Observation of a threshold enhancement in the $p\overline{p}$ mass spectrum from $J/\psi \to \gamma p\overline{p}$

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Abstract

We report the observation of a narrow enhancement near $2m_p$ in the mass spectrum of $p\overline{p}$ pairs from radiative $J/\psi \to \gamma p\overline{p}$ decays. The results are based on an analysis of a 58 million event sample of J/ψ decays accumulated with the BES detector at the Beijing electron-positron collider. If interpreted as a resonance, the mass and width of the observed enhancement are $M = 1897 \pm 2$ (stat)MeV/c^2 and $\Gamma = 54 \pm 7$ (stat) MeV/c^2, which are inconsistent with any known particle.

There is an accumulation of evidence for anomalous behavior in the proton-antiproton system very near the $M_{p\overline{p}} = 2m_p$ mass threshold. The observed cross section for $e^+e^- \to$ *hadrons* has a narrow dip-like structure at a center of mass (cm) energy of $\sqrt{s} \simeq 2m_pc^2$ [1]. In addition, the proton's time-like magnetic form-factor, determined from high statistics measurements of the $p\overline{p} \to e^+e^-$ annihilation process, exhibits a very steep fall-off just above the $p\overline{p}$ mass threshold [2]. These data are suggestive of a narrow, S-wave triplet $p\overline{p}$ resonance with $J^{PC} = 1^{--}$ and mass near $M_{p\overline{p}} \simeq 2m_p$, which may be related to a narrow dip structure that is observed just above $2m_p$ in diffractive photoproduction of $3\pi^+3\pi^-$ final states [3]. There is no known vector meson resonance that could be associated with such a state. The proximity in mass to $2m_p$ is suggestive of a nucleon-antinucleon bound state, an idea first proposed by Fermi and Yang in 1949 [4]. On the other hand, some authors have proposed that the steep fall-off of the proton's time-like formfactor is a dynamical effect and not due to a nearby resonance [5]. An investigation of the S-wave singlet $p\overline{p}$ system (*i.e.* with $J^{PC} = 0^{-+}$) may help clarify the situation.

The radiative decay process $J/\psi \to \gamma p\overline{p}$ is well suited for studies of the 0^{-+} $p\overline{p}$ system. Charge-parity conservation insures that the $p\overline{p}$ pairs have $C = +1$ and, for invariant masses near $M_{p\overline{p}} = 2m_p$, the p and $\overline{p}$ are expected to be in a relative S-wave. In this letter we report a study of the low mass $p\overline{p}$ pairs produced via radiative decays in a sample of 58 million J/ψ events accumulated in the Beijing Spectrometer (BES) located at the Beijing Electron-Positron Collider (BEPC) at the Beijing Institute of High Energy Physics.

BES is a large solid-angle magnetic spectrometer that is described in detail in ref. [6]. Charged particle momenta are determined with a resolution of $\sigma_p/p = 1.7\%\sqrt{1 + p^2(\text{GeV}^2)}$ in a 40-layer cylindrical drift chamber. Particle identification is accomplished by specific ionization (dE/dx) measurements in the drift chamber and time-of-flight (TOF) measurements in a barrel-like array of 48 scintillation counters. The dE/dx resolution is $\sigma_{dE/dx} = 8.4\%$;

the TOF resolution is $\sigma_{TOF} = 160$ ps; both systems independently provide more than 3σ separation of protons from any other charged particle species for the entire momentum range considered in this experiment. Radially outside of the time-of-flight counters is a 12-radiation-length barrel shower counter (BSC) comprised of gas proportional tubes interleaved with lead sheets. The BSC measures the energies and directions of photons with resolutions of $\sigma_E/E \simeq 22\%/\sqrt{E(\mathrm{GeV})}$, $\sigma_\phi = 4.5$ mrad, and $\sigma_\theta = 12$ mrad. The iron flux return of the magnet is instrumented with three double layers of counters that are used to identify muons.

For this analysis we use charged tracks with momentum greater than 80 MeV/c that are well fit to a helix originating near the interaction point. Candidate γ's are associated with energy clusters in the BSC that have less than 80% of their total energy in any one readout layer and do not match the extrapolated position of any charged track. Since antiprotons that stop in the material of the TOF or BSC can produce annihilation products that are reconstructed elsewhere in the detector as γ rays, no restrictions are placed on the total number of neutral clusters in the event. We use charged tracks and γ's that are within the polar angle region $|\cos\theta| < 0.8$. We reject events where both tracks are identified as muons, or produce high energy showers in the BSC that are characteristic of electrons. The dE/dx and TOF information for each track are combined to form a proton identification confidence level, $\mathcal{P}_{pid}$. We require that both tracks in the event have $\mathcal{P}_{pid} > 0.02$. Measurements with a sample of tagged protons and antiprotons from kinematically selected $J/\psi \to \Xi^-\Xi^+$ events, where $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$ (plus the charge conjugate decay chain), indicate that the confidence-level distributions are flat. A study based on a kinematically selected sample of $J/\psi \to K^{*\pm}K^{\mp} \to K^+K^-\pi^0$ events indicate that charged kaons survive this selection with a probability that is less than 1% per track.

We subject the surviving events to four-constraint kinematic fits to the hypotheses $J/\psi \to \gamma p\overline{p}$ and $J/\psi \to \gamma K^+K^-$. For events with more that one γ, we select the γ that has the highest fit confidence level. For multi-γ events, we also make five-constraint fits to the hypothesis $J/\psi \to \pi^0 p\overline{p}$, $\pi^0 \to \gamma\gamma$, for every combination of two γ rays. We select events that have fit confidence level $CL_{\gamma p\overline{p}} > 0.05$.

Figure 1 shows the $p\overline{p}$ invariant mass distribution for surviving events. The distribution has a very distinct peak at near $M_{p\overline{p}} = 2.9$ GeV/c^2 that is consistent in mass, width, and yield with expectations for $J/\psi \to \gamma\eta_C$, $\eta_C \to p\overline{p}$, and a narrow low-mass peak at the $p\overline{p}$ mass threshold that is the subject of this analysis.

FIGURES

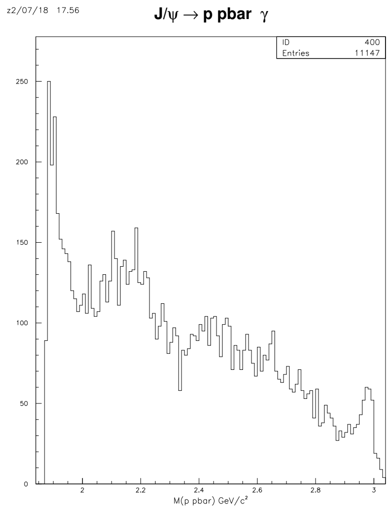

FIG. 1. The $p\overline{p}$ invariant mass distribution for the $J/\psi \to \gamma p\overline{p}$-enriched event sample.

Backgrounds from processes involving charged particles that are not protons and antiprotons are negligibly small. In addition to being well separated from other charged particles by the dE/dx and TOF systems, the protons and antiprotons from the low $M_{p\overline{p}}$ region stop in the TOF counters and, thus, have very characteristic BSC responses: the protons do not produce any matching signals in the BSC while annihilation products from antiproton annihilation can produce large signals. This BSC response is quite distinct from that of K^+K^-, $\pi^+\pi^-$ or e^+e^- pairs, where the positive and negative tracks produce similar, non-zero BSC responses, and is verified with tagged protons and antiprotons from the $J/\psi \to \Xi^-\Xi^+$ sample. The observed BSC energy distributions for the selected $J/\psi \to \gamma p\overline{p}$ events with $M_{p\overline{p}} \leq 1.9$ GeV/c^2 closely match expectations for protons and antiprotons and show no evidence for contamination from other particle species.

There is, however, a large background from $J/\psi \to \pi^0 p\overline{p}$ events, where one of the photons from the $\pi^0 \to \gamma\gamma$ decay is missed. This is studied using a sample of reconstructed $J/\psi \to \pi^0 p\overline{p}$ events that are selected with the same criteria as above except for $CL_{\pi^0 p\overline{p}} > 0.05$, $CL_{\pi^0 p\overline{p}} > CL_{\gamma p\overline{p}}$, and $CL_{\pi^0 p\overline{p}} > CL_{\pi^0 K^+K^-}$. The near-threshold $M_{p\overline{p}}$ distribution for these events, shown in Fig. 2, is well fit by a function of the form $f(\delta) = N(\delta^{1/2} + a_1\delta^{3/2} + a_2\delta^{5/2})$, where $\delta = M_{p\overline{p}} - 2m_p$; the fitted function is shown in the figure as a smooth curve. Monte Carlo simulations of other J/ψ decay processes with final-state $p\overline{p}$ indicate that background contributions from processes other than $J/\psi \to \pi^0 p\overline{p}$ are negligibly small.

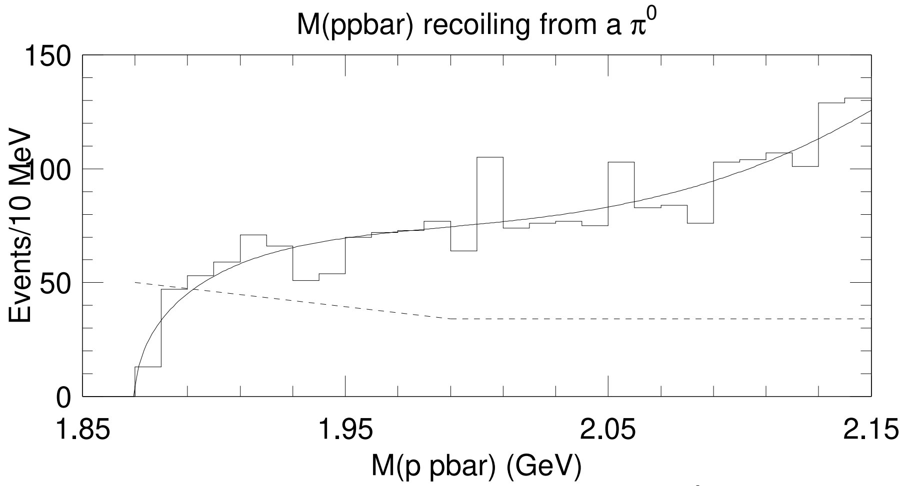

FIG. 2. The $p\overline{p}$ invariant mass distribution for selected $J/\psi \to \pi^0 p\overline{p}$ decays. The smooth curve is the result of the fit described in the text and the dashed curves indicate the mass dependence of the experimental acceptance.

In BES, the detection efficiency for protons and antiprotons falls sharply for three-momenta below 0.4 GeV/c. This produces a mass dependence in the experimental acceptance near $M_{p\overline{p}} \simeq 2m_p$ for $J/\psi \to \gamma p\overline{p}$ and $\pi^0 p\overline{p}$. For both processes, when $M_{p\overline{p}}$ is very near $2m_p$, the p and $\overline{p}$ both have three-momenta very near 0.5 GeV/c and are well detected. For increasing $p\overline{p}$ masses, more asymmetric energy sharing is possible and the acceptance decreases until $M_{p\overline{p}} \simeq 2.0$ GeV/c^2, where it is $\simeq 0.67$ of its value at $M_{p\overline{p}} = 2m_p$. Although this acceptance variation, shown as the dashed line in Fig. 2, enhances the near-threshold mass distributions, it is evident that it does not produces a low-mass peak in the $J/\psi \to \pi^0 p\overline{p}$ background (Fig. 2).

Figure 3 shows the low-mass region of the $M_{p\overline{p}}$ distribution from the signal-enriched $J/\psi \to \gamma p\overline{p}$ events together with the results of a fit using a background with the functional form of $f(\delta)$ used to fit the $\pi^0 p\overline{p}$ data of Fig. 2, with shape parameters a_1 and a_2 fixed at the values determined from that fit, plus an acceptance-weighted, S-wave Breit-Wigner (BW) function with mass and width that are allowed to vary. he fitting functions are convolved with a Gaussian resolution function with $\sigma = 3$ MeV, its Monte-Carlo determined value. This fit yields a total of 1061 ± 70 events in the BW function with a mass $M = 1897 \pm 2$ MeV/c^2 and a full width $\Gamma = 54 \pm 7$ MeV. For this fit, $\chi^2/d.o.f. = 29.2/26$.

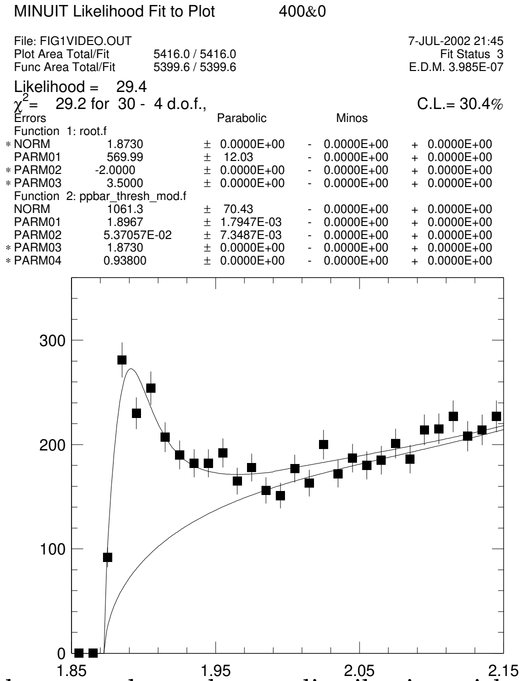

FIG. 3. Results of fit to the $\gamma p\overline{p}$-enhanced mass distribution with an S-wave BW function with mass and width free to vary plus a background (dotted curve) with shape determined from the $\pi^0 p\overline{p}$ data sample.

We tried to fit the data using known particle resonances to represent the low-mass peak. Since the peak is very close to threshold, we restrict ourselves to the case where the p and $\overline{p}$ are in an S-wave, which implies a $J^{PC} = 0^{-+}$ pseudoscalar state. There are two pseudoscalar resonances listed in the PDG tables in this mass region [7]: the $\eta(1760)$ with $M_{\eta(1760)} = 1760 \pm 11$ MeV$/c^2$ and $\Gamma_{\eta(1760)} = 60 \pm 16$ MeV, and the $\pi(1800)$ with $M_{\pi(1800)} = 1801 \pm 13$ MeV$/c^2$ and $\Gamma_{\pi(1800)} = 210 \pm 15$ MeV. Figure 4 shows the result of a fit with f_{bkg} with shape parameters fixed from the $\pi^0 p\overline{p}$ fit and an acceptance-weighted S-wave BW function with mass and width fixed at the PDG values for the $\eta(1760)$. This fit has a $\chi^2/d.o.f. = 138.5/28$; a fit with the $\pi(1800)$ parameters gives a similarly poor fit. These poor fits indicate conclusively that the observed structure cannot be explained by any known meson state.

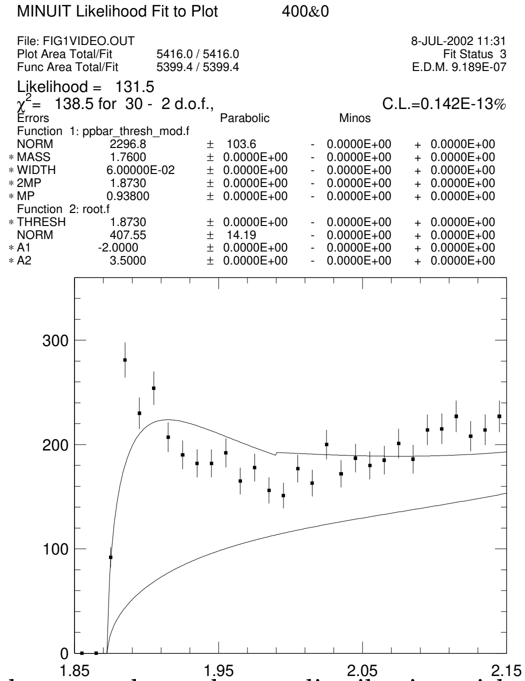

FIG. 4. Results of fit to the $\gamma p\overline{p}$-enhanced mass distribution with an S-wave BW function with mass and width fixed at the parameters of the $\eta(1760)$ plus a background (dotted curve) with shape determined from the $\pi^0 p\overline{p}$ data sample.

We verified that the observed low-mass signal originates from J/ψ decays and does not come from a radiative-return process $e^+e^- \rightarrow \gamma p\overline{p}$, where the γ is due to initial-state radiation, by searching for a similar signal in a sample of 3.8 million $\psi(2S)$ decays, also accumulated in the BES detector. If the observed peak is associated with J/ψ decays, we expect $n_{\psi(2S)}$, the number of events in the $\psi(2S)$ sample, to be of order $n_{\psi(2S)} \simeq 0.01 n_{J/\psi} \sim$ 1 event, where $n_{J/\psi}$ is the number of events in the low-mass peak in the J/ψ data [8]. In contrast, if the observed peak is due to radiative return, we expect $n_{\psi(2S)} \simeq 0.20 n_{J/\psi} \sim$ 15 events [9]. An application of the selection criteria to the $\psi(2S)$ event sample results in only one surviving event with $M_{p\overline{p}} < 1.9$ GeV; this strongly rules out the radiative-return hypothesis.

In summary, we report the observation of a narrow structure near $M_{p\overline{p}} \simeq 2m_p$ in the $p\overline{p}$ mass distribution for the radiative decay proceess $J/\psi \rightarrow \gamma p\overline{p}$. This structure can not be explained as being due to any known meson resonance; the possibility that the observed events are due to a radiative return process is ruled out with high reliability. If the observed structure is considered to be a resonance, we determine the parameters $M = 1897 \pm 2(\mathrm{stat})$ MeV$/c^2$ and $\Gamma = 54 \pm 7(\mathrm{stat})$ MeV$/c^2$.

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[5] See, for example, M. Karliner, hep-ph/0112047.
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[8] If the signal is from J/ψ decays, the expected event yield in the $\psi(2S)$ data sample is

$$n_{\psi(2S)} \sim n_{J/\psi} \times \frac{N_{\psi(2S)}}{N_{J/\psi}} \times 0.14 \simeq \ 0.01 \times n_{J/\psi},$$

where $N_{J/\psi}$ and $N_{\psi(2S)}$ are the total number of J/ψ and $\psi(2S)$ events, and the factor of 0.14 takes into account the charmonium cascade decay channels of the $\psi(2S)$ that are not accessible the the J/ψ, as first proposed by T. Applequist and D. Politzer, Phys. Rev. Lett. **34**, 43 (1975).
[9] If the signal is due to radiative return, an application of the formalism of G. Bonneau and F. Martin, Nucl. Phys. **B27**, 381 (1971) gives an expected event yield in the $\psi(2S)$ data sample of

$$n_{\psi(2S)} = n_{J/\psi} \times \frac{\mathcal{L}(\psi(2S))}{\mathcal{L}(J/\psi)} \frac{f(k_{\psi(2S)})}{f(k_{J/\psi})} \frac{M^2_{J/\psi}}{M^2_{\psi(2S)}} = 0.20 \times n_{J/\psi},$$

where $\mathcal{L}(J/\psi)$ and $\mathcal{L}(\psi(2S))$ are the luminosities (17.7 and 6.0 pb^{-1} for the J/ψ and $\psi(2S)$, respectively) and $f(k)$ is a function that describes the effective luminosity as a function of $k = 1 - 4m_p^2/s$, the fractional cm energy of the initial-state-radiation photon.