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

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(Received March 27, 2003)

We observe a narrow enhancement near $2m_p$ in the invariant mass spectrum of $p\overline{p}$ pairs from radiative $J/\psi \to \gamma p\overline{p}$ decays. No similar structure is seen in $J/\psi \to \pi^0 p\overline{p}$ decays. The results are based on an analysis of a 58 million event sample of J/ψ decays accumulated with the BESII detector at the Beijing electron-positron collider. The enhancement can be fit with either an S- or P-wave Breit Wigner resonance function; in the case of the S-wave fit, the peak mass is below $2m_p$ at $M = 1859^{+3}_{-10}$ (stat)$^{+5}_{-25}$ (sys) MeV/c^2 and the total width is $\Gamma < 30$ MeV/c^2 at the 90 percent confidence level. These mass and width values are not consistent with the properties of any known particle.

§1. Introduction

There is an accumulation of evidence for anomalous behavior in the proton-antiproton ($p\overline{p}$) system very near the $M_{p\overline{p}} = 2m_p$ mass threshold. The observed cross section [1] for $e^+e^- \to hadrons$ has a narrow dip-like structure at a center of mass energy of $\sqrt{s} \simeq 2m_pc^2$. 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 $2m_p$. In studies of $\overline{p}$ annihilations at rest in deuterium, anomalies in the charged pion momentum spectrum from $\overline{p}d \to \pi^-\pi^0 p$ and $\pi^+\pi^- n$ reactions [3] and the spectator proton spectrum from the $\overline{p}d \to 2\pi^+3\pi^- p_s$ process [4] have been interpreted as effects of narrow, below-threshold resonances. There are no well established mesons that could be associated with such states. Belle [5,6] has reported observations of the decays $B^+ \to K^+p\overline{p}$ and $\overline{B}^0 \to D^0 p\overline{p}$. In both processes there are enhancements in the $p\overline{p}$ invariant mass distributions near $M_{p\overline{p}} \simeq 2m_p$.

The proximity in mass to $2m_p$ is suggestive of nucleon-antinucleon ($N\overline{N}$) bound states, an idea that has a long history. In 1949, Fermi and Yang [7] proposed that the pion was a tightly bound $N\overline{N}$ state. Although this turned out not to be correct, the train of thought started by this paper had enormous consequences. In 1956, after the discovery of the strange particles Λ and K^0, Sakata [8] expanded this picture and used "fundamental baryon triplets" comprised of (p, n, Λ) and their antiparticles $(\bar{p}, \bar{n}, \bar{\Lambda})$ to make both pions and kaons. It was subsequently realized that the underlying mathematics of this model was that of the $SU(3)$ unitary group [9], a realization that inevitably led to the quark model. In 1961, Nambu and Jona-Lasinio [10] introduced a dynamical theory based on chiral invariance that also considers mesons as baryon-antibaryon composites. In this model, in addition to a low-mass pion, there is a scalar $p\overline{p}$ composite state with mass equal to $2m_p$. Here again, these ideas have been superseded by the quark model [11], and the scalar composite state is the famous σ meson that is a main subject of discussion at this meeting.

Although in both examples cited above the original motivation for nucleon-antinucleon composites is gone, the possibility of bound $N\overline{N}$ states with mass near $2m_p$, generally referred to as *baryonium*, continues to be considered [12]. An investigation of low mass $p\overline{p}$ systems with different quantum numbers may help clarify the situation.

In this talk I report on 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 upgraded Beijing Spectrometer (BESII) located at the Beijing Electron-Positron Collider (BEPC) at the Beijing Institute of High Energy Physics. In this reaction, the $p\overline{p}$ pair is produced in an environment that is not made complicated by the presence of other hadrons. Moreover, charge-parity conservation insures that the $p\overline{p}$ system has $C = +1$.

§2. Experimental considerations

BESII is a large-solid-angle magnetic spectrometer that is described in detail elsewhere [13]. For this analysis we use events with a high energy gamma ray and two oppositely charged tracks that are identified as protons by their specific ionization (dE/dx) in the tracking chamber. Since antiprotons that stop in the material of the detection systems can produce annihilation products that are reconstructed elsewhere as γ rays, no restrictions are placed on the total number of photons in the event.

We subject the selected event candidtes 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. We select events that have fit confidence level $CL_{\gamma p\overline{p}} > 0.05$ and reject events that have $CL_{\gamma K^+K^-} > CL_{\gamma p\overline{p}}$.

Figure 1 shows the $p\overline{p}$ invariant mass distribution for surviving events. The distribution has a peak near $M_{p\overline{p}} = 2.98$ GeV$/c^2$ that is consistent in mass, width, and yield with expectations for $J/\psi \to \gamma\eta_c$, $\eta_c \to p\overline{p}$ [14], a broad enhancement around $M_{p\overline{p}} \sim 2.2$ GeV$/c^2$, and a narrow, low-mass peak at the $p\overline{p}$ mass threshold that is the main subject of this talk [15].

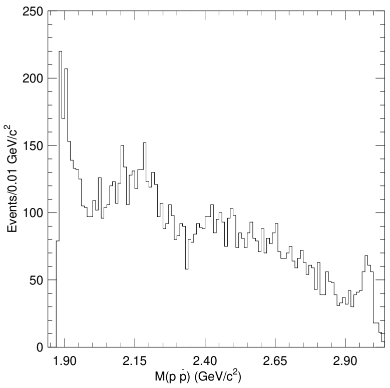

Fig. 1. The $p\overline{p}$ invariant mass distribution for the $J/\psi \to \gamma p\overline{p}$-enriched event sample

2.1. *Backgrounds*

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 measurements and the kinematic fit, the protons and antiprotons from the low $M_{p\overline{p}}$ region tend to stop in the material in front of the electromagnetic shower detector, where thet have very characteristic responses: protons do not produce any signals in the shower detector while secondary particles from antiproton annihilation usually produce large signals. This asymmetric behavior is quite distinct from that for K^+K^-, $\pi^+\pi^-$ or e^+e^- pairs, where the positive and negative tracks produce similar, non-zero responses. The observed shower counter energy distributions for the low-mass $J/\psi \to \gamma p\overline{p}$ events 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 with an asymmetric $\pi^0 \to \gamma\gamma$ decay where one of the photons has most of the π^0's energy. This is studied using a sample of $J/\psi \to \pi^0 p\overline{p}$ decays reconstructed from the same data sample. For these, we select events with oppositely charged tracks that are identified as protons and with two or more photons, apply a four-constraint kinematic fit to the hypothesis $J/\psi \to \gamma\gamma p\overline{p}$, and require $CL_{\gamma\gamma p\overline{p}} > 0.005$. For events with more than two γ's, we select the γ pair that produces the best fit. In the $M_{\gamma\gamma}$ distribution of the selected events there is a very distinct π^0 signal; we require $|M_{\gamma\gamma} - M_{\pi^0}| < 0.03$ GeV/c^2 ($\pm 2\sigma$). The distribution of events *vs.* $M_{p\overline{p}} - 2m_p$ near the $M_{p\overline{p}} = 2m_p$ threshold, shown in Fig. 2(a), is reasonably well described by a function of the form $f_{\rm bkg}(\delta) = N(\delta^{1/2} + a_1\delta^{3/2} + a_2\delta^{5/2})$, where $\delta \equiv M_{p\overline{p}} - 2m_p$ and the shape parameters a_1 and a_2 are determined from a fit to simulated MC events that were generated uniformly in phase space. This is shown in the figure as a smooth curve. There is no indication of a narrow peak at low $p\overline{p}$ invariant masses. Monte Carlo simulations of other J/ψ decay processes with final-state $p\overline{p}$ pairs indicate that backgrounds from processes other than $J/\psi \to \pi^0 p\overline{p}$ are negligibly small.

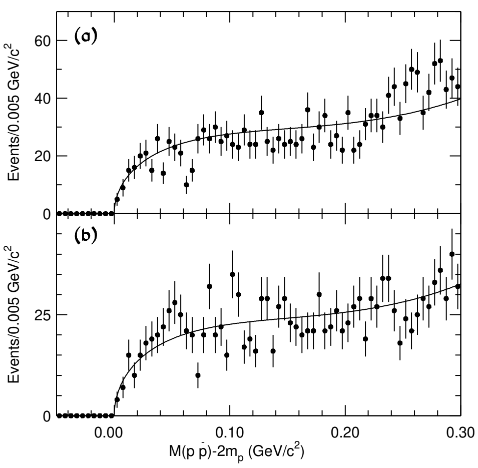

Fig. 2. The $M_{p\overline{p}} - 2m_p$ distribution for **(a)** selected $J/\psi \to \pi^0 p\overline{p}$ decays and **(b)** MC $J/\psi \to \pi^0 p\overline{p}$ events that satisfy the $\gamma p\overline{p}$ selection criteria. The smooth curves are the result of fits described in the text.

The $M_{p\overline{p}} - 2m_p$ distribution for the $\pi^0 p\overline{p}$ phase-space MC events that pass the $\gamma p\overline{p}$ selection is shown in Fig. 2(b). There is no clustering at threshold; the smooth curve is the result of a fit to $f_{\rm bkg}(\delta)$ with the same shape parameter values.

§3. Results

Figure 3(a) shows the near-threshold $M_{p\overline{p}} - 2m_p$ distribution for the selected $J/\psi \to \gamma p\overline{p}$ events. The solid curve shows the result of a fit using an acceptance-weighted S-wave Breit-Wigner (BW) function [16] to represent the low-mass enhancement plus $f_{\rm bkg}(\delta)$ to represent the background. The mass and width of the BW signal function are allowed to vary and the shape parameters of $f_{bkg}(\delta)$ are fixed at the values derived from the fit to the $\pi^0 p\overline{p}$ phase-space MC sample [17]. This fit yields 928 ± 57 events in the BW function with a peak mass of $M = 1859^{+3}_{-10}$ MeV/c^2 and a full width of $\Gamma = 0 \pm 21$ MeV/c^2. Here the errors are statistical only. The fit confidence level is 46.2% ($\chi^2/d.o.f. = 56.3/56$).

Further evidence that the peak mass is below the $2m_p$ threshold is provided in Fig. 3(b), which shows the $M_{p\overline{p}}-2m_p$ distribution when the kinematic threshold behavior is removed by weighting each event by q_0/q, where q is the proton momentum in the $p\overline{p}$ restframe and q_0 is the value for $M_{p\overline{p}} = 2$ GeV/c^2. The sharp and monotonic increase at threshold that is observed in this weighted histogram can only occur for an S-wave BW function when the peak mass is below $2m_p$.

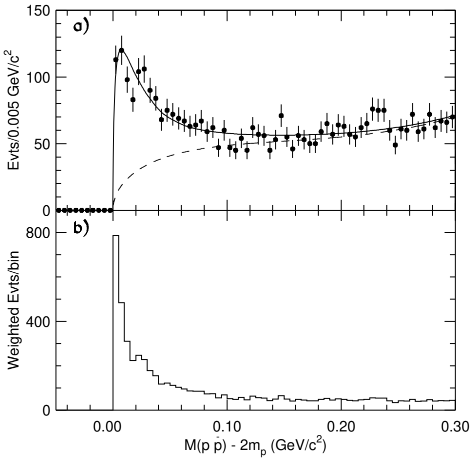

Fig. 3. (a) The near-threshold $M_{p\overline{p}}-2m_p$ distribution for the $\gamma p\overline{p}$ event sample. The solid curve curve is the result of the fit descibed in the text; the dashed curve shows the fitted background function. (b) The $M_{p\overline{p}} - 2m_p$ distribution with events weighted by q_0/q.

An S-wave $p\overline{p}$ system with even C-parity would correspond to a 0^{-+} pseudoscalar state. We also tried to fit the signal with a P-wave BW function, which would correspond to a 0^{++} (^3_0P) scalar state that occurs in some models [10),12)]. This fit yields a peak mass $M = 1876.4 \pm 0.9$ MeVc^2, which is very nearly equal to $2m_p$, and a very narrow total width: $\Gamma = 4.6 \pm 1.8$ MeVc^2 (statistical errors only). The fit quality, $\chi^2/d.o.f. = 59.0/56$, is worse than that for the S-wave BW but still acceptable. A fit with a D-wave BW fails badly with $\chi^2/d.o.f. = 1405/56$.

3.1. *Can this be the effect of any known resonance?*

In addition we tried fits that use known particle resonances to represent the low-mass peak. There are two spin-zero resonances listed in the PDG tables in this mass region [18]: 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. A fit with $f_{\rm bkg}$ and an acceptance-weighted S-wave BW function with mass and width fixed at the PDG values for the $\eta(1760)$ produces $\chi^2/d.o.f. = 323.4/58$. A fit using a BW with the $\pi(1800)$ parameters is worse.

3.2. *Production angle distribution*

For both the scalar or pseudoscalar case, the polar angle of the photon, θ_γ, would be distributed according to $1+\cos^2\theta_\gamma$. Figure 4 shows the background-subtracted, acceptance-corrected $|\cos\theta_\gamma|$ distribution for events with $M_{p\overline{p}} \leq 1.9$ GeV and $|\cos\theta_\gamma| \leq 0.8$. Here we have subtracted the $|\cos\theta_{\pi^0}|$ distribution from the $\pi^0 p\overline{p}$ data sample, normalized to the area of $f_{\rm bkg}(\delta)$ for $M_{p\overline{p}} < 1.9$ GeV$/c^2$ to account for background. The solid curve shows the result of a fit for $1+\cos^2\theta_\gamma$ to the $|\cos\theta_\gamma| < 0.8$ region; the dashed line shows the result of a similar fit to $\sin^2\theta_\gamma$. Although the data are not precise enough to establish a $1+\cos^2\theta_\gamma$ behavior, the distribution is consistent with expectations for a radiative transition to a pseudoscalar or scalar meson [19].

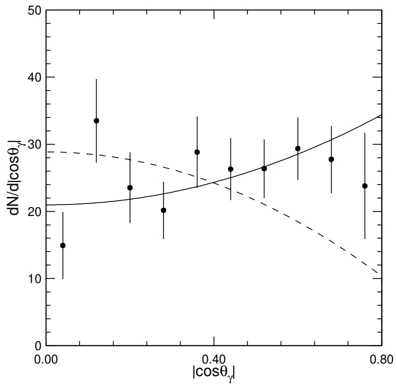

Fig. 4. The background-subtracted, acceptance-corrected $|\cos\theta_\gamma|$ distribution for $J/\psi \to \gamma p\overline{p}$-enriched events with $M_{p\overline{p}} \leq 1.9$ GeV$/c^2$. The solid curve is a fit to a $1+\cos^2\theta_\gamma$ shape for the region $|\cos\theta_\gamma| \leq 0.8$; the dashed curve is the result of a fit to $\sin^2\theta_\gamma$.

3.3. *Systematic Errors*

We evaluate systematic errors on the mass and width from changes observed in the fitted values for fits with different bin sizes, with background shape parameters left as free parameters, different shapes for the acceptance variation, and different resolutions. A study based on an ensemble of Monte Carlo experiments for sub-threshold resonances demonstrates that, in the presence of background, the farther the peak is below threshold, the less reliable is the determination of its mass. The MC studies also indicate that the mass determination of a below-threshold resonance can be biased. We include the range of differences between input and output values seen in the MC study in the systematic errors.

For the mass, we determine a systematic error of $^{+5}_{-25}$ MeVc^2. For the total width, we determine a 90% CL upper limit of $\Gamma < 30$ MeV$/c^2$, where the limit includes the systematic error.

3.4. *Branching Fraction*

Using a Monte-Carlo determined acceptance of 23%, we determine a product of branching fractions $\mathcal{B}(J/\psi \to \gamma X(1859))\mathcal{B}(X(1859) \to p\overline{p}) = (7.0 \pm 0.4({\rm stat})^{+1.9}_{-0.8}({\rm syst})) \times 10^{-5}$, where the systematic error includes uncertainties in the acceptance (10%), the total number of J/ψ decays in the data sample (5%), and the effects of changing the various inputs to the fit ($^{+24\%}_{-2\%}$).

§4. Summary

In summary, we observe a strong, near-threshold enhancement in the $p\overline{p}$ invariant mass distribution in the radiative decay process $J/\psi \to \gamma p\overline{p}$. No similar structure is seen in $J/\psi \to \pi^0 p\overline{p}$ decays. The structure has properties consistent with either a $J^{PC} = 0^{-+}$ or 0^{++} quantum number assignment and cannot be attributed to the effects of any known meson resonance. If interpreted as a single 0^{-+} resonance, its peak mass is below the $M_{p\overline{p}} = 2m_p$ threshold at $1859^{+3}_{-10}(\mathrm{stat})^{+5}_{-25}(\mathrm{syst})$ MeV/c^2 and its width is $\Gamma < 30$ MeV/c^2 at the 90% CL.

Acknowledgements

The author would like to express his sincere gratitude to Professors S. Ishida and K. Takamatsu and their colleagues for inviting me to speak at this meeting and for their gracious hospitality. I also thank Professors J. Rosner and S.F. Tuan for useful discussions. The BES collaboration thanks the staffs of BEPC and the IHEP computing center for their strong efforts.

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16) For the BW, we use the form:

$$BW(M) \propto \frac{q^{(2\ell+1)}k^3}{(M^2 - M_0^2)^2 + M_0^2\Gamma^2},$$

where M_0 and Γ are constants (determined from the fit), q is the proton momentum in the $p\overline{p}$ restframe, ℓ is the $p\overline{p}$ orbital angular momentum, and k is the photon momentum.
17) The $p\overline{p}$ invariant mass resolution varies from $\sigma \simeq 1.2$ MeV/c^2 at $M_{p\overline{p}} \simeq 2m_p$, to $\sim$ 3 MeV/c^2 at higher masses. Convolving the fitting function with a Gaussian with a width in this range has no significant effect on the results.
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