Recent charmonium results from BES

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Abstract. Using 58 million $J/\psi$ decays, we have investigated the $p\bar{p}$ invariant mass spectrum in the radiative decay $J/\psi \rightarrow \gamma p\bar{p}$ and observe a prominent structure with mass near $2m_p$. Fitting with an $S$-wave Breit-Wigner, we obtain a peak mass of $M = 1859^{+3}_{-10}^{+25}_{-25}$ (stat) MeV/$c^2$. $J/\psi \rightarrow \gamma \eta_c$ decays from the same sample are used to determine the mass, width, and hadronic branching ratios of the $\eta_c$. From a sample of 14 million $\psi(2S)$ events, the first observation of $\chi_{cJ}(J=0,1,2)$ decays to $Λ\bar{Λ}$ 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 $J/\psi$ 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 $J/\psi$ energy of approximately $5 \times 10^{30}$ cm$^{-2}$s$^{-1}$. BES (BESI) is described in detail in Ref. [1], and the upgraded BES detector (BESII) is described in Ref. [2]. This paper presents some recent results; details may be found in the references.

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

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 $e^+e^- \rightarrow$ hadrons has a narrow dip-like structure at a cm energy of $\sqrt{s} \approx 2m_p$ [3]. In addition, the proton’s time-like magnetic form-factor, determined from high statistics measurements of the $p\bar{p} \rightarrow e^+e^-$ 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 $M_{p\bar{p}} \approx 2m_p$.

Using 58 million $J/\psi$ decays, we have investigated the invariant mass spectrum of $p\bar{p}$ pairs in the radiative process $J/\psi \rightarrow \gamma p\bar{p}$ and observe a peak corresponding to $J/\psi \rightarrow \gamma \eta_c$ 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 $J/\psi \rightarrow \gamma p\bar{p}$ events.

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

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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 Ref. [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 ψ(2S) sample and obtained M_{η_c} = (2975.8 ± 3.0 ± 1.2) MeV [7]. BES also used 7.8 million BESI J/ψ events and obtained M_{η_c} = (2976.6 ± 2.9 ± 1.3) MeV [8]. For the two data sets combined, M_{η_c} = (2976.3 ± 2.1 ± 1.2) MeV and the total width Γ_{η_c} = (11.0 ± 8.1 ± 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/ψ → γη_c, with η_c → p\bar{p}, K^+K^−π^+π^−, π^+π^−π^+π^−, K^+K^0\bar{K}^0π^+, and φφ. Events are selected using particle identification and kinematic fitting. Figs. 3 and 4 show the mass distributions in the η_c mass region for J/ψ → γη_c, η_c → p\bar{p}, and η_c → K^+K^−π^+π^−, respectively. Fitting the five decay channels simultaneously, we obtain M_{η_c} = (2977.5 ± 1.0 ± 1.2) MeV and Γ_{η_c} = (17.0 ± 3.7 ± 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 Ref. [9].

### 4 χ_J → Λ\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
Table 1. Number of $\eta_c$ events and corresponding branching ratios for the individual channels. Preliminary.

| Process | Events detected | Product of branching ratios |
|---------|----------------|-----------------------------|
| $J/\psi \to \gamma \eta_c$ | 413 ± 54 | (1.5 ± 0.2 ± 0.2) $\times 10^{-4}$ |
| $\eta_c \to K^+ K^- \pi^+ \pi^-$ | 542 ± 75 | (1.3 ± 0.2 ± 0.4) $\times 10^{-4}$ |
| $\eta_c \to K^+ K^0 \bar{K}^0$ | 609 ± 71 | (2.2 ± 0.3 ± 0.5) $\times 10^{-4}$ |
| $\eta_c \to \phi \phi$ | 357 ± 64 | (3.3 ± 0.6 ± 0.6) $\times 10^{-7}$ |
| $\eta_c \to pp$ | 213 ± 33 | (1.9 ± 0.3 ± 0.3) $\times 10^{-9}$ |

state (color octet mechanism, COM) plays an important role [13,14]. A calculation of the partial width of $\chi_{cJ} \to pp$ using the COM and a carefully constructed nucleon wave function [15], obtains results in reasonable agreement with 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 $\chi_{cJ} \to \Lambda\bar{\Lambda}$ is about half of that of $\chi_{cJ} \to pp \ (J=1,2)$ [15].

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

Table 2. Branching fractions of the $\eta_c$. Preliminary.

| Process | BES(%) | PDG02(%) |
|---------|--------|----------|
| $Br(\eta_c \to K^+ K^- \pi^+ \pi^-)$ | 1.2 ± 0.4 | 2.0$^{+0.4}_{-0.3}$ |
| $Br(\eta_c \to \pi^+ \pi^- \pi^+ \pi^-)$ | 1.0 ± 0.5 | 1.2 ± 0.4 |
| $Br(\eta_c \to K^+ K^0 \bar{K}^0)$ | 1.7 ± 0.7 | (5.5 ± 1.7) |
| $Br(\eta_c \to \phi \phi)$ | 0.25 ± 0.09 | 0.71 ± 0.28 |
| $Br(\eta_c \to pp)$ | 0.15 ± 0.06 | 0.12 ± 0.04 |

Fig. 5. Mass measurements of the $\eta_c$ meson.

Fig. 6. Width measurements of the $\eta_c$ meson.

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

Background from non $\Lambda\bar{\Lambda}$ events is estimated from the $\Lambda$ mass sidebands. The background from channels with $\Lambda\bar{\Lambda}$ production, including $\psi(2S) \to \Lambda\bar{\Lambda}$, $\psi(2S) \to \Sigma^0\Sigma^0$, $\psi(2S) \to \Lambda\bar{\Lambda} + c.c.$, etc. are simulated by Monte Carlo. Fixing the $\chi_{c0}$, $\chi_{c1}$ and $\chi_{c2}$ mass resolutions at their Monte Carlo predicted values, and fixing the widths of the three $\chi_{cJ}$ states to their world average values [6], the mass spectrum (Fig. 7) was fit between 3.22 and 3.64 GeV/c² with three Breit-Wigner functions folded with Gaussian resolutions and background, including a linear term representing the non $\Lambda\bar{\Lambda}$ background and a component representing the $\Lambda\bar{\Lambda}$ background. Fig. 7 shows the fit result. The branching ratios of $\chi_{cJ} \to \Lambda\bar{\Lambda}$ obtained are

$$B(\chi_{c0} \to \Lambda\bar{\Lambda}) = (4.7^{+1.3}_{-1.2} \pm 1.0) \times 10^{-4},$$
$$B(\chi_{c1} \to \Lambda\bar{\Lambda}) = (2.6^{+1.0}_{-0.9} \pm 0.6) \times 10^{-4},$$
$$B(\chi_{c2} \to \Lambda\bar{\Lambda}) = (3.3^{+1.5}_{-1.3} \pm 0.7) \times 10^{-4},$$
5 Observation of $K_S^0 K_L^0$ in $\psi(2S)$ decays and $J/\psi$ decays

There is a longstanding "$\rho \pi$ puzzle" between $J/\psi$ and $\psi(2S)$ decays in some modes: compared with the corresponding $J/\psi$ decays, many $\psi(2S)$ decay channels are suppressed relative to the pQCD predicted "12% rule" [17]. Here $\psi(2S) \rightarrow K_S^0 K_L^0$ 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 $J/\psi$ and $\psi(2S)$ decays.

Candidate events are required to have two charged tracks with net charge zero. The two tracks are assumed to be $\pi^+$ and $\pi^-$, 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 Figure 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 $\psi(2S) \rightarrow \pi^+\pi^-$ and $\psi(2S) \rightarrow K^+K^-$, 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 $\pm 90^\circ$ can explain the result [18].

With a similar analysis using the BESII 58 million $J/\psi$ events, we also measured the branching ratio of $J/\psi \rightarrow K_S^0 K_L^0$. The $K_S^0$ momentum distribution in $J/\psi \rightarrow K_S^0 K_L^0$ decays is shown in Figure 9. The preliminary branching ratio of $J/\psi \rightarrow K_S^0 K_L^0$ 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 $\psi(2S) \rightarrow K_S^0 K_L^0$, and considering the common errors which cancel out in the calculation of the ratio of the two branching ratios, one obtains

$$Q_h = \frac{B(\psi(2S) \rightarrow K_S^0 K_L^0)}{B(J/\psi \rightarrow K_S^0 K_L^0)} = (28.2 \pm 3.7)\%.$$ (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 Refs. [19] and [20].

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 $2^3 S_1$ and $1^3 D_1$ 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 $\psi(3770) \rightarrow \pi^+\pi^-J/\psi$ based on $8.0 \pm 0.5 pb^{-1}$ 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 $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$. We developed a new generator isrpsi which includes production of $J/\psi$, $\psi(2S)$ and other resonances due to radiative return. The Monte Carlo simulation includes leading-log-order radiative return, where the cm energies after ISR are generated according to Ref. [24].

To search for the decay of $\psi(3770) \rightarrow \pi^+\pi^- J/\psi$ and $J/\psi \rightarrow e^+e^-$ 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 $l^+l^-$ masses. There are two clusters. The cluster whose energy is around 0.65 GeV is mostly composed of signal events from $\psi(3770) \rightarrow \pi^+\pi^- J/\psi$, 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 $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$, and the solid smooth curve is the fit to the data.

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

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