HEAVY FLAVOR, QUARKONIUM PRODUCTION AND DECAY

XIAOYAN SHEN

Institute of High Energy Physics, Chinese Academy of Science

Beijing 100049, P. R. China

E-mail: shenxy@ihep.ac.cn

Recent experimental results on quarkonium physics are reviewed. In particular, the new observed particles since last one or two years, such as $X(1835)$, $X(3872)$, $X(3940)$, $Y(3940)$ and $Y(4260)$ are discussed, the latest data on double charmonium production, heavy hadron spectroscopy and quarkonia decays are presented.

1 Introduction

The simplest QCD potential, the so called "Cornell" potential, can be written as:

$$V(r) = -\frac{4}{3} \frac{\alpha_s}{r} + k\dot{r}.$$

The first term describes the one-gluon exchange, dominating at short distances (< 0.1 fm) with large momentum transfers. This is the asymptotically "free" regime where the α_s is small and the perturbative calculations can be performed. The second term, important at large distances (> 1 fm) with low momentum transfers, leads to the "confinement" and is in a regime where the α_s is large, making the calculation non-perturbative.

QCD has been tested extensively at the high momentum transfer by lots of high precision experiments. At low energy, it is difficult to be tested due to the non-perturbative nature. Quarkonia, the bound states of quark and its antiquark, are the QCD equivalents of positronium (e^+e^-) in QED. Quarkonia form the simplest strongly interacting systems with only two constituents (unlike baryons) and identical flavor (unlike mesons with "open" flavor). Light quarkonia are highly relativistic. They also contain mixtures of quarks of different flavors and so can be easily fall apart into other mesons. Charmonium ($c\bar{c}$) is the first heavy quarkonium discovered and is less relativistic. Bottomonium ($b\bar{b}$) is heavier, therefore is less non-

relativistic and has a large number of long-lived states. The toponium system would have been completely non-relativistic. However, the weak decays will be dominant over the strong decays in such systems. Therefore, charmonium and bottomonium play a special role in probing the strong interactions. The properties of charmonia and bottomonia, and their productions and decays are good labs. for QCD in both perturbative and non-perturbative regimes.

Firstly, the new observations of $X(1835)$, $X(3940)$, $Y(3940)$ and $Y(4260)$ are reported. Then, the latest data on heavy quarkonium production, in particular the big discrepancy on double charmonium production between data and theory are presented. Recent experimental heavy hadron spectroscopy results, including the results from η'_c , h_c and $X(3872)$ are reviewed. Also reported are some latest experimental results in quarkonium decays, such as the production of σ and κ , as well as the non- $D\bar{D}$ decays of $\psi(3770)$.

2 New observations

There are long-standing predictions of baryonium states¹, multi-quark states, $q\bar{q}$ -gluon hybrids and glueballs. These states have been searched for by many experiments for many years. However, none of them is identified after all the efforts. Recently there has been a revival of interest in the possible existence of the states of non- $q\bar{q}$ or non- qqq . Reported

below are the new observations in searching for such states.

2.1 The observation of $X(1835)$ in $J/\psi \rightarrow \gamma\eta'\pi^+\pi^-$ at BESII

An anomalous enhancement near the mass threshold in the $p\bar{p}$ invariant mass spectrum from $J/\psi \rightarrow \gamma p\bar{p}$ decays was reported by the BESII experiment². This enhancement was fitted with a sub-threshold S -wave Breit-Wigner resonance function with a mass $M = 1859^{+3+5}_{-10-25}$ MeV/ c^2 , a width $\Gamma < 30$ MeV/ c^2 (at the 90% C.L.) and a product branching fraction (BF) $B(J/\psi \rightarrow \gamma X) \cdot B(X \rightarrow p\bar{p}) = (7.0 \pm 0.4(stat)^{+1.9}_{-0.8}(syst)) \times 10^{-5}$. This surprising experimental observation has stimulated a number of theoretical speculations^{3,4,5,6,7,8} and motivated the subsequent experimental observation of a strong $p\bar{\Lambda}$ mass threshold enhancement in $J/\psi \rightarrow pK^-\bar{\Lambda}$ decay⁹. Among various theoretical interpretations of the $p\bar{p}$ mass threshold enhancement, the most intriguing one is that of a $p\bar{p}$ bound state (or baronium)^{3,1,6}, which has been the subject of many experimental searches¹⁰.

If such a structure is interpreted as a $p\bar{p}$ bound states, it is desirable to observe this state in other decay modes. Possible decay modes for a $p\bar{p}$ bound state, suggested in Ref.^{5,6}, include $\pi^+\pi^-\eta'$.

The $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$ decay, with η' being tagged in its two decay modes, $\eta' \rightarrow \pi^+\pi^-\eta(\eta \rightarrow \gamma\gamma)$ and $\eta' \rightarrow \gamma\rho$, is analyzed based on 5.8×10^7 J/ψ events collected at BESII.

Figure 1(a) shows the $\pi^+\pi^-\eta$ invariant mass distribution. The η' signal is clearly seen. The $\pi^+\pi^-\eta'$ invariant mass spectrum for the selected events is shown in Fig. 1(b), where a peak at a mass around 1835 MeV/ c^2 is observed (named $X(1835)$). The $\gamma\rho$ invariant mass distribution also shows a clear η' signal (Fig. 1 (c)). A peak near 1835 MeV/ c^2 is evident in the $\pi^+\pi^-\eta'$ invariant mass spec-

Figure 1. Invariant mass distributions for selected $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$ candidate events: (a) The $\pi^+\pi^-\eta$ invariant mass distribution. (b) The $\pi^+\pi^-\eta'$ invariant mass distribution with $\eta' \rightarrow \pi^+\pi^-\eta$. (c) The $\gamma\rho$ invariant mass distribution. (d) The $\pi^+\pi^-\eta'$ invariant mass distribution with $\eta' \rightarrow \gamma\rho$. The open histograms are data and the shaded histograms represent $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$ phase-space MC events (with arbitrary normalization).

trum (Fig. 1 (d)).

The combined $\pi^+\pi^-\eta'$ spectrum with ($\eta' \rightarrow \pi^+\pi^-\eta$) and ($\eta' \rightarrow \gamma\rho$) is fitted with a Breit-Wigner (BW) function convoluted with a Gaussian mass resolution function and a smooth polynomial background function. The BW mass and width of $X(1835)$ obtained from the fit (shown in Fig. 2) are $M = 1833.7 \pm 6.1$ MeV/ c^2 and $\Gamma = 67.7 \pm 20.3$ MeV/ c^2 , respectively. The statistical significance for the signal is 7.7σ . The mass and width of the $X(1835)$ are not consistent with any known particle¹¹. The product branching fractions is determined to be

$$B(J/\psi \rightarrow \gamma X(1835)) \cdot B(X(1835) \rightarrow \pi^+\pi^-\eta') \\ = (2.2 \pm 0.4 \pm 0.4) \times 10^{-4}$$

The measured $X(1835)$ mass is consistent with the mass obtained from the $J/\psi \rightarrow \gamma p\bar{p}$ channel, while the width is higher by 1.9σ than the upper limit on the width reported in Ref.². However, the refitted mass and width of $p\bar{p}$ threshold enhancement, after including the final state interaction effect, are consistent with those of $X(1835)$.

Figure 2. The $\pi^+\pi^-\eta'$ invariant mass distribution for selected events from the $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'(\eta' \rightarrow \pi^+\pi^-\eta, \eta \rightarrow \gamma\gamma)$ and $J/\psi \rightarrow \pi^+\pi^-\eta'(\eta' \rightarrow \gamma\rho)$ analyses. The solid curve is the fit and the dashed curve indicates the background function.

Figure 3. $B \rightarrow K\omega J/\psi$ signal yields vs $M(\omega J/\psi)$. The curve in (a) indicates the result of a fit that includes only a phase-space-like threshold function. The curve in (b) shows the result of a fit that includes an S -wave Breit-Wigner resonance term.

2.2 Near $\omega J/\psi$ threshold enhancement $Y(3940)$ in $B \rightarrow K\omega J/\psi$ at Belle

B meson decays are a prolific source of $c\bar{c}$ pairs and the large B meson samples produced at B -factories are providing opportunities to search for missing $c\bar{c}$ charmonium mesons as well as more complex states.

Based on a 253 fb^{-1} data sample that contains 275 million $B\bar{B}$ pairs collected with the Belle detector, a study of the $\omega J/\psi$ system produced in exclusive $B \rightarrow K\omega J/\psi$ decays is performed.

The B -meson signal yields from the binned one-dimensional fits to the M_{bc} and ΔE distributions for events in different $M(\omega J/\psi)$ intervals are plotted in Figs. 3(a) and (b). Here, M_{bc} , the beam constrained

mass, is equal to $\sqrt{E_{\text{beam}}^2 - p_B^2}$ and ΔE , the energy difference, is $E_{\text{beam}} - E_B$, with E_{beam} representing the cms beam energy, p_B the vector sum of the cms momenta of the B meson decay products and E_B their cms energy sum.

An enhancement, denoted as $Y(3940)$, is evident around $M(\omega J/\psi) = 3940 \text{ MeV}$. The curve in Fig. 3(a) is the result of a fit with a threshold function of the form $f(M) = A_0 q^*(M)$, where $q^*(M)$ is the momentum of the daughter particles in the $\omega J/\psi$ rest frame. This functional form accurately reproduces the threshold behavior of Monte Carlo simulated $B \rightarrow K\omega J/\psi$ events that are generated uniformly distributed over phase-space. The fit quality to the observed data points is poor ($\chi^2/d.o.f. = 115/11$), indicating a significant deviation from phase-space.

Figure. 3(b) shows the results of a fit where an S -wave Breit-Wigner (BW) function is included to represent the enhancement. The fit, which has $\chi^2/d.o.f. = 15.6/8$ (CL = 4.8%), yields the mass and width of the signal to be $M = 3943 \pm 11 \pm 13 \text{ MeV}$ and $\Gamma = 87 \pm 22 \pm 26 \text{ MeV}$. The statistical significance of $Y(3940)$ is 8.1σ and the product branching fraction is

$$\begin{aligned} \mathcal{B}(B \rightarrow KY(3940))\mathcal{B}(Y(3940) \rightarrow \omega J/\psi) \\ = (7.1 \pm 1.3 \pm 3.1) \times 10^{-5} \end{aligned}$$

This $Y(3940)$ peaks above $D\bar{D}^*$. It is expected that a $c\bar{c}$ charmonium meson with this mass would dominantly decay to $D\bar{D}$ and/or $D\bar{D}^*$. While for the $c\bar{c}$ -gluon hybrid charmonium states, which were first predicted in 1978¹² and are expected to be produced in B meson decays¹³, their decays to $D^{(*)}\bar{D}^{(*)}$ meson pairs are forbidden or suppressed. Therefore, whether $Y(3940)$ can decay to $D\bar{D}$ and/or $D\bar{D}^*$ or not is crucial to identify its being a hybrid charmonium or a conventional charmonium state.

2.3 Observation of $X(3940)$ in e^+e^- annihilation at $\sqrt{s} \approx 10.6$ GeV at Belle

The double charmonium production process of $e^+e^- \rightarrow J/\psi + X$ is investigated using the integrated luminosity of 350 fb^{-1} data sample collected by the Belle detector at the $\Upsilon(4S)$ resonance and nearby continuum. The J/ψ is reconstructed from its $\ell^+\ell^-$ decays. A partial correction for final state radiation and bremsstrahlung energy loss is performed by including the four-momentum of every photon detected within a 50 mrad cone around the electron direction in the e^+e^- invariant mass calculation.

The recoil mass spectrum of J/ψ in inclusive $e^+e^- \rightarrow J/\psi X$ for the data is shown in Fig. 4. In addition to the three previously observed peaks, the η_c , χ_{c0} , $\eta_c(2S)$, another significant peak can be seen around a mass of $3.94 \text{ GeV}/c^2$.

A fit to this spectrum that includes three known (η_c , χ_{c0} , $\eta_c(2S)$) and one new ($X(3940)$) charmonium states is performed. In this fit, the mass positions for the η_c , χ_{c0} , $\eta_c(2S)$ and $X(3940)$ are free parameters. The signal function for the $X(3940)$ is a convolution of the Monte Carlo line shape, with assumed zero width, with a Breit-Wigner function. The background is parametrized by a second order polynomial function and a threshold term ($\sqrt{M_{\text{recoil}}(J/\psi) - 2M_D}$) to account for a possible contribution from $e^+e^- \rightarrow J/\psi D^{(*)}\bar{D}^{(*)}$. The mass of $X(3940)$ is measured to be $3.936 \pm 0.006 \pm 0.006 \text{ GeV}/c^2$ and the width less than $52 \text{ MeV}/c^2$ at 90% C.L.. The statistical significance of the signal is 5σ .

A search for $X(3940)$ decaying into $D\bar{D}$ and $D^*\bar{D}$ final states is performed. The decay $X(3940) \rightarrow D^*\bar{D}$ is found to be the dominant decay mode with a measured branching fraction of $96_{-32}^{+45} \pm 22\%$. The upper limits for the decay $X(3940) \rightarrow D\bar{D}$ and $X(3940) \rightarrow J/\psi\omega$ are set to be less than 41% and 26% at 90%

Figure 4. The distribution of masses recoiling against the reconstructed J/ψ in inclusive $e^+e^- \rightarrow J/\psi X$ events. The enhancements correspond to the η_c , χ_{c0} , $\eta_c(2S)$ and a new state, $X(3940)$. The curve represents the fit.

C.L., respectively.

2.4 Observation of $Y(4260)$ in the $J/\psi\pi^+\pi^-$ Mass Spectrum around $4.26 \text{ GeV}/c^2$

The initial-state radiation events, $e^+e^- \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-J/\psi$ are studied at BaBar, using an integrated luminosity of 211 fb^{-1} data collected at $\sqrt{s} = 10.58 \text{ GeV}/c^2$, near the peak of the $\Upsilon(4S)$ resonance and 22 fb^{-1} data collected approximately $40 \text{ MeV}/c^2$ below this energy at the SLAC PEP-II asymmetric-energy e^+e^- storage ring. The candidate J/ψ is reconstructed via its decay to e^+e^- and $\mu^+\mu^-$.

The $\pi^+\pi^-J/\psi$ invariant mass spectrum for candidates passing all criteria is shown in Fig. 5 as points with error bars. Events that have an e^+e^- ($\mu^+\mu^-$) mass in the J/ψ sidebands $[2.76, 2.95]$ or $[3.18, 3.25]$ ($[2.93, 3.01]$ or $[3.18, 3.25]$) GeV/c^2 but pass all the other selection criteria are represented by the shaded histogram after being scaled by the ratio of the widths of the J/ψ mass window and sideband regions. An enhancement near $4.26 \text{ GeV}/c^2$ is clearly observed. The Fig. 5 inset includes the ψ' region with a logarithmic scale for comparison.

An unbinned likelihood fit to the $\pi^+\pi^-J/\psi$ mass spectrum is performed using a single relativistic Breit-Wigner signal

Figure 5. The $\pi^+\pi^- J/\psi$ invariant mass spectrum in the range 3.8–5.0 GeV/c^2 and (inset) over a wider range that includes the ψ' . The points with error bars represent the selected data and the shaded histogram represents the scaled data from neighboring e^+e^- and $\mu^+\mu^-$ mass regions. The solid curve shows the result of the single-resonance fit; the dashed curve represents the background component.

function and a second-order polynomial background. The signal function is multiplied by a phase space factor and convoluted with a resolution function. The fit gives 125 ± 23 events with a mass of $4259 \pm 8(\text{stat})_{-6}^{+2}(\text{syst}) \text{ MeV}/c^2$ and a width of $88 \pm 23(\text{stat})_{-4}^{+6}(\text{syst}) \text{ MeV}/c^2$. The statistical significance of the signal is larger than 8σ . At the present level of the statistics, the existence of additional narrow resonance(s) in this region cannot be excluded. The broad structure at around 4.26 GeV/c^2 signifies the presence of one or more previously unobserved $J^{PC} = 1^{--}$ states containing hidden charm.

3 Heavy (flavor) quarkonium production

There are many challenging problems remaining unsolved in heavy quarkonium physics. The effective field theory NRQCD factorization approach provides a systematic method for calculating quarkonium decay and production rates. NRQCD has been very successful in describing many production data, such as the inclusive P-wave quarkonium decays, quarkonium production at Tevatron and quarkonium production in deep inelastic scattering at HERA. However

it is problematic in describing the quarkonium polarization data at the Tevatron, as well as the data from double charmonium production at B factories. One of the most challenging open problems in heavy quarkonium is the large discrepancy of the double charmonium production cross sections measured in e^+e^- annihilation at B factories and the theoretical calculations from NRQCD. Here, I'll only focus on this topic.

Belle¹⁴ observed the double $c\bar{c}$ production in e^+e^- annihilation at $\sqrt{s} \sim 10.6 \text{ GeV}$. The production cross sections measured by Belle are about one order of magnitude higher than those predicted by non-relativistic QCD (NRQCD) calculations^{15,16,17} for $e^+e^- \rightarrow \gamma^* \rightarrow J/\psi c\bar{c}$ reactions, where $c\bar{c}$ is a charmonium state with even C-parity. There have been attempts^{18,19,20,21,22} to reconcile the large discrepancy between the observed cross section and predictions, and the validity of NRQCD approximations has been questioned^{23,24}. It has also been suggested that at least part of the double charmonium production might be due to two virtual-photon interactions²⁰, *i.e.*, $e^+e^- \rightarrow \gamma^*\gamma^* \rightarrow J/\psi c\bar{c}$, where odd C-parity states could be produced. However, Belle's updated results show that the contamination from $e^+e^- \rightarrow \gamma\gamma \rightarrow J/\psi J/\psi$ is small²⁵.

Recently, Belle and Babar presented the new measurements of the cross sections for double charmonium productions, using their 155 fb^{-1} and 124 fb^{-1} data taken at around $\Upsilon(4S)$ peak, respectively.

The recoil mass distribution for events in the J/ψ mass window is shown as points with error bars in Fig. 6. The upper plot is from Belle and the lower from BaBar. The fits to the recoil mass distribution are represented by the solid curves and the backgrounds are shown as the dashed curves.

The fit results are given in Table 1. The cross sections measured by both experiments are much larger than those predicted by many NRQCD calculations.

Figure 6. The points with error bars refer to the events in the J/ψ mass window. The solid curves represent the fit and the dashed curves are for background. The upper plot is for Belle and the lower for BaBar.

Table 1. Comparison of experimental cross-sections with theoretical expectations (fb).

$J/\psi c\bar{c}$	η_c	χ_{c0}
BaBar	$17.6 \pm 2.8^{+1.5}_{-2.1}$	$10.3 \pm 2.5^{+1.4}_{-1.8}$
Belle	$25.6 \pm 2.8 \pm 3.4$	$6.4 \pm 1.7 \pm 1.0$
NRQCD ¹⁶	2.31 ± 1.09	2.28 ± 1.03
NRQCD ¹⁵	5.5	6.9

4 Heavy hadron spectroscopy

4.1 (Re)discovery of $\eta_c(2S)$ and $h_c(1P)$ states

The two $c\bar{c}$ states that are expected to be below open charm threshold are still not well established. They are the radially excited $n = 2$ singlet S state, the $\eta_c(2S)$ meson, and the $n = 1$ singlet P state, the $h_c(1P)$. The observation of these states and the determination of their masses would complete the below-threshold charmonium particle spectrum and provide useful information about the spin-spin part of the charmonium potential.

In 1982, the Crystal Ball collaboration²⁶ reported the observation of a small enhancement at $E_\gamma \sim 91$ MeV in the inclusive photon spectrum from $\psi' \rightarrow \gamma X$ decays, and interpreted it as due to $\eta_c(2S)$ with mass

Table 2. The measured $\eta_c(2S)$ mass

Exp.	reactions	Mass (MeV/ c^2)
Belle(02)	$B \rightarrow K K_s K \pi$	$3654 \pm 6 \pm 8$
Belle(03)	$e^+e^- \rightarrow J/\psi X$	3622 ± 12
BaBar(03)	$\gamma\gamma \rightarrow K_s K^+ \pi^-$	$3630.8 \pm 3.4 \pm 1.0$
CLEO(03)	$\gamma\gamma \rightarrow K_s K^+ \pi^-$	$3642.9 \pm 3.1 \pm 1.5$
Average		3637.7 ± 4.4

3594 ± 5 MeV/ c^2 . This result implies a $\psi(2S)$ - η'_c mass splitting that is considerably larger than heavy-quark potential model expectations. The result was not confirmed by other experiments²⁷.

The Belle experiment reported their observation of the $\eta_c(2S)$ in exclusive $B \rightarrow K K_s K \pi$ decays in 2002²⁸ and then in double charmonium production process $e^+e^- \rightarrow J/\psi X$ ²⁹. Later, both BaBar³⁰ and CLEO³¹ confirmed the observation of $\eta_c(2S)$ in $\gamma\gamma \rightarrow K_s K^+ \pi^-$ reaction. The measured masses of $\eta_c(2S)$ are listed in Table 2. Recent four measurements give consistent results on $\eta_c(2S)$ mass, and the averaged mass of $\eta_c(2S)$ from these experiments is significantly higher than that reported by Crystal Ball Collaboration. The deduced mass splitting of $m_{\psi(2S)} - m_{\eta_c(2S)} = 48.4 \pm 4.5$ MeV/ c^2 is consistent with the heavy quark potential model calculations (42 -103 MeV/ c^2)³² and recent quenched LQCD calculations (40 -74 MeV/ c^2)³³.

As mentioned above, QCD-based potential models have been quite successful in predicting masses, widths, and dominant decays of several charmonium states. The theoretical calculations also made the prediction that the hyperfine splitting $\Delta M_{hf}(\langle M(^3P_J) \rangle - M(^1P_1))$ for P -wave states should be zero. Higher-order corrections are expected to provide no more than a few MeV deviation from this result^{34,35}. Lattice QCD calculations³³ predict $\Delta M_{hf}(1P) = +1.5$ to $+3.7$ MeV, but with uncertainties at the few-MeV level. Larger values of $\Delta M_{hf}(1P)$ could result if the confinement potential had a vector component or if coupled channel effects were im-

portant. In order to discriminate between these possibilities, it is necessary to identify the $h_c(^1P_1)$ state and to precisely measure its mass.

About 20 years ago, R704 experiment at CERN observed a cluster of 5 events in an exclusive scan for $p\bar{p} \rightarrow J/\psi + X$ ³⁶. The mass of this cluster is $3525.4 \pm 0.8 \text{ MeV}/c^2$.

The Crystal Ball Collaboration searched for h_c in the reaction $\psi(2S) \rightarrow \pi^0 h_c, h_c \rightarrow \gamma \eta_c$, but did not see it in the mass range $M(h_c) = (3515 - 3535) \text{ MeV}$ ³⁷. The FNAL E760 Collaboration searched for h_c in the reaction $p\bar{p} \rightarrow h_c \rightarrow \pi^0 J/\psi, J/\psi \rightarrow e^+ e^-$, and reported a statistically significant enhancement with $M(h_c) = 3526.2 \pm 0.2 \pm 0.2 \text{ MeV}$, $\Gamma(h_c) \leq 1.1 \text{ MeV}$ ³⁸. The measurement was repeated twice by the E835 experiment with $\sim 2\times$ and $\sim 3\times$ larger luminosity, but no confirming signal for h_c was observed in $h_c \rightarrow \pi^0 J/\psi$ decay³⁹. E835 experiment also searched for h_c state by a scan of $p\bar{p}$ annihilation cross section for $p\bar{p} \rightarrow h_c \rightarrow \gamma \eta_c \rightarrow \gamma \gamma \gamma$. An excess of $\eta_c \gamma$ events is observed, with a mass of $M = 3525.8 \pm 0.2 \pm 0.2 \text{ MeV}$. It has a probability $\mathcal{P} \sim 0.001$ to arise from background fluctuations⁴⁰.

Using $3.08 \times 10^6 \psi(2S)$ events accumulated with CLEO III and CLEO-c detector at the Cornell Electron Storage Ring, the isospin-violating reaction $e^+ e^- \rightarrow \psi(2S) \rightarrow \pi^0 h_c, h_c \rightarrow \gamma \eta_c, \pi^0 \rightarrow \gamma \gamma$ is studied in exclusive and inclusive η_c decays, and h_c signal is observed in both cases. The statistical significance of h_c is larger than 5σ using a variety of methods to evaluate this quantity.

Table 3 shows the results for inclusive and exclusive analyses for the decay $\psi(2S) \rightarrow \pi^0 h_c \rightarrow \pi^0 \gamma \eta_c$. The combined inclusive and exclusive results give $M(h_c) = 3524.4 \pm 0.6 \pm 0.4 \text{ MeV}$, which is consistent with the spin-weighted average of the χ_{cJ} states.

Table 3. Results of the inclusive and exclusive analyses for the reaction $\psi(2S) \rightarrow \pi^0 h_c \rightarrow \pi^0 \gamma \eta_c$.

	Inclusive	Exclusive
Counts	150 ± 40	17.5 ± 4.5
Significance	$\sim 3.8\sigma$	6.1σ
$M(h_c) \text{ (MeV)}$	$3524.9 \pm 0.7 \pm 0.4$	$3523.6 \pm 0.9 \pm 0.5$
$\mathcal{B}_{\psi} \mathcal{B}_h (10^{-4})$	$3.5 \pm 1.0 \pm 0.7$	$5.3 \pm 1.5 \pm 1.0$

4.2 $X(3872)$

The $X(3872)$ was first observed by Belle⁴¹ in $B^\pm \rightarrow K^\pm(J/\psi \pi^+ \pi^-)$ and then confirmed by CDF⁴², D0⁴³ and BaBar⁴⁴ experiments. The four experiments give consistent mass values of $X(3872)$. The averaged mass of $X(3872)$ is $3871.9 \pm 0.6 \text{ MeV}/c^2$, which is just above $D^0 \bar{D}^{*0}$ threshold ($3871.3 \pm 1.0 \text{ MeV}/c^2$).

Numerous theoretical explanations have been proposed for this high-mass, narrow-width state decaying into $J/\psi \pi^+ \pi^-$. The possibilities include a $c\bar{c}$ charmonium state⁴⁵, $D^0 \bar{D}^{*0}$ molecular state⁴⁶, dominant $1^{++}(2P)$ $c\bar{c}$ component with $D^0 \bar{D}^{*0}/D^{*0} \bar{D}^0$ continuum component⁴⁷, $c\bar{c}g$ hybrid⁴⁸, vector glueball with a small mixture of $c\bar{c}$ ⁴⁹, S -wave threshold enhancement in $D^0 \bar{D}^{*0}$ scattering⁵⁰ and diquark-diquark bound state $cu\bar{c}u$ ⁵¹. The search for more decay modes of $X(3872)$ as well as the determination of its J^{PC} will be helpful in understanding the nature of $X(3872)$.

A more detailed examination of the $X(3872)$ indicates that the $\pi^+ \pi^-$ mass distributions peak near the kinematic upper limit and are consistent with the decay $\rho^0 \rightarrow \pi^+ \pi^-$. If the observed decay is $X(3872) \rightarrow J/\psi \rho^0$ and if these states and their decays obey isospin symmetry, then there must be a $X(3872)^-$, which decays to $J/\psi \rho^-$, and the rate for $B \rightarrow X^- K$ should be twice of that for $B \rightarrow X^0 K$. For this purpose, BaBar has performed a search for the decays of $B^0 \rightarrow X^- K^+$ and $B^- \rightarrow X^- K_s$, where $X^- \rightarrow J/\psi \pi^- \pi^0$ ⁵², using 234M $B\bar{B}$ events. No charged signal, $X^- \rightarrow J/\psi \pi^- \pi^0$, is evi-

dent at 3.872 GeV/c².

BaBar also searched for $X(3872) \rightarrow \eta J/\psi$ with 90M $B\bar{B}$ events and no signal is seen⁵³.

CLEO searched for $X(3872)$ in $\gamma\gamma$ fusion and radiative production data and no evidence is found⁵⁴.

In order to examine the experimental constraints on the possible J^{PC} of $X(3872)$, Belle searched for $B \rightarrow K\gamma J/\psi$ and $K\pi^+\pi^-\pi^0 J/\psi$ decays in a 275M $B\bar{B}$ events sample, accumulated at a center-of-mass system energy of $\sqrt{s} = 10.58$ GeV. In the $\gamma J/\psi$ mass spectrum, a peak around 3872 MeV/c² can be seen, which corresponds to a statistical significance of 4.0σ . The ratio of the decay widths is obtained from the fit as:

$$\Gamma(X \rightarrow \gamma J/\psi)/\Gamma(X \rightarrow \pi^+\pi^- J/\psi) = 0.14 \pm 0.05$$

. The $\pi^+\pi^-\pi^0$ mass spectrum in $B \rightarrow \pi^+\pi^-\pi^0 J/\psi$ also shows the evidence for sub-threshold decay $X(3872) \rightarrow \omega J/\psi$ and the statistical significance is 4.3σ . The ratio of the branching fractions is determined to be:

$$\frac{B(X \rightarrow \pi^+\pi^-\pi^0 J/\psi)}{B(X \rightarrow \pi^+\pi^- J/\psi)} = 1.0 \pm 0.4 \pm 0.3.$$

The evidence of these two decay modes suggests the C parity of $X(3872)$ to be $+1$.

In a search for $X(3872) \rightarrow D^0 \bar{D}^{*0}$ decay in $B \rightarrow K D^0 \bar{D}^{*0}$, with $\bar{D}^{*0} \rightarrow \bar{D}^0 \pi^0$, there is events excess at around 3872 MeV/c² in $D^0 \bar{D}^0 \pi^0$ spectrum. This implies that the 2^{++} is not favored.

The angular distributions of a sample of $X(3872)$, produced in $B \rightarrow K X(3872)$ from 256 pb^{-1} data are analyzed. From the χ^2 test, a 1^{++} $X(3872)$ is favored.

All the results seem to favor a 1^{++} $X(3872)$. However, the statistics is low for the evidences of $X(3872) \rightarrow \gamma J/\psi$, $X(3872) \rightarrow \omega J/\psi$ and $X(3872) \rightarrow D^0 \bar{D}^{*0}$. In the analyses of the angular distributions, the statistics is low to use χ^2 test. Therefore, more data are needed and the confirmation from BaBar is required to finally determine the spin-parity of $X(3872)$.

5 Selected topics from quarkonium decays

5.1 The σ production

There has been evidence for a low mass pole in the early DM2⁵⁵ and BES1⁵⁶ data on $J/\psi \rightarrow \omega\pi^+\pi^-$. A huge event concentration in the $I = 0$ S-wave $\pi\pi$ channel was seen in the region of $m_{\pi\pi}$ around 500-600 MeV in a pp central production experiment⁵⁷. This peak is too large to be explained as background⁵⁸. There have been many studies on the possible resonance structure in $\pi\pi$ elastic scattering⁵⁹. It was later proved that the σ resonance is unavoidable in chiral perturbation theory in order to explain the $\pi\pi$ scattering phase shift data⁶⁰. E791 experiment from FNAL shows the existence of a σ pole with $M = 478_{-23}^{+24} \pm 17$ MeV, $\Gamma = 324_{-40}^{+42} \pm 21$ MeV in $D^+ \rightarrow \pi^+\pi^-\pi^+$ ⁶¹.

BES studied $J/\psi \rightarrow \omega\pi^+\pi^-$ decays based on 58M J/ψ events collected at BESII. Figure 7 shows the $\pi^+\pi^-$ invariant mass spectrum recoiling against ω . In addition to the well known $f_2(1270)$, a broad bump in the low mass region is clearly seen. Two independent partial wave analyses (PWA) are performed and different parametrizations of σ amplitude are used. All give the consistent results for σ pole position. The averaged pole is determined to be $(541 \pm 39 - i(252 \pm 42))$ MeV/c².

Based on 14M $\psi(2S)$ events collected at BESII, a partial wave analysis is performed to $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$, with $J/\psi \rightarrow \mu^+\mu^-$. A severe suppression of the $\pi^+\pi^-$ invariant mass near the $\pi\pi$ threshold is distinctively different from the phase space shape, which suggests the σ production. Using different parametrizations of σ amplitude, the data can be fitted well through a strong cancellation between σ and a contact term. The obtained pole position is $(554 \pm 14 \pm 53) - i(242 \pm 5 \pm 24)$ MeV/c², which is consistent with that from $J/\psi \rightarrow \omega\pi^+\pi^-$.

Figure 7. The $\pi^+\pi^-$ invariant mass recoiling against ω

BaBar made a full amplitude analysis on $B^\pm \rightarrow \pi^\pm \pi^\pm \pi^\mp$ with $210.3 fb^{-1}$ data sample and found that the decays of $B^\pm \rightarrow \pi^\pm \pi^\pm \pi^\mp$ are dominated by decays through the intermediate resonances, such as $\rho^0(770)$ and $\rho^0(1450)$. There is no evidence for the existence of σ .

5.2 The κ production

The κ has been observed in the analyses on $K\pi$ scattering phase shifts by several groups. The observed mass and width are scattered in the ranges from 700 to 900 MeV/c^2 and 550 to 800 MeV/c^2 , respectively, depending on the model used. However, some analyses on $K\pi$ scattering data don't need a κ pole. The E791 experiment at Fermilab reported the evidence of κ in the $D^+ \rightarrow K^+ \pi^+ \pi^-$ ⁶² with the mass and width of $797 \pm 19 \pm 43 \text{ MeV}/c^2$ and $410 \pm 43 \pm 87 \text{ MeV}/c^2$. However, a slightly lower statistics of CLEO $D^0 \rightarrow K^- \pi^+ \pi^0$ data finds no evidence of κ ⁶³. The FOCUS experiment presented evidence for the existence of a coherent $K\pi$ S -wave contribution to $D^+ \rightarrow K^- \pi^+ \mu^+ \nu$ ⁶⁴.

BES performed partial wave analyses to both $J/\psi \rightarrow K^* K \pi$ ⁶⁵ and direct $J/\psi \rightarrow K^+ K^- \pi^+ \pi^-$ processes. The κ are needed in both fits. Fig. 8 is the $K\pi$ invariant mass spectrum which recoils against $K^*(892)$. The crosses are data and histograms represent the PWA fit projection. The shaded area

Figure 8. The $K\pi$ invariant mass recoiling against K^* . The crosses are data and histograms represent the PWA fit projection. The shaded area shows the κ contribution.

shows the κ contribution. The pole of κ from $J/\psi \rightarrow K^* K \pi$ is determined to be $(841 \pm 30^{+81}_{-73}) - i(309 \pm 45^{+48}_{-72}) \text{ MeV}/c^2$.

Both BaBar and Belle made the Dalitz plot analyses of $B \rightarrow K \pi \pi$, but no κ is included in the fit ⁶⁶.

5.3 $\psi(3770)$ non- $D\bar{D}$ decays

$\psi(3770)$ was considered to decay almost entirely to pure $D\bar{D}$ ⁶⁷ because its mass is above the open charm-pair threshold and its width is two orders of magnitude larger than that of $\psi(2S)$. Since $\psi(3770)$ is also believed to be a mixture of the 1^3D_1 and 2^3S_1 states ⁶⁸, other $\psi(2S)$ -like decays for $\psi(3770)$ are expected. Many theoretical calculations ^{69,70,71,72,73} estimated the partial width of $\Gamma(\psi(3770) \rightarrow \pi\pi J/\psi)$. Recently, Kuang ⁷³ obtained the partial width for $\psi(3770) \rightarrow J/\psi \pi^+ \pi^-$ to be in the range of 25 to 113 keV, using Chen-Kuang potential model.

Based on 27.7 pb^{-1} data sample taken in the center-of-mass (c.m.) energy region of 3.738 GeV to 3.885 GeV, BES reported the first evidence of $\psi(3770) \rightarrow J/\psi \pi^+ \pi^-$ with $J/\psi \rightarrow e^+ e^-$ and $\mu^+ \mu^-$ ⁷⁴. Figure 9 shows the dilepton masses determined from the fitted lepton momenta of the accepted events. Two peaks are clearly seen. The lower peak mostly comes from $\psi(3770) \rightarrow J/\psi \pi^+ \pi^-$, while the higher one is produced by the radiative return to the $\psi(2S)$ peak.

Figure 9. The distribution of the fitted dilepton masses for the events of $l^+l^-\pi^+\pi^-$ from the data; the hatched histogram is for $\mu^+\mu^-\pi^+\pi^-$, while the open one is for $e^+e^-\pi^+\pi^-$; the curves give the best fit to the data.

A maximum likelihood fit gives 17.8 ± 4.8 $J/\psi \rightarrow l^+l^-$ signal events. After subtracting the background, $(11.8 \pm 4.8 \pm 1.3)$ $\psi(3770) \rightarrow J/\psi\pi^+\pi^-$ non- $D\bar{D}$ decay events are observed, leading to a branching fraction of $BF(\psi(3770) \rightarrow J/\psi\pi^+\pi^-) = (0.34 \pm 0.14 \pm 0.09)\%$, and a partial width $\Gamma(\psi(3770) \rightarrow J/\psi\pi^+\pi^-) = (80 \pm 33 \pm 23)$ keV, which is consistent with Kuang's estimations⁷³.

With a much larger data sample (an integrated luminosity of $\mathcal{L} = (280.7 \pm 2.8)$ pb⁻¹), CLEO confirmed the non- $D\bar{D}$ decays of $\psi(3770) \rightarrow \pi\pi J/\psi$ with the statistical significances of 13σ and 3.8σ for $\pi^+\pi^-$ and $\pi^0\pi^0$ cases, respectively⁷⁵. More precise branching fractions are obtained to be: $BF(\psi(3770) \rightarrow J/\psi\pi^+\pi^-) = (0.214 \pm 0.25 \pm 0.22)\%$ and $BF(\psi(3770) \rightarrow J/\psi\pi^0\pi^0) = (0.097 \pm 0.035 \pm 0.020)\%$. The partial widths are $\Gamma(\psi(3770) \rightarrow J/\psi\pi^+\pi^-) = (50 \pm 6 \pm 8)$ keV and $\Gamma(\psi(3770) \rightarrow J/\psi\pi^0\pi^0) = (23 \pm 8 \pm 5)$ keV. The $\psi(3770) \rightarrow J/\psi\pi^+\pi^-$ results are consistent with those from BES but with higher precision.

Using the same data sample, CLEO first observed $\psi(3770) \rightarrow \gamma\chi_{c1} \rightarrow \gamma\gamma J/\psi$, with $J/\psi \rightarrow \mu^+\mu^-$ and e^+e^- ⁷⁶. Figure 10 shows the energy of the lower energy photon for the selected $\psi(3770) \rightarrow \gamma\gamma J/\psi$, $J/\psi \rightarrow \mu^+\mu^-$ (top) and $J/\psi \rightarrow e^+e^-$ (bottom). The excess in the χ_{c1} peak represents evidence for $\psi(3770) \rightarrow \gamma\chi_{c1}$ transitions. The fitted sig-

Figure 10. Energy of the lower energy photon for the selected $e^+e^- \rightarrow \gamma\gamma J/\psi$, $J/\psi \rightarrow \mu\mu$ (top) and $J/\psi \rightarrow e^+e^-$ (bottom) events at the $\psi(3770)$ resonance. The solid line shows the fit. The dotted line shows the smooth background. The dashed line shows the total background including the expected background-peaks from radiatively produced tail of the $\psi(2S)$ resonance.

nal amplitudes (for the sum of the dimuon and dielectron samples) are $0.3^{+7.7}_{-0.3}$, 62 ± 11 and 24^{+12}_{-15} events for χ_{c2} , χ_{c1} and χ_{c0} , respectively. The statistical significance of the evidence for χ_{c1} signal is 6.8σ and the decay width of $\psi(3770)$ to $\gamma\chi_{c1}$ is $75 \pm 14 \pm 13$ (keV).

Both CLEO and BES also performed many searches for $\psi(3770)$ non- $D\bar{D}$ decays^{77,78,79,80}. A statistically significant signal is found for $\phi\eta$ ⁷⁷ by CLEO and a suggestive suppression of $\pi^+\pi^-\pi^0$ and $\rho\pi$ is observed by CLEO and BES^{77,79}.

6 Summary

Many new discoveries and new results on heavy quarkonium productions and decays have been recently experimentally revitalized by BES, Belle, BaBar, CLEO, as well as other experiments. This report represents the results including the new observed particles, such as $X(1835)$, $X(3940)$, $Y(3940)$ and $Y(4260)$, further studies of $X(3872)$, the observation of h_c state, heavy flavor production, in particular the double charmonium production from BaBar and Belle, the production of

σ and κ , as well as $\psi(3770)$ non- $D\bar{D}$ decays.

More results on quarkonium are coming in the near future from BESII, CLEO-c, Belle, Babar and the experiments from Fermilab. The BESIII/BEPCII is being constructing and it will start taking physics data in the year of 2008. There is also a proposal for a new dedicated $p\bar{p}$ machine (PANDA at GSI) to explore charmonium physics. We expect more results on quarkonium production and decay to probe the strong interactions.

Acknowledgments

I would like to thank many colleagues from BaBar, Belle, BES, CLEO and the experiments at FNAL for providing me with information contained in this report. I apologize for not being able to discuss all the recent experimental results related to this talk due to the length limitation. I would also like to thank Prof. K.T. Chao and Y.P. Kuang for discussions concerning theoretical aspects.

References

1. I.S. Shapiro, *Phys. Rept.* **35**, 129 (1978); C.B. Dover, M. Goldhaber, *Phys. Rev. D* **15**, 1997 (1977).
2. BES Collaboration, J.Z. Bai *et al.*, *Phys. Rev. Lett.* **91**, 022001 (2003).
3. A. Datta, P.J. O'Donnell, *Phys. Lett. B* **567**, 273 (2003); M.L. Yan *et al.*, hep-ph/0405087; B. Loiseau, S. Wycech, hep-ph/0502127.
4. J. Ellis, Y. Frishman and M. Karliner, *Phys. Lett. B* **566**, 201 (2003); J.L. Rosner, *Phys. Rev. D* **68**, 014004 (2003).
5. C.S. Gao and S.L. Zhu, *Commun. Theor. Phys.* **42**, 844 (2004), hep-ph/0308205.
6. G.J. Ding and M.L. Yan, *Phys. Rev. C* **72**, 015208 (2005).
7. B.S. Zou and H.C. Chiang, *Phys. Rev. D* **69**, 034004 (2003).
8. A. Sibirtsev *et al.*, *Phys. Rev. D* **71**, 054010 (2005).
9. BES Collaboration, M. Ablikim *et al.*, *Phys. Rev. Lett.* **93**, 112002 (2004).
10. For recent reviews of this subject, see E. Klempt *et al.*, *Phys. Rep.* **368**, 119 (2002) and J-M. Richard, *Nucl. Phys. Proc. Suppl.* **86**, 361 (2000).
11. Particle Data Group, S. Eidelman *et al.*, *Phys. Lett. B* **592**, 1 (2004).
12. D. Horn and J. Mandula, *Phys. Rev. D* **17**, 898 (1978).
13. F.E. Close, I. Dunietz, P.R. Page, S. Veseli and H. Yamamoto, *Phys. Rev. D* **57**, 5653 (1987); G. Chiladze, A.F. Falk and A.A. Petrov *Phys. Rev. D* **58**, 034013 (1988); and F.E. Close and S. Godfrey, *Phys. Lett. B* **574**, 210 (2003).
14. Belle Collaboration, K. Abe *et al.*, *Phys. Rev. Lett.* **89**, 142001 (2002).
15. Kui-Yong Liu, Zhi-Guo He and Kuang-Ta Chao, *Phys. Lett. B* **557**, 45 (2003).
16. E. Braaten and J. Lee, *Phys. Rev. D* **67**, 054007 (2003).
17. K. Hagiwara, E. Kou and C.-F. Qiao, *Phys. Lett. B* **570**, 39 (2003).
18. Y. J. Zhang, Y. J. Gao and K. T. Chao, hep-ph/0506076.
19. J.P. Ma and Z.G. Si, *Phys. Rev. D* **70**, 074007 (2004).
20. G. T. Bodwin, J. Lee and E. Braaten, *Phys. Rev. D* **67**, 054023 (2003).
21. G. T. Bodwin, J. Lee and E. Braaten, *Phys. Rev. Lett.* **90**, 162001 (2003).
22. S. J. Brodsky, A. S. Goldhaber and J. Lee, *Phys. Rev. Lett.* **91**, 112001 (2003).
23. A. E. Bondar and V. L. Chernyak, *Phys. Lett. B* **612**, 215 (2005).
24. N. Brambilla *et al.*, hep-ph/0412158.
25. Belle Collaboration, K. Abe *et al.*, *Phys. Rev. D* **70**, 071102 (2004).
26. C. Edwards *et al.* (Crystal Ball Collab.), *Phys. Rev. Lett.* **48**, 70 (1982).
27. T.A. Armstrong *et al.* (E760 Collab.), *Phys. Rev. D* **52**, 4839 (1995); M. Ma-

- suzawa, Ph.D. Thesis, Northwestern Univ. report UMI-94-15774 (1993), unpublished; M. Ambrogiani *et al.*, *Phys. Rev. D* **64**, 052003 (2001); P. Abreu *et al.* (DELPHI), *Phys. Lett. B* **441**, 479 (1998); and M. Acciarri *et al.* (L3), *Phys. Lett. B* **461**, 155 (1999).
28. Belle Collaboration, S.-K. Choi *et al.*, *Phys. Rev. Lett.* **89** (2002) 102001; Erratum-ibid. **89** 129901 (2002).
 29. Belle Collaboration, K. Abe *et al.*, *Phys. Rev. Lett.* **89** 142001 (2002).
 30. BaBar Collaboration, *Phys. Rev. Lett.* **92** 142002 (2004).
 31. CLEO Collaboration, *Phys. Rev. Lett.* **92** 142001 (2004).
 32. E. Eichten and F. Feinberg, *Phys. Rev. D* **23**, 2724 (1981); W. Buchmüller and S. -H. H. Tye, *Phys. Rev. D* **24**, 132 (1981); S. Godfrey and N. Isgur, *Phys. Rev. D* **32**, 189 (1985); Y. Q. Chen and Y. P. Kuang, *Phys. Rev. D* **37**, 1210 (1988); E. J. Eichten and C. Quigg, *Phys. Rev. D* **49**, 5845 (1994); D. Ebert, R. N. Faustov and V. O. Galkin, *Phys. Rev. D* **62**, 034014 (2000).
 33. K. Okamoto, *Phys. Rev. D* **65**, 094508 (2002).
 34. T. Appelquist, R. M. Barnett and K. D. Lane, *Ann. Rev. Nucl. Part. Sci.* **28**, 387 (1978).
 35. S. Godfrey and J. L. Rosner, *Phys. Rev. D* **66**, 014012 (2002).
 36. R704 Collaboration, *Phys. Lett. B* **171**, 135 (1986).
 37. Proceedings of the 17th Rencontre de Moriond Workshop on New Flavors, Les Arcs, France, p. 27 (1982); E. D. Bloom and C. W. Peck, *Ann. Rev. Nucl. Part. Sci.*, **33**, 143 (1983).
 38. E760 Collaboration, *Phys. Rev. Lett.*, **69**, 2337 (1992).
 39. D. N. Joffe, Ph.D. thesis, Northwestern University, hep-ex/0505007
 40. Claudia Patrignani, hep-ex/0410085
 41. Belle Collaboration, *Phys. Rev. Lett.*, **91**, 262001 (2003).
 42. CDF-II Collaboration, *Phys. Rev. Lett.*, **93**, 072001 (2004).
 43. D0 Collaboration, *Phys. Rev. Lett.*, **93**, 162002 (2004).
 44. BaBar Collaboration, *Phys. Rev. D* **71**, 071103 (2005).
 45. E. Eichten, K. Lane, and C. Quigg, *Phys. Rev. Lett.* **89**, 162002 (2002); T. Barnes and S. Godfrey, *Phys. Rev. D* **69**, 054008 (2004).
 46. N. Tornqvist, *Phys. Lett. B* **590**, 209 (2004); M. B. Voloshin, *Phys. Lett. B* **579**, 316 (2004); F. Close and P. Page, *Phys. Lett. B* **578**, 119 (2004); C.Y. Wong, *Phys. Rev. C* **69**, 055202 (2004); E. Braaten and M. Kusunoki, *Phys. Rev. D* **69**, 074005 (2004); E. Swanson, *Phys. Lett. B* **588**, 189 (2004).
 47. C. Meng, Y.J. Gao and K.T. Chao, hep-ph/0506222
 48. F. Close and S. Godfrey, *Phys. Lett. B* **574**, 210 (2003) B.A. Li, *Phys. Lett. B* **605**, 306 (2005).
 49. K.K. Seth, hep-ph/0411122
 50. D.V. Bugg, *Phys. Rev. D* **71**, 016006 (2005).
 51. L. Maiani, F. Piccinini, A.D. Polosa, and V. Riquer, *Phys. Rev. D* **71**, 014028 (2005).
 52. BaBar Collaboration, *Phys. Rev. Lett.*, **93**, 041801 (2004).
 53. BaBar Collaboration, *Phys. Rev. D* **71**, 031501 (2005).
 54. CLEO Collaboration, *Phys. Rev. Lett.*, **94**, 032004 (2005).
 55. J.E. Augustin *et al.*, *Nucl. Phys. B* **320** 1 (1989).
 56. Ning Wu (BES Collaboration), Proceedings of the XXXVIth Rencontres de Moriond, Les Arcs, France, March 17-24, 2001.
 57. D. Alde *et al.*, *Phys. Lett. B* **397** 350 (1997).
 58. T. Ishida *et al.*, Proceedings of Int. Conf. Hadron'95, Manchester, UK,

- World Scientific, 1995.
59. V.E. Markushin and M.P. Locher, *Frascati Phys. Ser.* **15** 229 (1999).
 60. Z. Xiao, H. Q. Zheng, *Nucl. Phys.* **A695** 273 (2001).
 61. E791 Collaboration, *Phys. Rev. Lett.* **86** 770 (2001).
 62. E791 Collaboration, *Phys. Rev. Lett.* **89** 121801 (2002).
 63. CLEO Collaboration, *Phys. Rev.* **D63**, 0900001 (2001)
 64. FOCUS Collaboration, *Phys. Lett.* **B535** 430 (2002)
 65. BES Collaboration, hep-ex/0506055
 66. Belle Collaboration, *Phys. Rev. D* **71**, 092003 (2005), BaBar Collaboration, BABAR-PUB-05/027
 67. W. Bacino *et al.*, DELCO Collaboration, *Phys. Rev. Lett.* **40** 671 (1978).
 68. J.L. Rosner, *Phys. Rev. D* **64**, 094002 (2001).
 69. H.J. Lipkin, *Phys. Lett.* **B179** 278 (1986).
 70. K. Lane, Harvard Report No. HUTP-86/A045, (1986).
 71. Y.P. Kuang and T.M. Yan, *Phys. Rev. D* **24** 2874 (1981).
 72. Y.P. Kuang and T.M. Yan, *Phys. Rev. D* **41** 155 (1990).
 73. Y.P. Kuang, *Phys. Rev. D* **65** 094024 (2002).
 74. BES Collaboration, hep-ex/0307028, *Phys. Lett. B* **605**, 63 (2005).
 75. CLEO collaboration, hep-ex/0508023
 76. CLEO collaboration, hep-ex/0509030
 77. CLEO collaboration, hep-ex/0509011
 78. CLEO collaboration, CLNS 05/1921 (LP2005-443)
 79. BES Collaboration, *Phys. Rev.* **D70** 077101 (2004).
 80. BES Collaboration, hep-ex/0507092

DISCUSSION

Ulrich Wiedner (Uppsala University):

Could you explain in more detail why the enhanced double charmonium production rate could not be explained by J/ψ + glueball production?

Xiaoyan Shen: Belle¹ measured the production and J/ψ helicity angular distributions, $(1 + \alpha_{prod} \cos^2 \theta_{prod})$ and $(1 + \alpha_{heli} \cos^2 \theta_{heli})$, for $e^+e^- \rightarrow J/\psi \eta_c$. The α_{prod} and α_{heli} are measured to be: $\alpha_{prod} = \alpha_{heli} = 0.93^{+0.57}_{-0.47}$. It is consistent with the expectations for the production of $J/\psi \eta_c$ via a single virtual photon ($\alpha_{prod} = \alpha_{heli} = 1$). The prediction for a spin-0 glueball contribution² ($e^+e^- \rightarrow J/\psi G$) to the $J/\psi \eta_c$ peak, $\alpha_{prod} = \alpha_{heli} = -0.87$, is disfavored.

Tord Ekelof (Uppsala University):

I have a question on the X(1834). You said that the X(1860) has 10% branching ratio to $\bar{p}p$ which was an evidence that it is a $\bar{p}p$ bound state. The X(1834) you discovered in this specific decay channel - I don't know how well these 10% can be put into a model but if this lower state the X(1834) should also then have some small branching ratio to $\bar{p}p$, how small would it be-would it be measurable?

Xiaoyan Shen: The large branching ratio of X(1860), $p\bar{p}$ threshold enhancement from $J/\psi \rightarrow \gamma p\bar{p}$, to $p\bar{p}$ indicates X(1860) has a large coupling to $p\bar{p}$. If it is a $p\bar{p}$ bound state below $p\bar{p}$ mass threshold, the theory predicts that its $\eta'\pi^+\pi^-$ decay mode would be the most favorable one^{3,4}.

The mass and width of X(1835) from $J/\psi \rightarrow \gamma \eta'\pi^+\pi^-$ are consistent with those of X(1860). Therefore we think these two states could be the same state.

Jonathan L. Rosner (Uni. of Chicago):

The $\Upsilon(4260)$ is just above $D_s^* \bar{D}_s^*$ threshold in the same way that the $\Upsilon(4030)$ is just above $D^* \bar{D}^*$ threshold. It might therefore be useful to look for $\Upsilon(4260) \rightarrow D_s^* \bar{D}_s^*$.

Xiaoyan Shen: It is a good suggestion. BaBar might be able to check it.

References

1. Belle Collaboration, K. Abe *et al*, *Phys. Rev. D* **70**, 071102 (2004).
2. S. J. Brodsky, A. S. Goldhaber and J. Lee, *Phys. Rev. Lett.* **91**, 112001 (2003).
3. C.S. Gao and S.L. Zhu, *Commun. Theor. Phys.* **42**, 844 (2004), hep-ph/0308205.
4. G.J. Ding and M.L. Yan, *Phys. Rev. C* **72**, 015208 (2005).