a 1.4 T solenoidal magnetic field for the measurement of charged particle momenta transverse to the beam line, p_T. The outermost detection system consists of planes of multilayer drift chambers for detecting muons [9]. The central muon system (CMU) covers $|\eta| \leq 0.6$, where $\eta \equiv -\ln[\tan(\theta/2)]$ and θ is the angle of the particle with respect to the direction of the proton beam. Additional muon chambers (CMX) extend the rapidity coverage to $|\eta| = 1.0$.

In this analysis, $J/\psi \to \mu^+\mu^-$ decays are recorded using a dimuon trigger. The CDF II detector has a three-level trigger system. The level-1 trigger uses tracks in the muon chambers with a clear separation in azimuth from neighboring tracks. The extremely fast tracker (XFT) [10] uses information from the COT to select tracks based on p_T. XFT tracks with $p_T \geq 1.5$ GeV$/c$ ($p_T \geq 2.0$ GeV$/c$) are extrapolated into the CMU (CMX) muon chambers and compared with the positions of muon tracks. If there are two or more XFT tracks with matches to muon tracks, the event passes the level-1 trigger. Dimuon triggers have no requirements at level 2. At level 3, the full tracking information from the COT is used to reconstruct a pair of opposite-sign muon candidates in the mass range from 2.7 to 4.0 GeV$/c^2$. Events passing the level-3 trigger are recorded for further analysis.

The offline analysis makes use of the best available calibrations of the tracking system for reconstructing events. Well-reconstructed tracks are selected by accepting only those with ≥ 3 axial SVX II hits and >20 axial and >16 stereo COT hits. Tracks are refit to take into account the ionization energy loss appropriate for the particle hypotheses under consideration [11]. Dimuon candidates are selected in the mass range from 2.8 to 3.2 GeV$/c^2$ after being constrained to originate from a common point in a three-dimensional vertex fit. The resulting signal-to-background ratio for J/ψ candidates is about 5 to 1 [12]. Pairs of charged tracks, both having $p_T \geq 0.35$ GeV$/c$ and assumed to be pions, are then fit with the dimuon candidates to a common vertex. In this three-dimensional vertex fit, the dimuon mass is constrained to be the world average J/ψ mass [13]. We require that the χ^2 for the $J/\psi\pi\pi$ vertex fit must be less than 40 for 6 degrees of freedom.

The number of $J/\psi\pi\pi$ candidates per event passing the above preselection requirements can be quite large for events with a high multiplicity of charged tracks. These events contribute a large amount of combinatorial background relative to a small potential signal. We reject events that have more than 12 preselection candidates with masses below 4.5 GeV$/c^2$. A large number of candidates are accepted at this stage. However, after the final selection the average number of $J/\psi\pi^+\pi^-$ candidates within the mass window of 3.65–4.0 GeV$/c^2$ is less than 1.2 per event for events with at least one accepted candidate. The specific number of preselection candidates allowed per event is determined by the optimization procedure described below.

In order to suppress $J/\psi\pi^+\pi^-$ backgrounds, we tighten the selection criteria to $\chi^2 < 15$ for the 1 degree of freedom dimuon vertex fit, dimuon invariant mass within 60 MeV$/c^2$ ($\sim$4 standard deviations) of the world average J/ψ mass, $p_T(J/\psi) \geq 4$ GeV$/c$, $\chi^2 < 25$ for the $J/\psi\pi\pi$ vertex fit, $p_T(\pi) \geq 0.4$ GeV$/c$, and $\Delta R \leq 0.7$ for both pions. Here ΔR is defined as $\sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$, where $\Delta\phi$ is the difference in azimuthal angle between the pion and the $J/\psi\pi\pi$ candidate and $\Delta\eta$ is the difference in pseudorapidity.

The values used in the above selection criteria are determined by an iterative optimization procedure in which the significance $S/\sqrt{S+B}$ is maximized. The quantities S and B respectively represent the numbers of signal and background candidates obtained as a function of the values of the selection parameters. B is available from background fits of the data in a window around 3872 MeV$/c^2$. We use $\psi(2S) \to J/\psi\pi^+\pi^-$ decays to model the $X(3872)$ yield S as the selection is varied. The $\psi(2S)$ signal is much larger than that of the $X(3872)$ and must therefore be scaled down for the significance calculation. The scale factor is determined such that S matches the observed X yield from a reference selection. Because the $X(3872)$ signal is considerably smaller than the background, the denominator of the significance ratio is dominated by B, and the optimization is not sensitive to the precise value of the scaling.

The $J/\psi\pi^+\pi^-$ mass distribution of the selected candidates is displayed in Fig. 1. Besides the large peak showing the $\psi(2S)$, a small peak is observed at a $J/\psi\pi^+\pi^-$ mass around 3872 MeV$/c^2$. To fit the mass distribution, we model each peak by a single Gaussian and use a quadratic polynomial to describe the background. A binned maximum likelihood fit of the mass spectrum between 3.65 and 4.0 GeV$/c^2$ is also shown in Fig. 1. The fit yields signals of 5790 ± 140 $\psi(2S)$ candidates and 580 ± 100 $X(3872)$ candidates.

The "wrong-sign" $J/\psi\pi^\pm\pi^\pm$ mass distribution is also shown in Fig. 1, and no significant structures are apparent. We examine the hypothesis that the 3872 peak may originate from another state by incorrect assignment of the pion mass. The masses of $J/\psi\pi^+\pi^-$ candidates in a window around the 3872 peak are recomputed for the

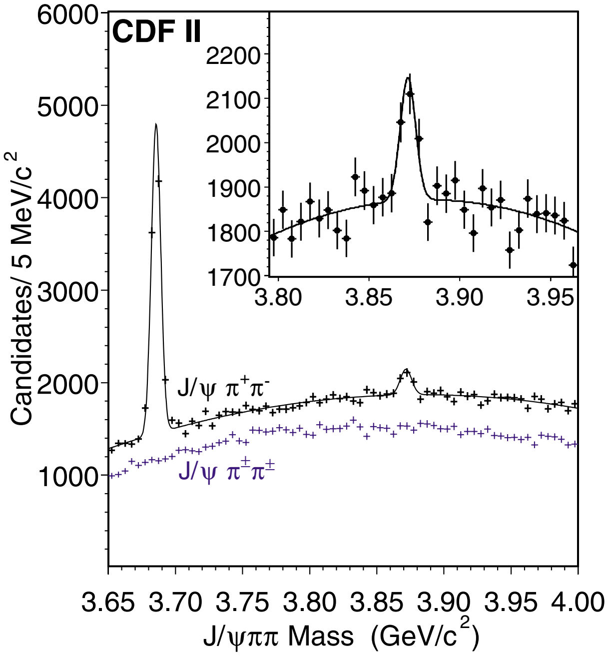

FIG. 1 (color online). The mass distributions of $J/\psi\pi^+\pi^-$ and $J/\psi\pi^\pm\pi^\pm$ candidates passing the selection described in the text. A large peak for the $\psi(2S)$ is seen in the $J/\psi\pi^+\pi^-$ distribution as well as a small signal near a mass of 3872 MeV$/c^2$. The curve is a fit using two Gaussians and a quadratic background to describe the data. The inset shows an enlargement of the $J/\psi\pi^+\pi^-$ data and fit around 3872 MeV$/c^2$.

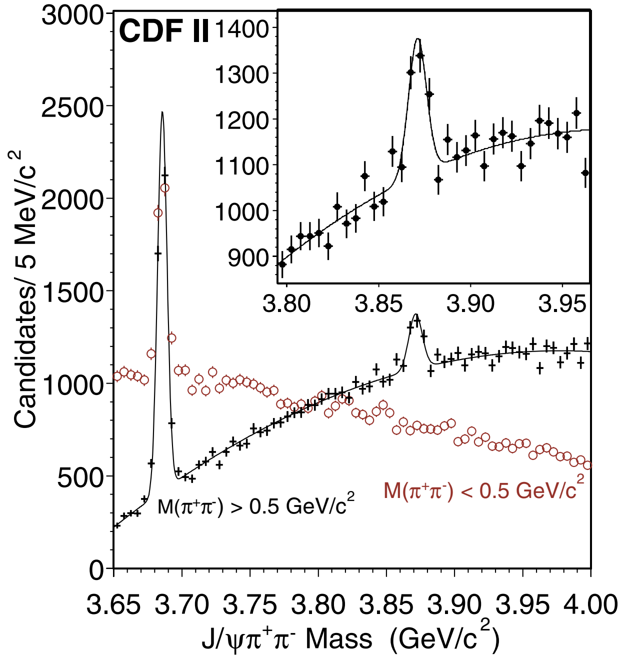

FIG. 2 (color online). The mass distributions of $J/\psi\pi^+\pi^-$ candidates with $m(\pi^+\pi^-) > 0.5$ GeV$/c^2$ (points) and $m(\pi^+\pi^-) < 0.5$ GeV$/c^2$ (open circles). The curve is a fit with two Gaussians and a quadratic background. The inset shows an enlargement of the high dipion-mass data and fit.

alternate hypotheses $J/\psi h_1^+ h_2^-$, where $h_1^+ h_2^-$ are π^+K^-, K^+K^-, $p\pi^-$, pK^-, and $p\bar{p}$ (and charge conjugates). This results in broad mass distributions with no peaklike structures. Thus, the 3872 peak is not an artifact of some other state, known or unknown, decaying into a J/ψ and a pair of hadrons in which one or both hadrons are misassigned as pions.

The $X(3872)$ signal reported by the Belle Collaboration favors large $\pi^+\pi^-$ masses. Our data support this conclusion as well. We divide the data into two subsamples: candidates with dipion masses greater, or less, than 0.5 GeV$/c^2$. From the Belle results, this is a large enough value to probe the high-mass behavior of the $X(3872)$ candidates and yet not eliminate all the $\psi(2S)$ reference signal from the high-mass subsample. Figure 2 shows the resulting $J/\psi\pi^+\pi^-$ mass distributions. The prominence of the $X(3872)$ peak is enhanced over the background in the high-mass sample, and no peak is apparent for low masses. Fitting the high-mass spectrum between 3.65 and 4.0 GeV$/c^2$ gives 3530 ± 100 $\psi(2S)$ candidates and 730 ± 90 $X(3872)$ candidates. The fitted mass and width of the $\psi(2S)$ are 3685.65 ± 0.09(stat) MeV$/c^2$ and 3.44 ± 0.09(stat) MeV$/c^2$, respectively. For $X(3872)$ we obtain a mass of 3871.3 ± 0.7(stat) MeV$/c^2$ and a width of 4.9 ± 0.7 MeV$/c^2$. The latter value is consistent with detector resolution. Our mass is in good agreement with the Belle result of 3872.0 ± 0.6(stat) ± 0.5(syst) MeV$/c^2$ [2].

Requiring $M(\pi^+\pi^-) > 0.5$ MeV$/c^2$ reduces the background by almost a factor of 2 and apparently increases the amount of fitted $X(3872)$ signal. A significant part of the additional signal is attributable to an increase in the fitted width. The original fit over all dipion masses returns a smaller but consistent width of 4.2 ± 0.8 MeV$/c^2$. We conclude that the $X(3872)$ signal yield after the dipion requirement is unchanged within statistics, and thus there is little signal with dipion masses below 0.5 GeV$/c^2$. The same conclusion is reached by direct examination of the low dipion-mass distribution shown in Fig. 2. We use the high-mass sample for measuring the $X(3872)$ mass as the improved signal-to-noise ratio reduces the statistical uncertainty.

The fit displayed in Fig. 2 has a χ^2 of 74.9 for 61 degrees of freedom, which corresponds to a probability of 10.9%. To estimate the significance of the signal, we first count the number of candidates in the three bins centered on the peak, i.e., 3893. The three-bin background is estimated from the fit to be 3234 candidates, leaving a signal of 659 candidates. In a Gaussian approach, this corresponds to a significance of $659/\sqrt{3234} = 11.6$ standard deviations. The Poisson probability for 3234 to fluctuate up to or above 3893 is in good agreement with the Gaussian estimate, considering the approximations of each method.

The systematic uncertainty on the mass scale is related to the momentum scale calibration, the various tracking systematics, and the vertex fitting. These effects

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were studied in detail for our measurement of the mass difference $m(D_s^+) - m(D^+)$ [11], where the systematic uncertainty was ± 0.21 MeV$/c^2$. A larger systematic uncertainty arises for our $X(3872)$ mass determination because it is an absolute measurement. We use the $\psi(2S)$ mass to gauge our systematic uncertainty. With the dipion mass requirement, the $\psi(2S)$ mass is measured to be 0.3 MeV$/c^2$ below the world average mass of 3685.96 ± 0.09 [13], a difference substantially larger than the statistical uncertainty of 0.1 MeV$/c^2$. However, studies of the stability of the $\psi(2S)$ mass for different selection requirements indicate that an uncertainty of 0.4 MeV$/c^2$ should be assigned. Variations of the fit model and fit range have negligible effect on the mass.

In summary, we report the observation of a state consistent with $X(3872)$ decaying into $J/\psi\pi^+\pi^-$. From a sample of 730 ± 90 candidates we measure the $X(3872)$ mass to be $3871.3 \pm 0.7(\text{stat}) \pm 0.4(\text{syst})$ MeV$/c^2$ and find that the observed width is consistent with the detector resolution. This is in agreement with the measurement by the Belle Collaboration using $B^{\pm}$ decays [2]. The average mass from the two experiments, assuming uncorrelated systematic uncertainties, is 3871.7 ± 0.6 MeV$/c^2$. Our large sample of this new particle opens up avenues for future investigations, such as production mechanisms, the dipion mass distribution, and spin-parity analysis.

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