Spin-Parity Analysis of $p\bar{p}$ Mass Threshold Structure in J/ψ and $\psi(3686)$ Radiative Decays

M. Ablikim,[1] M. N. Achasov,[5] D. Alberto,[41] D. J. Ambrose,[38] F. F. An,[1] Q. An,[39] Z. H. An,[1] J. Z. Bai,[1] R. B. F. Baldini Ferroli,[17] Y. Ban,[25] J. Becker,[2] N. Berger,[1] M. B. Bertani,[17] J. M. Bian,[1] E. Boger,[18,*] O. Bondarenko,[19] I. Boyko,[18] R. A. Briere,[3] V. Bytev,[18] X. Cai,[1] A. C. Calcaterra,[17] G. F. Cao,[1] J. F. Chang,[1] G. Chelkov,[18,*] G. Chen,[1] H. S. Chen,[1] J. C. Chen,[1] M. L. Chen,[1] S. J. Chen,[23] Y. Chen,[1] Y. B. Chen,[1] H. P. Cheng,[13] Y. P. Chu,[1] D. Cronin-Hennessy,[37] H. L. Dai,[1] J. P. Dai,[1] D. Dedovich,[18] Z. Y. Deng,[1] I. Denysenko,[18,†] M. Destefanis,[41] W. L. Ding Ding,[27] Y. Ding,[21] L. Y. Dong,[1] M. Y. Dong,[1] S. X. Du,[44] J. Fang,[1] S. S. Fang,[1] C. Q. Feng,[39] C. D. Fu,[1] J. L. Fu,[23] Y. Gao,[34] C. Geng,[39] K. Goetzen,[7] W. X. Gong,[1] M. Greco,[41] M. H. Gu,[1] Y. T. Gu,[9] Y. H. Guan,[6] A. Q. Guo,[24] L. B. Guo,[22] Y. P. Guo,[24] Y. L. Han,[1] X. Q. Hao,[1] F. A. Harris,[36] K. L. He,[1] M. He,[1] Z. Y. He,[24] Y. K. Heng,[1] Z. L. Hou,[1] H. M. Hu,[1] J. F. Hu,[6] T. Hu,[1] B. Huang,[1] G. M. Huang,[14] J. S. Huang,[11] X. T. Huang,[27] Y. P. Huang,[1] T. Hussain,[40] C. S. Ji,[39] Q. Ji,[1] X. B. Ji,[1] X. L. Ji,[1] L. K. Jia,[1] L. L. Jiang,[1] X. S. Jiang,[1] J. B. Jiao,[27] Z. Jiao,[13] D. P. Jin,[1] S. Jin,[1] F. F. Jing,[34] N. Kalantar-Nayestanaki,[19] M. Kavatsyuk,[19] W. Kuehn,[35] W. Lai,[1] J. S. Lange,[35] J. K. C. Leung,[33] C. H. Li,[1] Cheng Li,[39] Cui Li,[39] D. M. Li,[44] F. Li,[1] G. Li,[1] H. B. Li,[1] J. C. Li,[1] K. Li,[10] Lei Li,[1] N. B. Li,[22] Q. J. Li,[1] S. L. Li,[1] W. D. Li,[1] W. G. Li,[1] X. L. Li,[27] X. N. Li,[1] X. Q. Li,[24] X. R. Li,[26] Z. B. Li,[31] H. Liang,[39] Y. F. Liang,[29] Y. T. Liang,[35] G. R. Liao,[34] X. T. Liao,[1] B. J. Liu,[32] C. L. Liu,[3] C. X. Liu,[1] C. Y. Liu,[1] F. H. Liu,[28] Fang Liu,[1] Feng Liu,[14] H. Liu,[1] H. B. Liu,[6] H. H. Liu,[12] H. M. Liu,[1] H. W. Liu,[1] J. P. Liu,[42] K. Liu,[25] K. Liu,[6] K. Y. Liu,[21] Q. Liu,[36] S. B. Liu,[39] X. Liu,[20] X. H. Liu,[1] Y. B. Liu,[24] Yong Liu,[1] Z. A. Liu,[1] Zhiqiang Liu,[1] Zhiqing Liu,[1] H. Loehner,[19] G. R. Lu,[11] H. J. Lu,[13] J. G. Lu,[1] Q. W. Lu,[28] X. R. Lu,[6] Y. P. Lu,[1] C. L. Luo,[22] M. X. Luo,[43] T. Luo,[36] X. L. Luo,[1] M. Lv,[1] C. L. Ma,[6] F. C. Ma,[21] H. L. Ma,[1] Q. M. Ma,[1] S. Ma,[1] T. Ma,[1] X. Y. Ma,[1] M. Maggiora,[41] Q. A. Malik,[40] H. Mao,[1] Y. J. Mao,[25] Z. P. Mao,[1] J. G. Messchendorp,[19] J. Min,[1] T. J. Min,[1] R. E. Mitchell,[16] X. H. Mo,[1] N. Yu. Muchnoi,[5] Y. Nefedov,[18] I. B. Nikolaev,[5] Z. Ning,[1] S. L. Olsen,[26] Q. Ouyang,[1] S. P. Pacetti,[17,‡] J. W. Park,[26] M. Pelizaeus,[36] K. Peters,[7] J. L. Ping,[22] R. G. Ping,[1] R. Poling,[37] C. S. J. Pun,[33] M. Qi,[23] S. Qian,[1] C. F. Qiao,[6] X. S. Qin,[1] J. F. Qiu,[1] K. H. Rashid,[40] G. Rong,[1] X. D. Ruan,[9] A. Sarantsev,[18,§] J. Schulze,[2] M. Shao,[39] C. P. Shen,[36,‖] X. Y. Shen,[1] H. Y. Sheng,[1] M. R. Shepherd,[16] X. Y. Song,[1] S. Spataro,[41] B. Spruck,[35] D. H. Sun,[1] G. X. Sun,[1] J. F. Sun,[11] S. S. Sun,[1] X. D. Sun,[1] Y. J. Sun,[39] Y. Z. Sun,[1] Z. J. Sun,[1] Z. T. Sun,[39] C. J. Tang,[29] X. Tang,[1] E. H. Thorndike,[38] H. L. Tian,[1] D. Toth,[37] G. S. Varner,[36] B. Wang,[9] B. Q. Wang,[25] K. Wang,[1] L. L. Wang,[4] L. S. Wang,[1] M. Wang,[27] P. Wang,[1] P. L. Wang,[1] Q. Wang,[1] Q. J. Wang,[1] S. G. Wang,[25] X. F. Wang,[11] X. L. Wang,[39] Y. D. Wang,[39] Y. F. Wang,[1] Y. Q. Wang,[27] Z. Wang,[1] Z. G. Wang,[1] Z. Y. Wang,[1] D. H. Wei,[8] Q. G. Wen,[39] S. P. Wen,[1] U. Wiedner,[2] L. H. Wu,[1] N. Wu,[1] W. Wu,[24] Z. Wu,[1] Z. J. Xiao,[22] Y. G. Xie,[1] Q. L. Xiu,[1] G. F. Xu,[1] G. M. Xu,[25] H. Xu,[1] Q. J. Xu,[10] X. P. Xu,[30] Y. Xu,[24] Z. R. Xu,[39] Z. Xue,[1] L. Yan,[39] W. B. Yan,[39] Y. H. Yan,[15] H. X. Yang,[1] T. Yang,[9] Y. Yang,[14] Y. X. Yang,[8] H. Ye,[1] M. Ye,[1] M. H. Ye,[4] B. X. Yu,[1] C. X. Yu,[24] S. P. Yu,[27] C. Z. Yuan,[1] W. L. Yuan,[22] Y. Yuan,[1] A. A. Zafar,[40] A. Z. Zallo,[17] Y. Zeng,[15] B. X. Zhang,[1] B. Y. Zhang,[1] C. C. Zhang,[1] D. H. Zhang,[1] H. H. Zhang,[31] H. Y. Zhang,[1] J. Zhang,[22] J. Q. Zhang,[1] J. W. Zhang,[1] J. Y. Zhang,[1] J. Z. Zhang,[1] L. Zhang,[23] S. H. Zhang,[1] T. R. Zhang,[22] X. J. Zhang,[1] X. Y. Zhang,[27] Y. Zhang,[1] Y. H. Zhang,[1] Y. S. Zhang,[9] Z. P. Zhang,[39] Z. Y. Zhang,[42] G. Zhao,[1] H. S. Zhao,[1] Jingwei Zhao,[1] Lei Zhao,[39] Ling Zhao,[1] M. G. Zhao,[24] Q. Zhao,[1] S. J. Zhao,[44] T. C. Zhao,[1] X. H. Zhao,[23] Y. B. Zhao,[1] Z. G. Zhao,[39] A. Zhemchugov,[18,*] B. Zheng,[1] J. P. Zheng,[1] Y. H. Zheng,[6] Z. P. Zheng,[1] B. Zhong,[1] J. Zhong,[2] L. Zhou,[1] X. K. Zhou,[6] X. R. Zhou,[39] C. Zhu,[1] K. Zhu,[1] K. J. Zhu,[1] S. H. Zhu,[1] X. L. Zhu,[34] X. W. Zhu,[1] Y. S. Zhu,[1] Z. A. Zhu,[1] J. Zhuang,[1] B. S. Zou,[1] J. H. Zou,[1] and J. X. Zuo[1]

(BESIII Collaboration)

[1]*Institute of High Energy Physics, Beijing 100049, People's Republic of China*
[2]*Bochum Ruhr-University, 44780 Bochum, Germany*
[3]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*
[4]*China Center of Advanced Science and Technology, Beijing 100190, People's Republic of China*
[5]*G.I. Budker Institute of Nuclear Physics SB RAS (BINP), Novosibirsk 630090, Russia*
[6]*Graduate University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China*
[7]*GSI Helmholtzcentre for Heavy Ion Research GmbH, D-64291 Darmstadt, Germany*
[8]*Guangxi Normal University, Guilin 541004, People's Republic of China*
[9]*GuangXi University, Nanning 530004, People's Republic of China*
[10]*Hangzhou Normal University, Hangzhou 310036, 541004, People's Republic of China*
[11]*Henan Normal University, Xinxiang 453007, People's Republic of China*

0031-9007/12/108(11)/112003(6)

[12]Henan University of Science and Technology, Luoyang 471003, People's Republic of China
[13]Huangshan College, Huangshan 245000, People's Republic of China
[14]Huazhong Normal University, Wuhan 430079, People's Republic of China
[15]Hunan University, Changsha 410082, People's Republic of China
[16]Indiana University, Bloomington, Indiana 47405, USA
[17]INFN Laboratori Nazionali di Frascati, Frascati, Italy
[18]Joint Institute for Nuclear Research, 141980 Dubna, Russia
[19]KVI/University of Groningen, 9747 AA Groningen, The Netherlands
[20]Lanzhou University, Lanzhou 730000, People's Republic of China
[21]Liaoning University, Shenyang 110036, People's Republic of China
[22]Nanjing Normal University, Nanjing 210046, People's Republic of China
[23]Nanjing University, Nanjing 210093, People's Republic of China
[24]Nankai University, Tianjin 300071, People's Republic of China
[25]Peking University, Beijing 100871, People's Republic of China
[26]Seoul National University, Seoul, 151-747 Korea
[27]Shandong University, Jinan 250100, People's Republic of China
[28]Shanxi University, Taiyuan 030006, People's Republic of China
[29]Sichuan University, Chengdu 610064, People's Republic of China
[30]Soochow University, Suzhou 215006, China
[31]Sun Yat-Sen University, Guangzhou 510275, People's Republic of China
[32]The Chinese University of Hong Kong, Shatin, N.T., Hong Kong
[33]The University of Hong Kong, Pokfulam, Hong Kong
[34]Tsinghua University, Beijing 100084, People's Republic of China
[35]Universitaet Giessen, 35392 Giessen, Germany
[36]University of Hawaii, Honolulu, Hawaii 96822, USA
[37]University of Minnesota, Minneapolis, Minnesota 55455, USA
[38]University of Rochester, Rochester, New York 14627, USA
[39]University of Science and Technology of China, Hefei 230026, People's Republic of China
[40]University of the Punjab, Lahore-54590, Pakistan
[41]University of Turin and INFN, Turin, Italy
[42]Wuhan University, Wuhan 430072, People's Republic of China
[43]Zhejiang University, Hangzhou 310027, People's Republic of China
[44]Zhengzhou University, Zhengzhou 450001, People's Republic of China
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A partial wave analysis of the $p\bar{p}$ mass-threshold enhancement in the reaction $J/\psi \to \gamma p\bar{p}$ is used to determine its J^{PC} quantum numbers to be 0^{-+}, its peak mass to be below threshold at $M = 1832^{+19}_{-5}(\mathrm{stat})^{+18}_{-17}(\mathrm{syst}) \pm 19(\mathrm{model})\ \mathrm{MeV}/c^2$, and its total width to be $\Gamma < 76\ \mathrm{MeV}/c^2$ at the 90% C.L. The product of branching ratios is measured to be $\mathrm{BR}[J/\psi \to \gamma X(p\bar{p})]\mathrm{BR}[X(p\bar{p}) \to p\bar{p}] = [9.0^{+0.4}_{-1.1}(\mathrm{stat})^{+1.5}_{-5.0}(\mathrm{syst}) \pm 2.3(\mathrm{model})] \times 10^{-5}$. A similar analysis performed on $\psi(3686) \to \gamma p\bar{p}$ decays shows, for the first time, the presence of a corresponding enhancement with a production rate relative to that for J/ψ decays of $R = [5.08^{+0.71}_{-0.45}(\mathrm{stat})^{+0.67}_{-3.58}(\mathrm{syst}) \pm 0.12(\mathrm{model})]\%$.

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An anomalously strong $p\bar{p}$ mass-threshold enhancement was first observed by the BESII experiment in the radiative decay process $J/\psi \to \gamma p\bar{p}$ [1] and was recently confirmed by the BESIII [2] and CLEO-c [3] experiments. Curiously, no apparent corresponding structures were seen in near-threshold $p\bar{p}$ cross section measurements, in B-meson decays [4], in radiative $\psi(3686)$ or $\Upsilon \to \gamma p\bar{p}$ decays [5], or in $J/\psi \to \omega p\bar{p}$ decays [6]. These nonobservations disfavor the attribution of the mass-threshold enhancement to the effects of $p\bar{p}$ final state interactions (FSI) [7–9].

A number of theoretical speculations have been proposed to interpret the nature of this structure [7–11]. Among them, one intriguing suggestion is that it is due to a $p\bar{p}$ bound state, sometimes called baryonium [11], an object with a long history and the subject of many experimental searches [12]. The observation of the $p\bar{p}$ mass-threshold enhancement also stimulated an experimental analysis of $J/\psi \to \gamma\pi^+\pi^-\eta'$ decays, in which a $\pi^+\pi^-\eta'$ resonance, the $X(1835)$, was first observed by the BESII experiment [13] and recently confirmed with high statistical significance by the BESIII experiment [14]. Whether or not the $p\bar{p}$ mass-threshold enhancement and the $X(1835)$ are related to the same source still needs further study; among these, spin-parity determinations and precise measurements of the masses, widths, and branching ratios are especially important.

In this Letter, we report the first partial wave analysis (PWA) of the $p\bar{p}$ mass-threshold structure produced via the decays of $J/\psi \to \gamma p\bar{p}$ and $\psi(3686) \to \gamma p\bar{p}$. Data samples containing $(225.2 \pm 2.8) \times 10^6$ J/ψ events and $(106 \pm 4) \times 10^6$ $\psi(3686)$ events [15] accumulated in the Beijing Spectrometer (BESIII) [16] located at the Beijing Electron-Positron Collider (BEPCII) [17] are used.

The cylindrical core of the BESIII detector consists of a helium-gas-based drift chamber (MDC), a plastic scintillator Time-of-Flight system (TOF), and a CsI(Tl) Electromagnetic Calorimeter (EMC), all enclosed in a superconducting solenoidal magnet that provides a 1.0-T magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identifier modules interleaved with steel plates. The solid angle for the charged particle and photon acceptance is 93% of 4π, and the charged-particle momentum and photon energy resolutions at 1 GeV are 0.5% and 2.5%, respectively. The time resolution of TOF is 80 ps in the barrel and 110 ps in the end caps, and the dE/dx resolution is 6%.

Charged-particle tracks in the polar angle range $|\cos\theta| < 0.93$ are reconstructed from hits in the MDC. The TOF and dE/dx information are combined to form particle identification confidence levels for the π, K and p hypotheses; the particle type with the highest confidence level is assigned to each track. Photon candidates are required to have an energy deposit of at least 25 MeV in the barrel EMC ($|\cos\theta| < 0.8$) and 50 MeV in the endcap EMCs ($0.86 < |\cos\theta| < 0.92$), and be isolated from antiprotons by more than 30°.

Candidate $J/\psi \to \gamma p\bar{p}$ events are required to have at least one photon and two charged tracks identified as a proton and an antiproton. Requirements of $|U_{\mathrm{miss}}| < 0.05$ GeV, where $U_{\mathrm{miss}} = (E_{\mathrm{miss}} - |P_{\mathrm{miss}}|)$, and $P^2_{t\gamma} < 0.0005$ $(\mathrm{GeV}/c)^2$, where $P^2_{t\gamma} = 4|P_{\mathrm{miss}}|^2 \sin^2\theta_\gamma/2$, are imposed to suppress backgrounds from multiphoton events. Here E_{miss} and P_{miss} are, respectively, the missing energy and momentum of all charged particles, and θ_γ is the angle between the missing momentum and the photon direction. A four-constraint (4C) energy-momentum conservation kinematic fit is performed to the $\gamma p\bar{p}$ hypothesis. For events with more than one photon candidate, the combination with the minimum χ^2 is used. For all events, $\chi^2 < 20$ is also required. Since there are differences in detection efficiency between data and Monte Carlo (MC) simulated low-momentum tracks, we reject events containing any tracks with momentum below 0.3 GeV/c.

The $p\bar{p}$ mass spectrum for events that satisfy all of the criteria listed above is shown in Fig. 1(a). There is a clear signal of η_c, a broad enhancement around $M_{p\bar{p}} \sim 2.1$ GeV/c^2, and a prominent and narrow low-mass peak at the $p\bar{p}$ mass threshold, consistent with that reported by BESII [1] and BESIII [2]. The Dalitz plot for above events is shown in Fig. 1(b).

Potential background processes are studied with an inclusive MC sample of 2×10^8 J/ψ events generated according to the Lund model [18]. None of the background sources produces an enhancement at the $p\bar{p}$ mass-threshold region. The dominant background is from $J/\psi \to \pi^0 p\bar{p}$ events, with asymmetric $\pi^0 \to \gamma\gamma$ decays where one of the photons has most of the π^0 energy. An exclusive MC sample, generated according to the PWA results of $J/\psi \to \pi^0 p\bar{p}$ at BESII [19], indicates that the level of this background in the selected data sample with $M_{p\bar{p}} < 2.2$ GeV/c^2 is 3.7% of the total. The $J/\psi \to \pi^0 p\bar{p}$ decay channel is also studied with data, and there is no evidence of a $p\bar{p}$ mass-threshold enhancement, which provides further evidence that the enhancement observed in J/ψ decays is not from background.

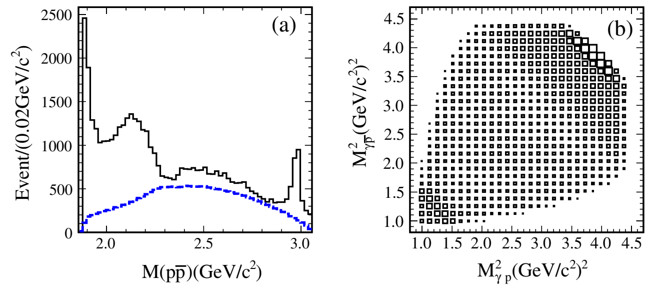

FIG. 1 (color online). The $p\bar{p}$ invariant mass spectrum for the selected $J/\psi \to \gamma p\bar{p}$ candidate events. (a) The $p\bar{p}$ invariant mass spectrum; the open histogram is data and the dashed line is from $J/\psi \to \gamma p\bar{p}$ phase-space MC events (with arbitrary normalization). (b) An $M^2(\gamma p)$ (horizontal) *versus* $M^2(\gamma\bar{p})$ (vertical) Dalitz plot for the selected events.

A PWA of the events with $M_{p\bar{p}} < 2.2$ GeV/c^2 is performed to focus on determining the parameters of the $p\bar{p}$ mass-threshold structure, which we denote as $X(p\bar{p})$. The maximum likelihood method applied in the fit uses a likelihood function that is constructed from $\gamma p\bar{p}$ signal amplitudes described by the relativistic covariant tensor amplitude method [20] and MC efficiencies. The background contribution from the $\pi^0 p\bar{p}$ process is removed by subtracting the log-likelihood values of background events from that of data, since the log-likelihood value of data is the sum of the log-likelihood values of signal and background events [21]. Here, the background events are estimated by the MC sample of $J/\psi \to \pi^0 p\bar{p}$ decays described above. We include the effect of FSI in the PWA fit using the Julich formulation [7].

Four components, the $X(p\bar{p})$, $f_2(1910)$, $f_0(2100)$, and 0^{++} phase space (PS) are included in the PWA fit. The intermediate resonances are described by Breit-Wigner (BW) propagators, and the parameters of the $f_2(1910)$ and $f_0(2100)$ are fixed at PDG values. In the optimal PWA fit, the $X(p\bar{p})$ is assigned to be a 0^{-+} state. The statistical significance of the $X(p\bar{p})$ component of the fit is much larger than 30σ; those for the other components are larger than 5σ, where the statistical significance is determined from the changes of likelihood value and degrees of freedom in the PWA fits with and without the signal hypotheses. The mass, width and product of branching ratios (BRs) of the $X(p\bar{p})$ are measured to be $M = 1832^{+19}_{-5}$ MeV/c^2, $\Gamma = 13 \pm 39$ MeV/c^2, and $\mathrm{BR}(J/\psi \to \gamma X)\mathrm{BR}(X \to p\bar{p}) = (9.0^{+0.4}_{-1.1}) \times 10^{-5}$, respectively, where the errors are statistical only. Figure 2 shows comparisons of the mass and angular distributions between the data and the PWA fit projections. For the spin-parity determination of the $X(p\bar{p})$, the 0^{-+} assignment fit is better than that for 0^{++} or other J^{PC} assignments with statistical significances that are larger than 6.8σ.

Variations of the fit included replacing the $f_0(2100)$ with the $f_2(2150)$, the $f_2(1910)$ with the $f_2(1950)$, and replacing both components simultaneously; changing the J^{PC} of the PS contribution, as well as consideration of the parameter uncertainties of the $f_0(2100)$ and $f_2(1910)$, were performed, and it is found the changes of the log-likelihood values and the parameters of the $X(p\bar{p})$ are quite small. However, when replacing 0^{++} PS with 0^{-+} PS the event fraction of the $X(p\bar{p})$ decreases by 52%. We also tried fits that include other possible resonances listed in the PDG table [22] [$\eta_2(1870)$, $f_2(2010)$, $f_2(1950)$, $f_2(2150)$, $f_J(2220)$, $\eta(2225)$, $f_2(2300)$, $f_2(2340)$, etc.] as well as $X(2120)$ and $X(2370)$ [14], and different J^{PC} PS contributions. The statistical significances of these additional resonances are lower than 3σ. All of the parameter changes that are found in these alternative fits are folded into the systematic uncertainties.

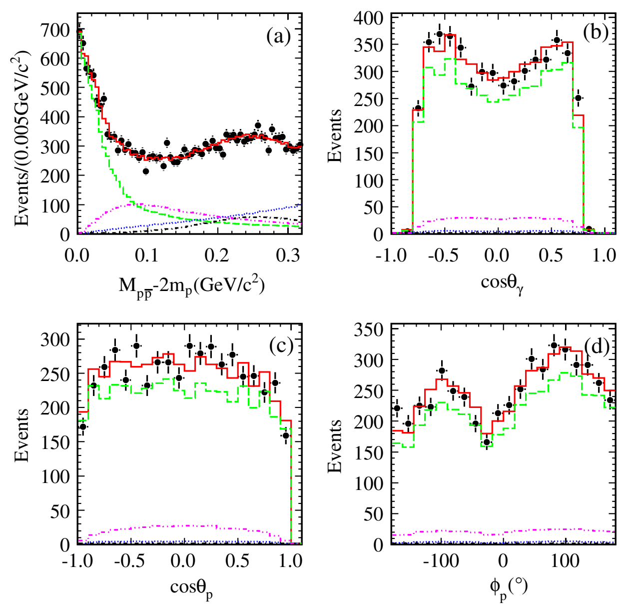

FIG. 2 (color online). Comparisons between data and PWA fit projection: (a) the $p\bar{p}$ invariant mass; (b)–(d) the polar angle θ_γ of the radiative photon in the J/ψ center of mass system, the polar angle θ_p and the azimuthal angle ϕ_p of the proton in the $p\bar{p}$ center of mass system with $M_{p\bar{p}} - 2m_p < 50$ MeV/c^2, respectively. Here, the black dots with error bars are data, the solid histograms show the PWA total projection, and the dashed, dotted, dash-dotted, and dash-dot-dotted lines show the contributions of the $X(p\bar{p})$, 0^{++} phase space, $f_0(2100)$ and $f_2(1910)$, respectively.

For systematic errors on the mass and width of the $X(p\bar{p})$, in addition to those discussed above, we include uncertainties from different fit ranges of $M_{p\bar{p}} < 2.15$ GeV/c^2 and $M_{p\bar{p}} < 2.25$ GeV/c^2, different parameterizations for the BW formula, as well as different background levels. For the systematic errors of the BR measurement, there are additional uncertainties from the efficiencies of charged track detection, photon detection and particle identification, kinematic fit and the total number of J/ψ events. The total systematic errors on the mass and width of the $X(p\bar{p})$ are $^{+18}_{-17}$ MeV/c^2 and $^{+10}_{-13}$ MeV/c^2, respectively, and the corresponding relative systematic error on the product of BRs is $^{+17}_{-56}$%.

Various FSI models [7–9] have been proposed to interpret the $p\bar{p}$ mass-threshold enhancement. Among them, a BW function times a one-pion-exchange FSI factor [9] can also describe the data well. For this case, the mass and width of the $X(p\bar{p})$ shift by 19 MeV/c^2 and 4 MeV/c^2, respectively, while the relative change in the product of BRs is 25%. These errors are considered as second (model) systematic errors due to the model dependence.

The $\psi(3686) \to \gamma p\bar{p}$ decay channel is also studied using event selection criteria similar to those used in the $J/\psi \to \gamma p\bar{p}$ study. The $p\bar{p}$ mass spectrum of the surviving events is shown in Fig. 3(a). Besides the well known η_c and χ_{cJ} peaks, there is also a $p\bar{p}$ mass-threshold excess relative to PS. However, here the line shape of the mass spectrum in the threshold region appears to be less pronounced than that in J/ψ decays. Potential background processes were studied extensively with an inclusive MC sample of 1×10^8 $\psi(3686)$ events and with a data sample of selected $\psi(3686) \to \pi^0 p\bar{p}$ events, and these indicate that the $p\bar{p}$ mass-threshold structure is not from any background source. An exclusive MC sample, generated

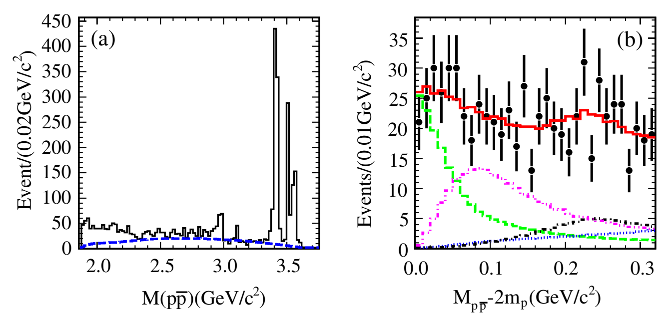

FIG. 3 (color online). (a) The $p\bar{p}$ invariant mass spectrum for the selected $\psi(3686) \to \gamma p\bar{p}$ candidate events; the open histogram is data and the dashed line is from a $\psi(3686) \to \gamma p\bar{p}$ phase-space MC events (with arbitrary normalization). (b) Comparisons between data and PWA fit projection for $p\bar{p}$ mass spectrum, the representations of the error bars and histograms are same as those in Fig. 2.

according to preliminary PWA results of $\psi(3686) \rightarrow \pi^0 p\bar{p}$ decays with BESIII data [23], is applied to the background estimation, and the background level from this source in the selected data sample with $M_{p\bar{p}} < 2.2\ \mathrm{GeV}/c^2$ is determined to be 3.4%.

A PWA similar to that applied for $J/\psi \rightarrow \gamma p\bar{p}$ decays was performed on the $\psi(3686) \rightarrow \gamma p\bar{p}$ data in order to check the contribution of $X(p\bar{p})$ in $\psi(3686)$ decays and to measure the production ratio between J/ψ and $\psi(3686)$ radiative decays, $R = \mathrm{BR}[\psi(3686) \rightarrow \gamma X(p\bar{p})]/\mathrm{BR}[J/\psi \rightarrow \gamma X(p\bar{p})]$. Because of the limited statistics of the $\psi(3686)$ event sample, the $X(p\bar{p})$ mass, width and J^{PC} were fixed in the PWA to the results obtained from J/ψ decays. Figure 3(b) shows comparisons between data and MC projections for the $p\bar{p}$ mass spectrum. As in J/ψ decays, replacing the $f_0(2100)$ with the $f_2(2150)$ and the $f_2(1910)$ with the $f_2(1950)$ yields no significant change in fit quality. The determined product of BRs and R value are $\mathrm{BR}[\psi(3686) \rightarrow \gamma X]\mathrm{BR}(X \rightarrow p\bar{p}) = (4.57 \pm 0.36) \times 10^{-6}$ and $R = (5.08^{+0.71}_{-0.45})\%$, respectively.

The systematic uncertainties are derived similarly to those for J/ψ decays, and the uncertainty of the total number of $\psi(3686)$ events, the total relative systematic error on the product of BRs is $[^{+27}_{-89}(\mathrm{syst}) \pm 28(\mathrm{model})]\%$, and systematic error on the R value is $[^{+0.67}_{-3.58}(\mathrm{syst}) \pm 0.12(\mathrm{model})]\%$. As in all cases studied in J/ψ analysis, the statistical significance of the $X(p\bar{p})$ signal in $\psi(3686)$ decays is larger than 6.9σ.

The PWA fits to both the J/ψ and $\psi(3686)$ samples were performed without the correction for FSI effects. The corresponding log-likelihood value for the J/ψ fit worsens by 25.6 compared to those with FSI effect included. The mass, width and product of BRs of the $X(p\bar{p})$ are $M = 1861 \ \pm 1(\mathrm{stat}) \ ^{+13}_{-4}(\mathrm{syst})\ \mathrm{MeV}/c^2$, $\Gamma = 1 \pm 6(\mathrm{stat}) \ ^{+18}_{-1}(\mathrm{syst})\ \mathrm{MeV}/c^2$ (a total width of $\Gamma < 32\ \mathrm{MeV}/c^2$ at the 90% C.L), $\mathrm{BR}[J/\psi \rightarrow \gamma X(1860)]\ \mathrm{BR}[X(1860) \rightarrow p\bar{p}] = [8.6^{+0.3}_{-0.2}(\mathrm{stat})^{+2.4}_{-3.5}(\mathrm{syst})] \times 10^{-5}$ and $\mathrm{BR}[\psi(3686) \rightarrow \gamma X(1860)]\ \mathrm{BR}[X(1860) \rightarrow p\bar{p}] = [4.15 \pm 0.39(\mathrm{stat})^{+2.51}_{-1.71}(\mathrm{syst})] \times 10^{-6}$, respectively. The corresponding R value is $[4.80^{+0.46}_{-0.48}(\mathrm{stat})^{+2.24}_{-1.29}(\mathrm{syst})]\%$.

In summary, the PWA of $J/\psi \rightarrow \gamma p\bar{p}$ and $\psi(3686) \rightarrow \gamma p\bar{p}$ decays are performed. In J/ψ radiative decays, the near-threshold enhancement $X(p\bar{p})$ in the $p\bar{p}$ invariant mass is determined to be a 0^{-+} state. With the inclusion of Julich-FSI effects, the mass, width and product of BRs for the $X(p\bar{p})$ are measured to be: $M = 1832^{+19}_{-5}(\mathrm{stat})^{+18}_{-17}(\mathrm{syst}) \pm 19(\mathrm{model})\ \mathrm{MeV}/c^2$, $\Gamma = 13 \pm 39(\mathrm{stat})^{+10}_{-13}(\mathrm{syst}) \pm 4(\mathrm{model})\ \mathrm{MeV}/c^2$ (a total width of $\Gamma < 76\ \mathrm{MeV}/c^2$ at the 90% C.L) and $\mathrm{BR}(J/\psi \rightarrow \gamma X)\mathrm{BR}(X \rightarrow p\bar{p}) = [9.0^{+0.4}_{-1.1}(\mathrm{stat})^{+1.5}_{-5.0}(\mathrm{syst}) \pm 2.3(\mathrm{model})] \times 10^{-5}$, respectively. The product of BRs for $X(p\bar{p})$ in $\psi(3686)$ decay is measured for the first time to be $\mathrm{BR}[\psi(3686) \rightarrow \gamma X]\mathrm{BR}(X \rightarrow p\bar{p}) = [4.57 \pm 0.36(\mathrm{stat})^{+1.23}_{-4.07}(\mathrm{syst}) \pm 1.28(\mathrm{model})] \times 10^{-6}$ and the ratio of product branching ratios for the $X(p\bar{p})$ between J/ψ and $\psi(3686)$ radiative decays is $R = [5.08^{+0.71}_{-0.45}(\mathrm{stat})^{+0.67}_{-3.58}(\mathrm{syst}) \pm 0.12(\mathrm{model})]\%$.

The mass of the $X(p\bar{p})$ measured in the PWA fit with FSI effect included is consistent with the $X(1835)$, but the width is significantly narrower. This indicates either that the $X(p\bar{p})$ and the $X(1835)$ come from different sources, or that interference effects in the $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$ process should not be ignored in the determination of the $X(1835)$ mass and width, or that there may be more than one resonance in the mass peak around $1.83\ \mathrm{GeV}/c^2$ in $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$ decays. When more J/ψ data are collected at BESIII, more sophisticated analyses, including a PWA, will be performed for the $J/\psi \rightarrow \gamma\pi\pi\eta'$ decay channel. A measurement of the relative production ratios for the $X(1835)$ in J/ψ and $\psi(3686)$ radiative decays may further clarify whether or not the $X(p\bar{p})$ and the $X(1835)$ are the same states.

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*Also at the Moscow Institute of Physics and Technology, Moscow, Russia.

†On leave from the Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine.

‡Present address: University of Perugia and INFN, Perugia, Italy.

§Also at the PNPI, Gatchina, Russia.

‖Present address: Nagoya University, Nagoya, Japan.

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