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Recent charmonium results from BES*

Jiangchuan Chen[1] and Frederick A. Harris[2], on behalf of the BES Collaboration

[1] Institute of High Energy Physics, Beijing, China
[2] Dept. of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, USA

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Abstract. Using 58 million J/ψ decays, we have investigated the $p\bar{p}$ invariant mass spectrum in the radiative decay $J/\psi \to \gamma p\bar{p}$ and observe a prominent structure with mass near $2m_p$. Fitting with an S-wave Breit-Wigner, we obtain a peak mass of $M = 1859^{+3}_{-10}(\text{stat})^{+5}_{-25}(\text{sys})$ MeV/c^2. $J/\psi \to \gamma\eta_c$ decays from the same sample are used to determine the mass, width, and hadronic branching ratios of the η_c. From a sample of 14 million $\psi(2S)$ events, the first observation of χ_{cJ} (J=0,1,2) decays to $\Lambda\bar{\Lambda}$ is made, and branching ratios are determined, which are larger than expected from the Color Octet Model. Branching ratios of $K^0_s K^0_L$ in both $\psi(2S)$ and J/ψ decays are measured, and a more than four sigma deviation from the pQCD-predicted "12% rule" is observed. In $\psi(3770)$ decays, evidence for the non-$D\bar{D}$ decay to $\pi^+\pi^- J/\psi$ is observed.

PACS. 13.20.Gd Decays of J/psi, Upsilon, and other quarkonia

1 Introduction

The Beijing Spectrometer (BES) is a general purpose solenoidal detector at the Beijing Electron Positron Collider (BEPC). BEPC operates in the center of mass (cm) energy range from 2 to 5 GeV with a luminosity at the J/ψ energy of approximately 5×10^{30} cm^{-2}s^{-1}. BES (BESI) is described in detail in [1], and the upgraded BES detector (BESII) is described in [2]. This paper presents some recent results; details may be found in the references.

2 Studies of $J/\psi \to \gamma p\bar{p}$

There is evidence for anomalous behavior in the proton-antiproton system very near the $M_{p\bar{p}} = 2m_p$ mass threshold. The cross section for $e^+e^- \to$ hadrons has a narrow dip-like structure at a cm energy of $\sqrt{s} \simeq 2m_pc^2$ [3]. In addition, the proton's time-like magnetic form-factor, determined from high statistics measurements of the $p\bar{p} \to e^+e^-$ annihilation process, exhibits a very steep fall-off just above the $p\bar{p}$ mass threshold [4]. These data are suggestive of a narrow, S-wave triplet $p\bar{p}$ resonance with $J^{PC} = 1^{--}$ and mass near $M_{p\bar{p}} \simeq 2m_p$.

Using 58 million J/ψ decays, we have investigated the invariant mass spectrum of $p\bar{p}$ pairs in the radiative process $J/\psi \to \gamma p\bar{p}$ and observe a peak corresponding to $J/\psi \to \gamma\eta_c$ at high mass and a prominent structure with mass near $2m_p$, as shown in Fig. 1. Figure 2(a) shows the threshold region for the selected $J/\psi \to \gamma p\bar{p}$ events. The solid curve is the result of a fit using an acceptance-weighted S-wave Breit-Wigner function to represent the low-mass enhancement plus the dashed curve to represent the background, primarily due to $J/\psi \to \pi^0 p\bar{p}$ where one of the photons from the $\pi^0 \to \gamma\gamma$ is missed. The fit yields a peak mass of $M = 1859^{+3}_{-10}(\text{stat})^{+5}_{-25}(\text{sys})$ MeV/c^2 and a full width of $\Gamma < 30$ MeV. Here the systematic errors include errors determined by generating Monte Carlo samples with below threshold peak masses and measuring the shift in the output fit masses.

Further evidence that the peak mass is below the $2m_p$ threshold is provided by Fig. 2(b), which shows the $M_{p\bar{p}} - 2m_p$ distribution when the threshold behavior is removed by weighting each event by q_o/q, where q is the proton momentum in the $p\bar{p}$ restframe and q_o is the value for $M_{p\bar{p}} = 2$ GeV/c^2. The sharp and monotonic increase at threshold can only occur for an S-wave BW function when the peak mass is below $2m_p$. A P-wave BW yields a fit which is worse than the S-wave fit, but still acceptable. The structure is not consistent with the properties of any known particle. More detail may be found in [5].

3 η_c parameters

The mass and width of the η_c are rather poorly known; the confidence level for the Particle Data Group (PDG) weighted average mass is only 0.001 [6]. Previously BES measured the η_c mass using the BESI 4.02 million $\psi(2S)$ sample and obtained $M_{\eta_c} = (2975.8 \pm 3.9 \pm 1.2)$ MeV [7]. BES also used 7.8 million BESI J/ψ events and obtained $M_{\eta_c} = (2976.6 \pm 2.9 \pm 1.3)$ MeV [8]. For the two data sets

* Talk presented by Jiangchuan Chen

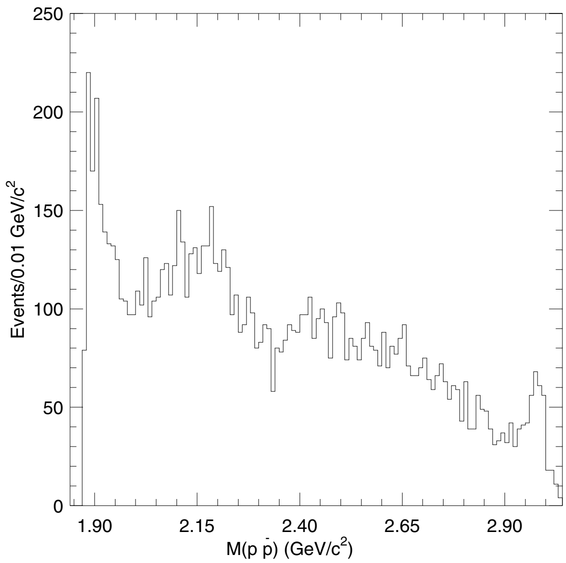

Fig. 1. The $p\bar{p}$ invariant mass distribution for the $J/\psi \to \gamma p\bar{p}$ event sample

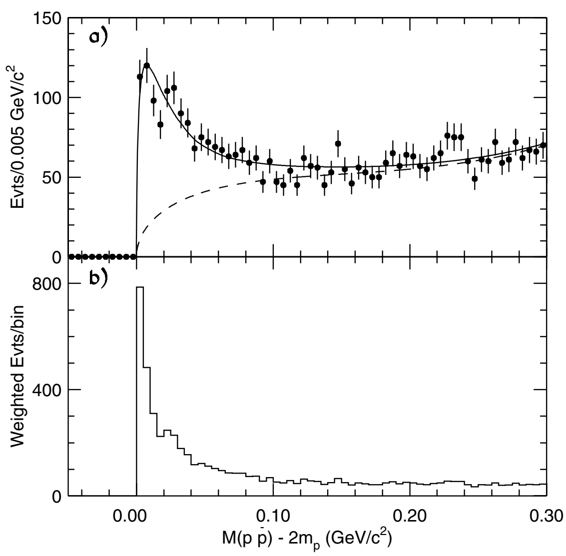

Fig. 2. a The near-threshold $M_{p\bar{p}} - 2m_p$ distribution for the $\gamma p\bar{p}$ event sample. The *solid curve* is the result of the fit; the *dashed curve* shows the fitted background function. **b** The $M_{p\bar{p}} - 2m_p$ distribution with events weighted by q_0/q

combined, $M_{\eta_c} = (2976.3 \pm 2.3 \pm 1.2)$ MeV and the total width $\Gamma_{\eta_c} = (11.0 \pm 8.1 \pm 4.1)$ MeV [8].

Here, the mass and width have been determined using our BESII 58 million J/ψ event sample. We use the channels $J/\psi \to \gamma\eta_c$, with $\eta_c \to p\bar{p}$, $K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^\pm K^o_S\pi^\mp$, and $\phi\phi$. Events are selected using particle identification and kinematic fitting. Figures 3 and 4 show the mass distributions in the η_c mass region for $J/\psi \to \gamma\eta_c$, $\eta_c \to p\bar{p}$ and $\eta_c \to K^+K^-\pi^+\pi^-$, respectively. Fitting the five decay channels simultaneously, we obtain $M_{\eta_c} = (2977.5 \pm 1.0 \pm 1.2)$ MeV and $\Gamma_{\eta_c} = (17.0 \pm 3.7 \pm 7.4)$ MeV. The results for the mass and width are compared with previous measurements, including previous BES measurements, in Figs. 5 and 6. The results are in good agreement with previous BES measurements and the PDG fit values. More detail on this analysis may be found in [9].

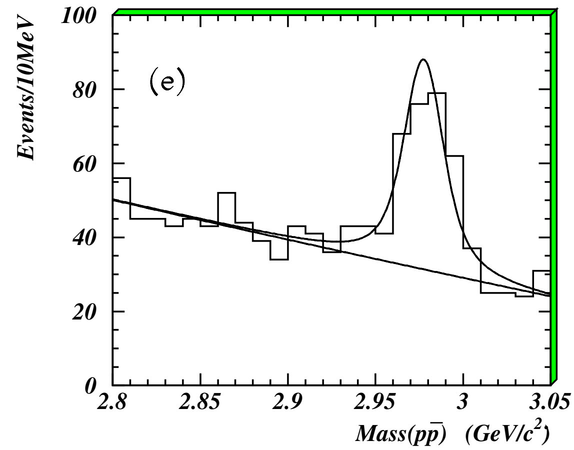

Fig. 3. The $m_{p\bar{p}}$ invariant mass distribution in the η_c region

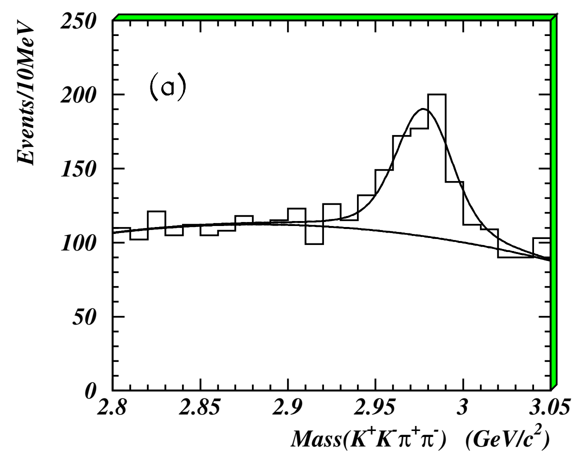

Fig. 4. The $m_{K^+K^-\pi^+\pi^-}$ invariant mass distribution in the η_c region

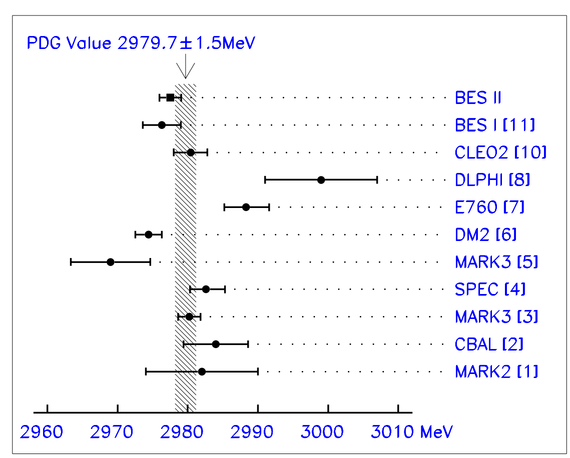

Fig. 5. Mass measurements of the η_c meson

The numbers of η_c events determined from the fit and the corresponding product branching ratios, by decay channel, are listed in Table 1. Using the branching

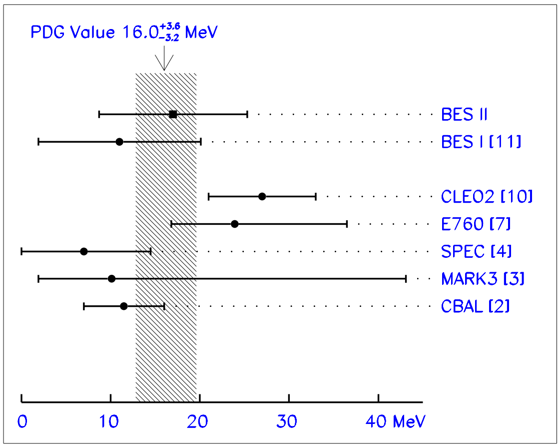

Fig. 6. Width measurements of the η_c meson

Table 1. Number of η_c events and corresponding branching ratios for the individual channels. Preliminary

Process $J/\psi \to \gamma\eta_c$,	Events detected	Product of branching ratios
$\eta_c \to K^+K^-\pi^+\pi^-$	413 ± 54	$(1.5 \pm 0.2 \pm 0.2) \times 10^{-4}$
$\eta_c \to \pi^+\pi^-\pi^+\pi^-$	542 ± 75	$(1.3 \pm 0.2 \pm 0.4) \times 10^{-4}$
$\eta_c \to K^\pm K^0_S\pi^\mp$	609 ± 71	$(2.2 \pm 0.3 \pm 0.5) \times 10^{-4}$
$\eta_c \to \phi\phi$	357 ± 64	$(3.3 \pm 0.6 \pm 0.6) \times 10^{-5}$
$\eta_c \to p\bar{p}$	213 ± 33	$(1.9 \pm 0.3 \pm 0.3) \times 10^{-5}$

Table 2. Branching fractions of the η_c. Preliminary

Process	BES(%)	PDG02(%) [6]
$Br(\eta_c \to K^+K^-\pi^+\pi^-)$	1.2 ± 0.4	$2.0^{+0.7}_{-0.6}$
$Br(\eta_c \to \pi^+\pi^-\pi^+\pi^-)$	1.0 ± 0.5	1.2 ± 0.4
$Br(\eta_c \to K^\pm K^0_S\pi^\mp)$	1.7 ± 0.7	$\frac{1}{3}(5.5 \pm 1.7)$
$Br(\eta_c \to \phi\phi)$	0.25 ± 0.09	0.71 ± 0.28
$Br(\eta_c \to p\bar{p})$	0.15 ± 0.06	0.12 ± 0.04

fraction $Br(J/\psi \to \gamma\eta_c) = (1.3 \pm 0.4)\%$ [6], preliminary η_c branching fractions can be obtained. Table 2 shows the BES results together with the PDG [6] values. The BES $Br(\eta_c \to \phi\phi)$ is smaller than the current PDG value of $(7.1 \pm 2.8) \times 10^{-3}$ and is consistent with Belle [10] and DM2 [11] measurements within errors. Details may be found in [12].

4 $\chi_J \to \Lambda\overline{\Lambda}$

The lowest Fock state expansion (color singlet mechanism, CSM) of charmonium states is insufficient to describe P-wave quarkonium decays. Instead, the next higher Fock state (color octet mechanism, COM) plays an important role [13,14]. A calculation of the partial width of $\chi_{cJ} \to p\overline{p}$ using the COM and a carefully constructed nucleon wave function [15], obtains results in reasonable agreement with

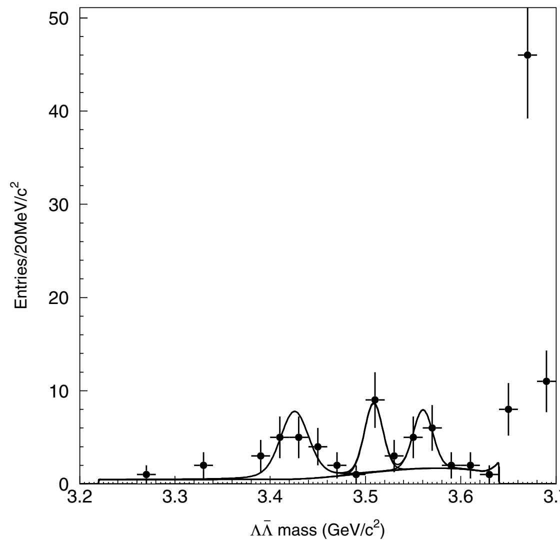

Fig. 7. Mass distribution of $\gamma\Lambda\overline{\Lambda}$ candidates fitted with three resolution smeared Breit-Wigner functions and background, as described in the text

measurements [6]. Generalizing the nucleon wave function to other baryons, the partial widths of many other baryon anti-baryon pairs can be predicted. Among these predictions, the partial width of $\chi_{cJ} \to \Lambda\overline{\Lambda}$ is about half of that of $\chi_{cJ} \to p\overline{p}$ (J=1,2) [15].

Using 14 million $\psi(2S)$ events and making a scatter plot of the $\pi^+\overline{p}$ versus the π^-p invariant mass for events with $\pi^+\pi^-p\overline{p}$ mass between 3.38 GeV/c^2 and 3.60 GeV/c^2, a clear $\Lambda\overline{\Lambda}$ signal is observed. After requiring that both the $\pi^+\overline{p}$ and the π^-p mass lie within twice the mass resolution around the nominal Λ mass, the $\Lambda\overline{\Lambda}$ invariant mass distribution shown in Fig. 7 is obtained. There are clear χ_{c0}, χ_{c1}, and $\chi_{c2} \to \Lambda\overline{\Lambda}$ signals. The highest peak around the $\psi(2S)$ mass is due to $\psi(2S) \to \Lambda\overline{\Lambda}$ with a fake photon.

Background from non $\Lambda\overline{\Lambda}$ events is estimated from the Λ mass sidebands. The background from channels with $\Lambda\overline{\Lambda}$ production, including $\psi(2S) \to \Lambda\overline{\Lambda}$, $\psi(2S) \to \Sigma^0\overline{\Sigma^0}$, $\psi(2S) \to \Lambda\overline{\Sigma^0} + c.c.$, etc. are simulated by Monte Carlo.

Fixing the χ_{c0}, χ_{c1} and χ_{c2} mass resolutions at their Monte Carlo predicted values, and fixing the widths of the three χ_{cJ} states to their world average values [6], the mass spectrum (Fig. 7) was fit between 3.22 and 3.64 GeV/c^2 with three Breit-Wigner functions folded with Gaussian resolutions and background, including a linear term representing the non $\Lambda\overline{\Lambda}$ background and a component representing the $\Lambda\overline{\Lambda}$ background. Figure 7 shows the fit result. The branching ratios of $\chi_{cJ} \to \Lambda\overline{\Lambda}$ obtained are

$$\mathcal{B}(\chi_{c0} \to \Lambda\overline{\Lambda}) = (4.7^{+1.3}_{-1.2} \pm 1.0) \times 10^{-4},$$

$$\mathcal{B}(\chi_{c1} \to \Lambda\overline{\Lambda}) = (2.6^{+1.0}_{-0.9} \pm 0.6) \times 10^{-4},$$

$$\mathcal{B}(\chi_{c2} \to \Lambda\overline{\Lambda}) = (3.3^{+1.5}_{-1.3} \pm 0.7) \times 10^{-4},$$

where the first errors are statistical and the second are systematic.

The results are in contradiction with the expectations from [15], although the errors are large. There is no prediction for $\mathcal{B}(\chi_{c0} \to \Lambda\overline{\Lambda})$. More detail may be found in [16].

5 Observation of $K_S^0 K_L^0$ in $\psi(2S)$ decays and J/ψ decays

There is a longstanding "$\rho\pi$ puzzle" between J/ψ and $\psi(2S)$ decays in some modes: compared with the corresponding J/ψ decays, many $\psi(2S)$ decay channels are suppressed relative to the pQCD-predicted "12% rule" [17]. Here $\psi(2S) \to K_S^0 K_L^0$ is observed for the first time in the BESII 14 million $\psi(2S)$ event sample, and the branching ratio is used to test the "12% rule" between J/ψ and $\psi(2S)$ decays.

Candidate events are required to have two charged tracks with net charge zero. The two tracks are assumed to be π^+ and π^-, and the fitted intersection of the two tracks is taken as the K_S^0 vertex. After requiring the $\pi^+\pi^-$ invariant mass within twice the mass resolution around the nominal K_S^0 mass and a K_S^0 decay length in the transverse plane longer than 1 cm, the K_S^0 momentum distribution, shown in Fig. 8, is obtained. Also shown are the K_S^0 mass side band events and Monte Carlo simulated backgrounds. The signal peak at 1.77 GeV is fitted with a Gaussian, and the background below the peak is fitted with an exponential function. The preliminary branching ratio obtained is $(5.24 \pm 0.47 \pm 0.48) \times 10^{-5}$. This branching ratio, together with results for $\psi(2S) \to \pi^+\pi^-$ and $\psi(2S) \to K^+K^-$, have been used to extract the relative phase between the three-gluon and the one-photon annihilation amplitudes of $\psi(2S)$ decays to pseudoscalar meson pairs. It is found that a phase around $\pm 90°$ can explain the result [18].

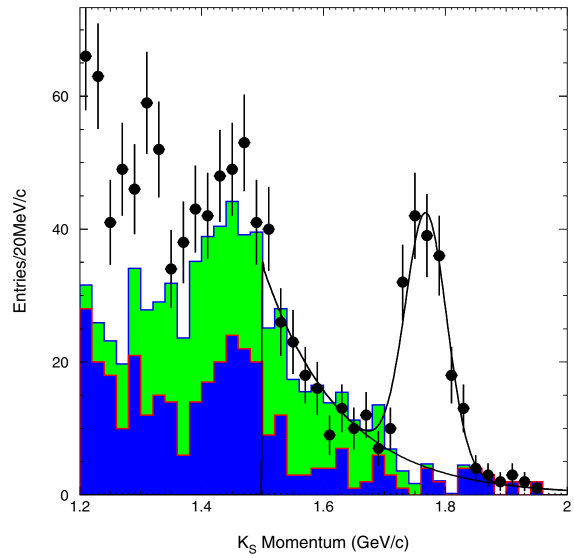

Fig. 8. The K_S^0 momentum distribution in the $\psi(2S) \to K_S^0 K_L^0$. The *dots* with error bars are data, the *dark shaded histogram* is from K_S^0 mass side band events, and the *light shaded histogram* is the Monte Carlo simulated background. The *curve* shown in the plot is the best fit of the distribution

With a similar analysis using the BESII 58 million J/ψ events, we also measured the branching ratio of $J/\psi \to K_S^0 K_L^0$. The K_S^0 momentum distribution in $J/\psi \to K_S^0 K_L^0$ decays is shown in Fig. 9. The preliminary branching ratio of $J/\psi \to K_S^0 K_L^0$ is $(1.82 \pm 0.04 \pm 0.13) \times 10^{-4}$. This result is significantly larger than the world average of $((1.08 \pm 0.14) \times 10^{-4})$ [6]. Using the branching ratio of $\psi(2S) \to K_S^0 K_L^0$, and considering the common errors which cancel out in the calculation of the ratio of the two branching ratios, one obtains

$$Q_h = \frac{B(\psi(2S) \to K_s^0 K_L^0)}{B(J/\psi \to K_s^0 K_L^0)} = (28.2 \pm 3.7)\%. \qquad (1)$$

This number deviates from the pQCD predicted "12% rule" by more than four sigma. Most interesting is that this channel is enhanced in $\psi(2S)$ decays, while in almost all other channels which deviate from the "12% rule", $\psi(2S)$ decays are suppressed. These results are preliminary. More detail may be found in [19] and [20].

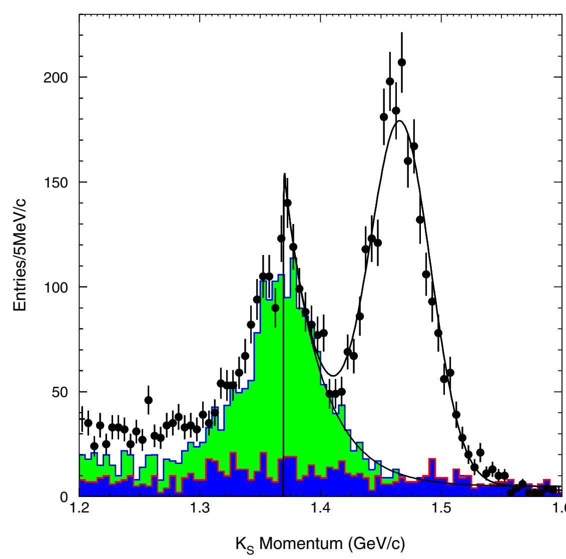

Fig. 9. The K_S^0 momentum distribution in $J/\psi \to K_S^0 K_L^0$

6 Search for $\psi(3770)$ non-$D\bar{D}$ decay to $\pi^+\pi^- J/\psi$

The $\psi(3770)$ resonance is believed to be a mixture of 2^3S_1 and 1^3D_1 states of the $c\bar{c}$ system [21]. Since its mass is above open charm-pair threshold and its width is two orders of the magnitude larger than that of the $\psi(2S)$, it is thought to decay almost entirely to pure $D\bar{D}$ [22]. However, recently some theoretical calculations point out that $\psi(3770)$ could decay to non-$D\bar{D}$ final states [23].

Here, we report evidence for $\psi(3770) \to \pi^+\pi^- J/\psi$ based on 8.0 ± 0.5 pb^{-1} of data taken in the cm energy region around 3.773 GeV with BESII. Another source of $\pi^+\pi^- J/\psi$ is from the radiative return process (due to initial state radiation (ISR)) to the $\psi(2S)$ followed by $\psi(2S) \to \pi^+\pi^- J/\psi$. We developed a new generator *isrpsi* which includes production of J/ψ, $\psi(2S)$ and other resonances due to radiative return. The Monte Carlo sim-

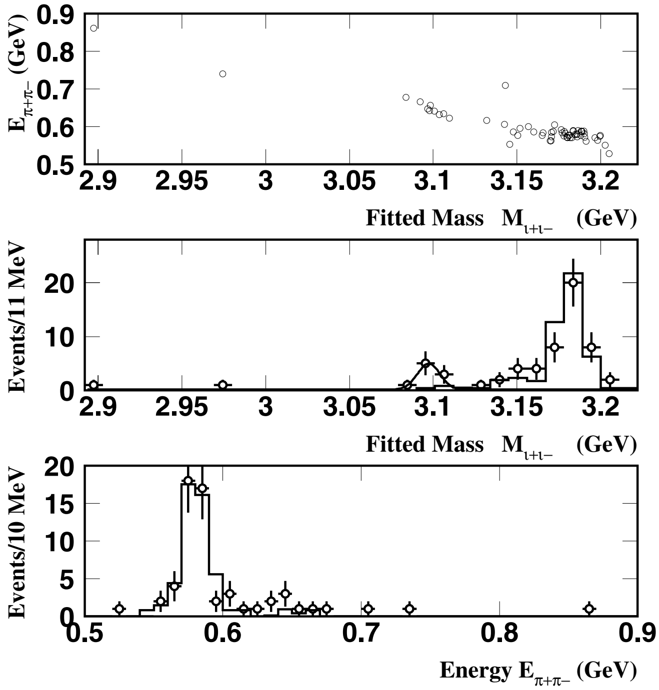

Fig. 10. Scatter plot of the measured $\pi^+\pi^-$ energies versus the fitted l^+l^- masses. There are two clusters. The cluster whose energy is around 0.65 GeV is mostly composed of signal events from $\psi(3770) \to \pi^+\pi^- J/\psi$, while the events whose energies are around 0.57 GeV are due to radiative return events. The projections are shown in the *middle* and *bottom plots*. The *open circles* are data, the histograms are the results of the Monte Carlo simulation for $\psi(2S) \to \pi^+\pi^- J/\psi$, and the *solid smooth curve* is the fit to the data

ulation includes leading-log-order radiative return, where the cm energies after ISR are generated according to [24].

To search for the decay of $\psi(3770) \to \pi^+\pi^- J/\psi$ and $J/\psi \to e^+e^-$ or $\mu^+\mu^-$, $e^+e^-\pi^+\pi^-$ and $\mu^+\mu^-\pi^+\pi^-$ candidate events are selected. They are required to have four charged tracks with zero total charge.

Figure 10 shows a scatter plot of the $\pi^+\pi^-$ energies versus the fitted masses of the l^+l^- after a four constraint fit to the process $\psi(3770) \to \pi^+\pi^- J/\psi$. In the middle sub-figure, the higher mass peak is due to radiative return to the $\psi(2S)$ followed by $\psi(2S) \to \pi\pi J/\psi$. This peak is shifted to 3.18 GeV because E_{cm} is set to 3.773GeV in the kinematic fitting. The fit to this peak yields a total of 2.2 ± 0.4 background events near the signal peak at 3.097 GeV, out of the 9.0 ± 3.0 events. After background subtraction, 6.8 ± 3.0 signal events remain. The branching fraction for the non-$D\bar{D}$ decay $\psi(3770) \to \pi^+\pi^- J/\psi$ is measured to be

$$BF(\psi(3770) \to \pi^+\pi^- J/\psi) = (0.59 \pm 0.26 \pm 0.16)\%, \quad (2)$$

where the first error is statistical and the second systematic. Using the total width of the $\psi(3770)$ resonance from the PDG [6], this branching ratio corresponds to a partial width of

$$\Gamma(\psi(3770) \to \pi^+\pi^- J/\psi) = (139 \pm 61 \pm 41)\ \text{keV}. \quad (3)$$

More detail may be found in [25]. These results are preliminary.

References

1. J.Z. Bai et al., (BES Collab.): Nuc. Inst. Meth. A **344**, 319 (1994)
2. J.Z. Bai et al., (BES Collab.): Nuc. Inst. Meth. A **458**, 627 (2001)
3. A. Antonelli et al.: Nucl. Phys. B **517**, 3 (1998)
4. G. Bardin et al.: Nucl. Phys. B **411**, 3 (1994)
5. J.Z. Bai et al., (BES Collab.): Phys. Rev. Lett. **91**, 022001 (2003)
6. K. Hagiwara et al.: Phys. Rev. D **66**, 010001 (2002)
7. J.Z. Bai et al., (BES Collab.): Phys. Rev. D **60**, 72001 (1999)
8. J.Z. Bai et al., (BES Collab.): Phys. Rev. D **62**, 72001 (2000)
9. J.Z. Bai et al., (BES Collab.): Phys. Lett. B **555**, 174 (2003)
10. H.-C Huang et al., (Belle Collaboration): hep-ex/0305068
11. D. Bisello et al., (DM2 Collaboration): Nucl. Phys. B **350**, 1 (1991)
12. J.Z. Bai et al., (BES Collab.): submitted to Phys. Lett. B, hep-ex/0308073 (2003)
13. See, for example G.T. Bodwin, E. Braaten, and G.P. Lepage: Phys. Rev. D **51**, 1125 (1995); Han-Wen Huang and Kuang-Ta Chao: Phys. Rev. D **54**, 6850 (1996); J. Bolz, P. Kroll, and G.A. Schuler: Phys. Lett. B **392**, 198 (1997)
14. J.Z. Bai et al., (BES Collab.): Phys. Rev. Lett. **81**, 3091 (1998)
15. S.M. Wong: Eur. Phys. J. C **14**, 643 (2000)
16. J.Z. Bai et al., (BES Collab.): Phys. Rev. D **67**, 112001 (2003)
17. J.Z. Bai et al., (BES Collab.): Phys. Rev. D **67**, 052002 (2003)
18. C.Z. Yuan, P. Wang, and X.H. Mo: Phys. Lett. B **567**, 73 (2003)
19. J.Z. Bai et al., (BES Collab.): submitted to Phys. Rev. Lett., hep-ex/0310024 (2003)
20. J.Z. Bai et al., (BES Collab.): submitted to Phys. Rev. D, hep-ex/0310023 (2003)
21. P.A. Rapidis et al., (MARK-I Collaboration): Phys. Rev. Lett. **39**, 526 (1978)
22. W. Bacino et al.: Phys. Rev. Lett. **40**, 671 (1978)
23. H.J. Lipkin: Phys. Lett. B **179**, 278 (1986); Y.P. Kuang: Phys. Rev. D **65**, 094024 (2002)
24. E.A. Kuraev and V.S. Fadin: Yad Fiz **41**, 377 (1985); Sov. J. Nucl. Phys. **41**, 466 (1985)
25. J.Z. Bai et al., (BES Collab.): hep-ex/0307028 (2003)