Recent ψ' results at BES

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Based on $(3.79 \pm 0.31) \times 10^6$ ψ' data sets collected with the BES detector at BEPC, the recent ψ', χ_{cJ} and η_c results from BES are presented.

1. STUDIES OF ψ' DECAYS

Charmonium physics is always one of the interesting and intriguing fields of particle physics. Charmonium provides us an excellent and simple system to study QCD, the production and decay mechanisms of heavy quarkonia and light hadron spectra from its decays, and can be treated nonrelativistically and perturbatively. Using $(3.79 \pm 0.31) \times 10^6$ ψ' sample collected with the BEijing Spectrometer (BES) at BEPC, the recent ψ', χ_c and η_c results are presented. The BES detector is described in detail in Ref. [1].

Out of the charmonium decays, there exists a mysterious and longstanding $\rho\pi$ puzzle of J/ψ and ψ' decays [2], first revealed by Mark-II Collaboration. In QCD, both ψ' and J/ψ decays are expected to be dominated by annihilations into three gluons. Based on the similarity between the ψ' and J/ψ wave functions and the slow running of the strong interaction coupling constant α_s, the non-relativistic perturbative QCD predicts [3]: the ratios of the decays widths of ψ' into hadrons to those of J/ψ into hadrons are:

$$Q_h = \frac{Br(\psi' \to h)}{Br(J/\psi \to h)} \simeq \frac{Br(\psi' \to e^+e^-)}{Br(\psi \to e^+e^-)} = (14.7 \pm 2.3)\%$$

named as the "14%" rule. Mark II first observed the vector-pseudoscalar (V for vector, P pseudoscalar, B baryon, A axial-vector and T tensor) $\rho\pi$ and $K^*\bar{K}$ channels are highly suppressed w.r.t. the "14%" expectation – known as the $\rho\pi$ puzzle. BES has confirmed the puzzle with much lower upper limit by a suppression factor of ~ 60 and observed new highly suppressed decay modes, meanwhile BES presents many observations (Table 1).

From Table 1, a large number of ψ' decay branching ratios have been measured, and most for the first time [4]. And it is found that some VP, VPP, VT, PBB and AP decay modes are suppressed w.r.t. the "14%" rule, where VT modes [5] is the first evidence for suppression other than VP. While for ψ' decays into AP modes [6], the normal decay $b_1\pi$, enhanced mode $K_1(1270)\bar{K}$ and suppressed decay $K_1(1400)\bar{K}$ are observed. The "14%" rule holds for the radiative decays into VT modes [7] within errors, but it is suppressed for the decays into VP modes[8]. Now the suppressed decays also extend to the 3-body

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decays, but the "14%" rule holds for the baryonic decays [9]. Quite a few models [10] have been put forward to explain the puzzle, but none of them is satisfactory. From the measured results, it has also been observed that the **strong double OZI (DOZI) violation** in $\psi' \to \phi\pi^+\pi^-$ and the isospin violation in the decays between $\psi' \to \omega\pi^0$ and the isospin-conserving and SU(3)-allowed decay $\psi' \to \rho\pi$, and between the charged and neutral decays $\psi' \to K^{*+}K^- + c.c$ and $\psi' \to K^{*0}\bar{K}^0 + c.c.$ Fig. 1 shows the K^+K^- and $\pi^+\pi^-$ invariant masses for $\psi' \to \phi\pi^+\pi^-$ and $\phi f_0(980)$ [11]. Also BES first measures $Br(\psi' \to \tau^+\tau^-) = (2.82 \pm 0.45 \pm 0.56) \times 10^{-3}$ (preliminary) and has precisely determined $Br(J/\psi \to \ell^+\ell^-) = (5.87 \pm 0.04 \pm 0.09)\%$ [12] with errors half of those in PDG98.

Table 1
ψ' decay branching ratios (the unpublished results indicated by * are preliminary).

Channels	$Br_{PDG}(\times 10^{-4})$	$Br_{BES}(\times 10^{-4})$	$Q_h^{BES} = \frac{Br_{\psi'}}{Br_{J/\psi}}(\%)$
* $\rho\pi$	< 0.83	< 0.28	< 0.22
* $K^+\overline{K}^*(892)^- + c.c.$	< 0.54	< 0.30	< 0.6
* $K^0\overline{K}^*(892)^0 + c.c.$	–	$0.81 \pm 0.24 \pm 0.16$	1.9 ± 0.7
* $\omega\pi^0$	–	$0.38 \pm 0.17 \pm 0.11$	9.1 ± 5.0
* $\omega\eta$	–	< 0.33	< 2.1
* $\pi^+\pi^-\pi^0$	0.9 ± 0.5	$1.06 \pm 0.11 \pm 0.16$	7.1 ± 1.6
* $K\overline{K}\pi$	–	$1.25 \pm 0.18 \pm 0.26$	2.1 ± 0.6
$\gamma\eta$	–	$0.53 \pm 0.31 \pm 0.08$	6.2 ± 3.8
$\gamma\eta'(958)$	–	$1.54 \pm 0.31 \pm 0.20$	3.6 ± 0.9
ωf_2	–	< 1.7	< 3.9
ρa_2	–	< 2.3	< 2.1
$K^*(892)^0\overline{K}_2^*(1430)^0 + c.c.$	–	< 1.2	< 1.8
$\phi f_2'(1525)$	–	< 0.45	< 3.66
$b_1\pi$	–	$5.2 \pm 0.8 \pm 1.0$	17.3 ± 5.2
$K_1(1270)\overline{K}$	–	$10.0 \pm 1.8 \pm 2.1$	> 33.4
$K_1(1400)\overline{K}$	–	< 3.1	< 8.2
* $\gamma f_2(1270)$	–	$2.36 \pm 0.24 \pm 0.32$	17.1 ± 2.9
* $\gamma f_J(1710)$	–	$1.24 \pm 0.20 \pm 0.16$	12.8 ± 3.4
* ϕK^+K^-	–	$0.61 \pm 0.18 \pm 0.15$	7.3 ± 3.0
* $\phi\pi^+\pi^-$	–	$1.76 \pm 0.22 \pm 0.24$	22.0 ± 5.3
* $\phi f_0(980)$	–	$0.66 \pm 0.17 \pm 0.07$	20.5 ± 8.1
* $\omega\pi^+\pi^-$	–	$4.47 \pm 0.57 \pm 0.54$	6.3 ± 1.4
* ωK^+K^-	–	$1.26 \pm 0.43 \pm 0.39$	17.0 ± 9.6
* $\omega p\bar{p}$	–	$0.60 \pm 0.23 \pm 0.14$	4.6 ± 2.2
* $\phi p\bar{p}$	–	$0.86 \pm 0.50 \pm 0.20$	18.9 ± 13.4
* $\pi^+\pi^-\pi^0 p\bar{p}$	–	$3.85 \pm 0.37 \pm 0.56$	16.7 ± 7.1
* $\eta\pi^+\pi^- p\bar{p}$	–	$2.58 \pm 0.68 \pm 0.73$	
* $\eta p\bar{p}$	–	$0.84 \pm 0.48 \pm 0.48$	4.00 ± 4.00
* $p\bar{p}$	1.9 ± 0.5	$2.62 \pm 0.17 \pm 0.55$	12.3 ± 2.8
* $\Lambda\overline{\Lambda}$	< 4.0	$1.89 \pm 0.21 \pm 0.21$	14.0 ± 2.7
* $\Sigma^0\overline{\Sigma}^0$	–	$1.20 \pm 0.40 \pm 0.30$	9.2 ± 4.1
* $\Xi^-\overline{\Xi}^+$	< 2.0	$1.00 \pm 0.30 \pm 0.10$	11.1 ± 4.3
* $\Delta^{++}\overline{\Delta}^{--}$	–	$1.34 \pm 0.11 \pm 0.33$	12.2 ± 4.5
* $\Sigma^{*+}\overline{\Sigma}^{*-}$	–	$1.10 \pm 0.30 \pm 0.30$	10.7 ± 4.3

2. HADRONIC χ_{cJ} DECAYS

The $(3.79 \pm 0.31) \times 10^6$ ψ' sample permits studies of χ_{cJ} with unprecedented precision ($\sim 1.0 \times 10^6 \chi's$). Table 2 shows the results of χ_{cJ} decays [13,14]. From the table, the measurement precision is improved much, and many decay modes are presented first time, like $\chi_{c0} \to p\bar{p}$ [13]. The results of the neutral decays are preliminary.

Table 2
Results on χ_{cJ} Hadronic Decays (the unpublished results indicated by * are preliminary).

decay channels	BES ($\times 10^{-3}$)	PDG($\times 10^{-3}$)
$Br(\chi_{c0} \to \pi^+\pi^-)$	$4.68 \pm 0.26 \pm 0.65$	7.5 ± 2.1
$Br(\chi_{c2} \to \pi^+\pi^-)$	$1.49 \pm 0.14 \pm 0.22$	1.9 ± 1.0
$Br(\chi_{c0} \to K^+K^-)$	$5.68 \pm 0.35 \pm 0.85$	7.1 ± 2.4
$Br(\chi_{c2} \to K^+K^-)$	$0.79 \pm 0.14 \pm 0.13$	1.5 ± 1.1
$Br(\chi_{c0} \to p\overline{p})$	$0.159 \pm 0.043 \pm 0.053$	< 0.9
$Br(\chi_{c1} \to p\overline{p})$	$0.042 \pm 0.022 \pm 0.028$	0.086 ± 0.012
$Br(\chi_{c2} \to p\overline{p})$	$0.058 \pm 0.031 \pm 0.032$	0.10 ± 0.01
$Br(\chi_{c0} \to \pi^+\pi^-\pi^+\pi^-)$	$15.4 \pm 0.5 \pm 3.7$	37 ± 7
$Br(\chi_{c1} \to \pi^+\pi^-\pi^+\pi^-)$	$4.9 \pm 0.4 \pm 1.2$	16 ± 5
$Br(\chi_{c2} \to \pi^+\pi^-\pi^+\pi^-)$	$9.6 \pm 0.5 \pm 2.4$	22 ± 5
$Br(\chi_{c0} \to K_s^0K_s^0)$	$1.96 \pm 0.28 \pm 0.52$	-
$Br(\chi_{c2} \to K_s^0K_s^0)$	$0.61 \pm 0.17 \pm 0.16$	-
$Br(\chi_{c0} \to \pi^+\pi^-K^+K^-)$	$14.7 \pm 0.7 \pm 3.8$	30 ± 7
$Br(\chi_{c1} \to \pi^+\pi^-K^+K^-)$	$4.5 \pm 0.4 \pm 1.1$	9 ± 4
$Br(\chi_{c2} \to \pi^+\pi^-K^+K^-)$	$7.9 \pm 0.6 \pm 2.1$	19 ± 5
$Br(\chi_{c0} \to \pi^+\pi^-p\bar{p})$	$1.57 \pm 0.21 \pm 0.54$	5.0 ± 2.0
$Br(\chi_{c1} \to \pi^+\pi^-p\bar{p})$	$0.49 \pm 0.13 \pm 0.17$	1.4 ± 0.9
$Br(\chi_{c2} \to \pi^+\pi^-p\bar{p})$	$1.23 \pm 0.20 \pm 0.35$	–
$Br(\chi_{c0} \to K^+K^-K^+K^-)$	$2.14 \pm 0.26 \pm 0.40$	–
$Br(\chi_{c1} \to K^+K^-K^+K^-)$	$0.42 \pm 0.15 \pm 0.12$	–
$Br(\chi_{c2} \to K^+K^-K^+K^-)$	$1.48 \pm 0.26 \pm 0.32$	–
$Br(\chi_{c0} \to \phi\phi)$	$0.92 \pm 0.34 \pm 0.38$	–
$Br(\chi_{c2} \to \phi\phi)$	$2.00 \pm 0.55 \pm 0.61$	–
$Br(\chi_{c0} \to K_s^0K^+\pi^- + c.c.)$	< 0.71	–
$Br(\chi_{c1} \to K_s^0K^+\pi^- + c.c.)$	$2.46 \pm 0.44 \pm 0.65$	–
$Br(\chi_{c2} \to K_s^0K^+\pi^- + c.c.)$	< 1.06	–
$Br(\chi_{c0} \to 3(\pi^+\pi^-))$	$11.7 \pm 1.0 \pm 2.3$	15 ± 5
$Br(\chi_{c1} \to 3(\pi^+\pi^-))$	$5.8 \pm 0.7 \pm 1.2$	22 ± 8
$Br(\chi_{c2} \to 3(\pi^+\pi^-))$	$9.0 \pm 1.0 \pm 2.0$	12 ± 8
$^*Br(\chi_{c0} \to \pi^0\pi^0)$	$2.80 \pm 0.32 \pm 0.51$	3.1 ± 0.6
$^*Br(\chi_{c2} \to \pi^0\pi^0)$	$0.92 \pm 0.27 \pm 0.52$	1.1 ± 0.3
$^*Br(\chi_{c0} \to \eta\eta)$	$2.03 \pm 0.84 \pm 0.58$	2.5 ± 1.1
$^*Br(\chi_{c2} \to \eta\eta)$	< 2.5	0.8 ± 0.5

The mass differences between $\chi_{c0,1,2}$ and between η_c and J/ψ reflect the hyperfine structure of the spin-spin interactions, the $\chi_{c1,2}$ and J/ψ masses have been precisely determined. BES improves [13] the χ_{c0} mass with $(3414.1 \pm 0.6 \pm 0.8)$ MeV over PDG98 value with an error of 2.8 MeV, and χ_{c0} decay width with $\Gamma_{\chi_{c0}} = (14.3 \pm 3.6)$ MeV over PDG98 value $(13.5 \pm 5.3$ MeV). Fig. 2 shows χ_{cJ} hadronic decays [13,14]. From ψ' radiative transition to η_c, BES gives the η_c mass with $(2975.8 \pm 3.9 \pm 1.2)$ MeV [14].

3. COMPARISON WITH NRQCD

Recent years, non-relativistic QCD (NRQCD) [15] are successfully applied into description of the production and decays of heavy quarkonia. Its key idea is that heavy quark $Q\bar{Q}$ pairs are produced at short distances in color-octet states and subsequently evolve into physical (color-singlet) quarkonia by nonperturbative emission of soft gluons. Using the total decay widths of J/ψ, ψ' and $\chi_{c0,1,2}$ from PDG98 and the BES measured branching fractions, the corresponding partial decay widths are extracted, see Table 3. From Table 3, it is shown that the experimental results accord with NRQCD predictions [16] within errors. But for some decay modes, the errors are large due to the low statistic.

Table 3
Charmonium Partial Decay Decay Widths.

Channels	NRQCD	PDG	BES
$J/\psi \to p\bar{p}$	174 eV	(186 ± 14) eV	–
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	113 eV	(110 ± 16) eV	–
$J/\psi \to \Lambda\bar{\Lambda}$	117 eV	(117 ± 14) eV	–
$J/\psi \to \Xi^-\bar{\Xi}^+$	62.5 eV	(78 ± 18) eV	–
$J/\psi \to \Delta^{++}\overline{\Delta}^{--}$	65.1 eV	(96 ± 26) eV	–
$J/\psi \to \Sigma^{*-}\bar{\Sigma}^{*+}$	40.8 eV	(45 ± 6) eV	–
$\psi' \to p\bar{p}$	76.8 eV	(52.6 ± 15.1) eV	(72.6 ± 18.0) eV
$\psi' \to \Sigma^0\bar{\Sigma}^0$	55.0 eV	–	(33.2 ± 14.3) eV
$\psi' \to \Lambda\bar{\Lambda}$	54.6 eV	–	(52.4 ± 10.2) eV
$\psi' \to \Xi^-\bar{\Xi}^+$	33.9 eV	–	(27.7 ± 9.4) eV
$\psi' \to \Delta^{++}\overline{\Delta}^{--}$	32.1 eV	–	(37.2 ± 10.5) eV
$\psi' \to \Sigma^{*-}\bar{\Sigma}^{*+}$	24.4 eV	–	(30.5 ± 12.1) eV
$\chi_{c1} \to p\bar{p}$	56.2 eV	(75.7 ± 16.0) eV	(37.0 ± 32.2) eV
$\chi_{c2} \to p\bar{p}$	154.2 eV	(200.0 ± 27.0) eV	(116.0 ± 90.6) eV
$\chi_{c0} \to K^+K^-$	38.6 keV	(99 ± 49) keV	(79.5 ± 31.2) keV
$\chi_{c2} \to K^+K^-$	2.89 keV	(3.0 ± 2.2) keV	(1.58 ± 0.41) keV
$\chi_{c0} \to \pi^+\pi^-$	45.4 keV	(105 ± 48) keV	(65.5 ± 25.4) keV
$\chi_{c2} \to \pi^+\pi^-$	3.64 keV	(3.8 ± 2.0) keV	(2.98 ± 0.59) keV
$\chi_{c0} \to \pi^0\pi^0$	23.5 keV	(43 ± 18) keV	(39.2 ± 16.3) keV
$\chi_{c2} \to \pi^0\pi^0$	1.93 keV	(2.2 ± 0.6) keV	(1.84 ± 1.20) keV
$\chi_{c0} \to \eta\eta$	24.0 keV	(35.0 ± 20.2) keV	(28.4 ± 17.5) keV
$\chi_{c2} \to \eta\eta$	1.91 keV	(1.6 ± 1.0) keV	< 5 keV

4. SUMMARY

Using the $(3.79 \pm 0.31) \times 10^6$ ψ' data sets at BES, a large number of ψ' and χ_{cJ} results have been presented, many of them for the first measurements and/or with the unprecedented precision. BES has observed new suppressed decay modes and first observed enhanced decay from ψ' among a large number of the normal hadronic decays. Some results are also compared with NRQCD calculations.

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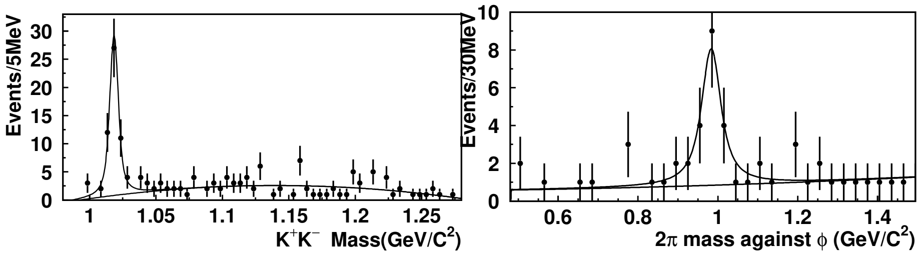

Figure 1. K^+K^- and $\pi^+\pi^-$ masses for $\psi' \to \phi\pi^+\pi^-$ and $\phi f_0(980)$ (preliminary).

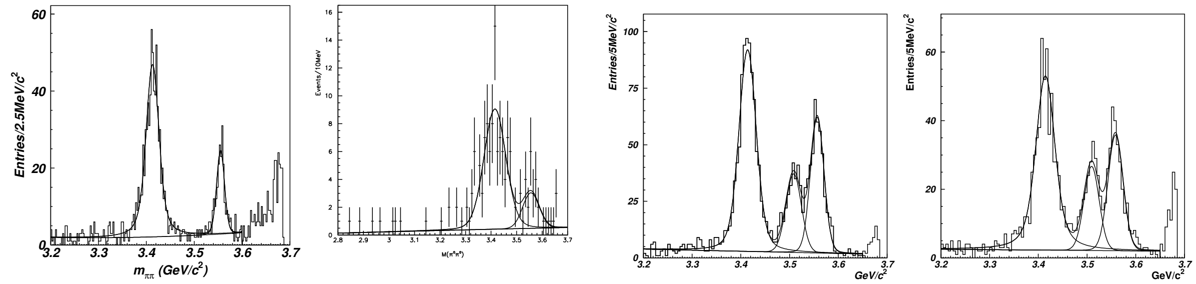

Figure 2. χ_{cJ} decays into $\pi^+\pi^-$ [13], $\pi^0\pi^0$ (preliminary), $2(\pi^+\pi^-)$ and $\pi^+\pi^-K^+K^-$ [14] respectively.

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