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Study of charmonium decays at BESIII

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Based on the data samples collected at the energies of J/ψ, $\psi(3686)$, $\psi(3770)$ and $\psi(4040)$ resonances with the BESIII detector at the BEPCII storage ring, we present charmonium decays in two aspects. One is the search for baryonic decays of $\psi(3770)$ and $\psi(4040)$, including $\Lambda\overline{\Lambda}\pi^+\pi^-$, $\Lambda\overline{\Lambda}\pi^0$, $\Lambda\overline{\Lambda}\eta$, $\Sigma^+\overline{\Sigma}^-$, $\Sigma^0\overline{\Sigma}^0$, $\Xi^-\overline{\Xi}^+$ and $\Xi^0\overline{\Xi}^0$. None are observed, and upper limits are set at the 90% confidence level. The other is the light hadron spectroscopy from charmonium radiative decays, including the spin-parity analysis of the $p\overline{p}$ mass-threshold enhancement in J/ψ radiative decays and the $\eta\eta$ system in $J/\psi \to \gamma\eta\eta$ radiative decays.

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1 Introduction

The world largest datasets in τ-charm energy region have been accumulated with the BESIII dectector at the BEPCII collider. Based on the data samples of 225 million J/ψ decays, 106 million $\psi(3686)$ decays, 2.9 fb^{-1} at the $\psi(3770)$ resonance and 482 pb^{-1} at the $\psi(4040)$ resonance, we present two aspects of charmonium decays at BESIII. One is the search for baryonic decays of $\psi(3770)$ and $\psi(4040)$, including $\Lambda\overline{\Lambda}\pi^+\pi^-$, $\Lambda\overline{\Lambda}\pi^0$, $\Lambda\overline{\Lambda}\eta$, $\Sigma^+\overline{\Sigma}^-$, $\Sigma^0\overline{\Sigma}^0$, $\Xi^-\overline{\Xi}^+$ and $\Xi^0\overline{\Xi}^0$. The other is the light hadron spectroscopy from charmonium radiative decays, including the partial wave analysis results of the $p\overline{p}$ mass-threshold enhancement and $\eta\eta$ system in J/ψ radiative decays.

2 Search for baryonic decays of $\psi(3770)$ and $\psi(4040)$

The $\psi(3770)$ and $\psi(4040)$, broad $c\overline{c}$ resonances above $D\overline{D}$ threshold, decay quite abundantly into open-charm final states. While charmless decays of the $\psi(3770)$ and $\psi(4040)$ are possible, their branching fractions are supposed to be highly suppressed.

The BES Collaboration measured the branching fraction for $\psi(3770)$ decay to non-$D\overline{D}$ to be $(15 \pm 5)\%$ by using different methods [1, 2, 3, 4] under the hypothesis that only one simple $\psi(3770)$ resonance exists in the center-of-mass energy region from 3.70 to 3.87 GeV. The CLEO Collaboration obtained the branching fraction $\mathcal{B}(\psi(3770) \to \text{non-}D\overline{D}) = (-3.3 \pm 1.4^{+6.6}_{-4.8})\%$ [5] under the assumption that the interference of the resonance decay, $\psi(3686) \to \gamma^* \to q\overline{q} \to hadrons$, with the continuum annihilation, $\gamma^* \to q\overline{q} \to hadrons$, is destructive at $\sqrt{s} = 3.671$ GeV and constructive at $\sqrt{s} = 3.773$ GeV [6].

The BES Collaboration observed the first non-$D\overline{D}$ decay, $\psi(3770) \to \pi^+\pi^- J/\psi$, with a branching fraction of $(0.34 \pm 0.14 \pm 0.09)\%$ [7]. The CLEO Collaboration confirmed the same hadronic transition [8], and observed other hadronic transitions $\pi^0\pi^0 J/\psi$, $\eta J/\psi$ [8], and radiative transitions $\gamma\chi_{cJ}(J = 0, 1)$ [9, 10] to lower-lying charmonium states, and the decay to light hadrons $\phi\eta$ [11]. While BES and CLEO have continued to search for exclusive non-$D\overline{D}$ decays of $\psi(3770)$, the total non-$D\overline{D}$ exclusive components are less than 2% [12]. Meanwhile, there are fewer experimental measurements for $\psi(4040)$ charmless decays. The BESIII Collaboration observed for the first time the production of $e^+e^- \to \eta J/\psi$ at $\sqrt{s} = 4.009$ GeV. Assuming the $\eta J/\psi$ signal is from a hadronic transition of the $\psi(4040)$, the fractional transition rate is determined to be $\mathcal{B}(\psi(4040) \to \eta J/\psi) = (5.2 \pm 0.5 \pm 0.2 \pm 0.5) \times 10^{-3}$ [13]. Search for other exclusive non-$D\overline{D}$ decays of $\psi(3770)$ and $\psi(4040)$ is urgently needed.

By analyzing data samples of 2.9 fb^{-1} collected at $\sqrt{s} = 3.773$ GeV, 482 pb^{-1} collected at $\sqrt{s} = 4.009$ GeV and 67 pb^{-1} collected at $\sqrt{s} = 3.542$, 3.554, 3.561, 3.600 and 3.650 GeV, the BESIII experiment report the results of searches for baryonic decays of $\psi(3770)$ and $\psi(4040)$, including final states with the baryon pairs ($\Sigma^+\overline{\Sigma}^-$,

$\Sigma^0\overline{\Sigma}^0$, $\Xi^-\overline{\Xi}^+$, $\Xi^0\overline{\Xi}^0$) and other $\Lambda\overline{\Lambda}$X modes (X = $\pi^+\pi^-$, π^0 and η) [14]. In Figs. 1 and 2, the two dimensional scatter plots are shown for each mode.

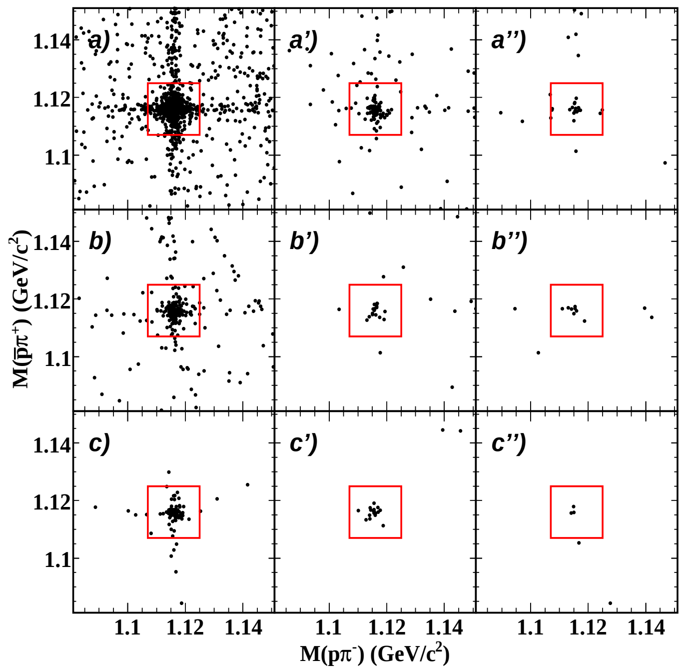

Figure 1: Invariant mass of $p\pi^-$ versus $\overline{p}\pi^+$ distributions for $\Lambda\overline{\Lambda}\pi^+\pi^-$ [(a), (a') and (a")], $\Lambda\overline{\Lambda}\pi^0$ [(b), (b') and (b")], $\Lambda\overline{\Lambda}\eta$ [(c), (c') and (c")]. The rectanglar regions indicate signal regions. The figures on the left (middle, right) side: data at $\sqrt{s} = 3.773$ [4.009, continuum (3.543, 3.554, 3.561, 3.600 and 3.650)] GeV.

We assume that there is no interference between continuum production and the $\psi(3770)/\psi(4040)$ resonance decay to the same baryonic final state. We give the branching fractions $\mathcal{B}_{\psi(3770)/\psi(4040)\to f}$ and the upper limits $\mathcal{B}^{up}$ of $\psi(3770)/\psi(4040)$ baryonic decays for each mode in Table 1. Since the available continuum data is limited, the dominant error on each of the seven branching fractions is from the continuum subtraction.

3 Light hadron spectroscopy in charmonium radiative decays

3.1 Partial wave analysis of $J/\psi \to \gamma p\overline{p}$

An anomalously strong $p\overline{p}$ mass-threshold enhancement was first observed by the BESII experiment in the radiative decay process $J/\psi \to \gamma p\overline{p}$ [15] and was recently

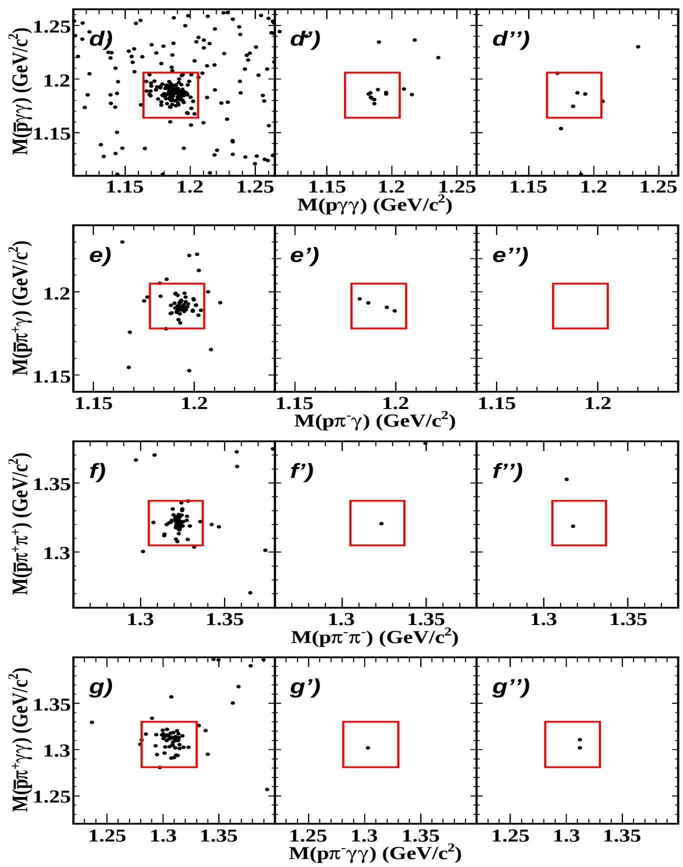

Figure 2: Invariant mass of $p\gamma\gamma$, $p\pi^-\gamma$, $p\pi^-\pi^-$ or $p\pi^-\gamma\gamma$ versus $\overline{p}\gamma\gamma$, $\overline{p}\pi^+\gamma$, $\overline{p}\pi^+\pi^+$ or $\overline{p}\pi^+\gamma\gamma$ distributions for $\Sigma^+\overline{\Sigma}^-$ [(d), (d') and (d")], $\Sigma^0\overline{\Sigma}^0$ [(e), (e') and (e")], $\Xi^-\overline{\Xi}^+$ [(f), (f') and (f")], $\Xi^0\overline{\Xi}^0$ [(g), (g') and (g")].

confirmed by the BESIII [16] and CLEO-c [17] experiments. The observation of the $p\overline{p}$ mass-threshold enhancement also stimulated an experimental analysis of $J/\psi \to \gamma\pi^+\pi^-\eta'$ decays, in which a $\pi^+\pi^-\eta'$ resonance, the $X(1835)$, was first observed by the BESII experiment [18] and recently confirmed with high statistical significance by the BESIII experiment [19]. Whether or not the $p\overline{p}$ mass-threshold enhancement and $X(1835)$ are related to the same source still needs further study. Spin-parity determinations and precise measurements of the masses, width, and branching ratios are especially important.

The BESIII experiment reports the first partial wave analysis (PWA) of the $p\overline{p}$ mass-threshold structure produced via the decays of $J/\psi \to \gamma p\overline{p}$ and $\psi(3686) \to \gamma p\overline{p}$ [20]. Data samples containing $(225.2 \pm 2.8) \times 10^6$ J/ψ events and $(106 \pm 4) \times 10^6$ $\psi(3686)$ events accumulated with BESIII dector are used. The PWA of $J/\psi \to \gamma p\overline{p}$ and $\psi(3686) \to \gamma p\overline{p}$ are performed. In J/ψ radiative decays, the near-threshold

Table 1: For each mode f, the following quantities are given: the number of observed events N^f_{obs} and background events N^f_B at 3.773, 4.009 and 3.650 GeV; the scale factors $f^{3.773}_{co}$ and $f^{4.009}_{co}$; the branching fractions $\mathcal{B}_{\psi(3770)\to f}$ and $\mathcal{B}_{\psi(4040)\to f}$, and the branching fraction upper limits $\mathcal{B}^{up}$ at 90% C.L.

Mode f	N^f_{obs} (3.773)	N^f_B (3.773)	N^f_{obs} (3.650)	N^f_B (3.650)	$f^{3.773}_{co}$	$\mathcal{B}_{\psi(3770)\to f}$ [$\times 10^{-4}$]	$\mathcal{B}^{up}$ [$\times 10^{-4}$]
$\Lambda\overline{\Lambda}\pi^+\pi^-$	844.0 ± 33.6	5.2	$14.2^{+5.6}_{-4.2}$	0.1	45.27	$1.80^{+1.74}_{-2.30} \pm 0.40$	< 4.7
$\Lambda\overline{\Lambda}\pi^0$	124.9 ± 14.4	3.4	$7.1^{+5.0}_{-2.2}$	0.0	42.50	$-1.28^{+0.67}_{-1.51} \pm 0.15$	< 0.7
$\Lambda\overline{\Lambda}\eta$	74.0 ± 9.5	0.9	$3.0^{+3.6}_{-1.6}$	0.0	44.76	$-1.22^{+1.44}_{-3.21} \pm 0.19$	< 1.9
$\Sigma^+\overline{\Sigma}^-$	100.5 ± 11.9	0.7	$3.3^{+4.3}_{-1.7}$	0.1	38.27	$-0.21^{+0.63}_{-1.56} \pm 0.05$	< 1.0
$\Sigma^0\overline{\Sigma}^0$	43.5 ± 6.7	0.0	$0.0^{+2.2}_{-0.0}$	0.0	38.69	$0.30^{+0.05}_{-0.58} \pm 0.05$	< 0.4
$\Xi^-\overline{\Xi}^+$	48.5 ± 7.0	0.0	$0.5^{+2.8}_{-1.4}$	0.0	41.74	$0.31^{+0.66}_{-1.32} \pm 0.05$	< 1.5
$\Xi^0\overline{\Xi}^0$	43.5 ± 6.6	1.3	$2.0^{+3.2}_{-1.2}$	0.0	40.13	$-0.80^{+1.03}_{-2.72} \pm 0.14$	< 1.4
Mode f	N^f_{obs} (4.009)	N^f_B (4.009)	N^f_{obs} (3.650)	N^f_B (3.650)	$f^{4.009}_{co}$	$\mathcal{B}_{\psi(4040)\to f}$ [$\times 10^{-4}$]	$\mathcal{B}^{up}$ [$\times 10^{-4}$]
$\Lambda\overline{\Lambda}\pi^+\pi^-$	79.2 ± 10.0	20.0	$14.2^{+5.6}_{-4.2}$	0.1	7.69	$-3.57^{+2.45}_{-3.21} \pm 0.79$	< 2.9
$\Lambda\overline{\Lambda}\pi^0$	$14.5^{+4.1}_{-4.3}$	0.5	$7.1^{+5.0}_{-2.2}$	0.0	6.80	$-2.14^{+0.97}_{-2.14} \pm 0.28$	< 0.9
$\Lambda\overline{\Lambda}\eta$	$16.0^{+4.2}_{-4.3}$	3.6	$3.0^{+3.6}_{-1.6}$	0.0	7.38	$-1.60^{+2.06}_{-4.43} \pm 0.57$	< 3.0
$\Sigma^+\overline{\Sigma}^-$	$8.5^{+3.0}_{-3.2}$	0.2	$3.3^{+4.3}_{-1.7}$	0.1	4.92	$-0.74^{+0.89}_{-2.14} \pm 0.17$	< 1.3
$\Sigma^0\overline{\Sigma}^0$	$4.0^{+3.2}_{-1.9}$	0.0	$0.0^{+2.2}_{-0.0}$	0.0	5.03	$0.28^{+0.23}_{-0.79} \pm 0.04$	< 0.7
$\Xi^-\overline{\Xi}^+$	$1.0^{+2.2}_{-0.8}$	0.0	$0.5^{+2.8}_{-1.4}$	0.0	5.61	$-0.21^{+0.94}_{-1.81} \pm 0.04$	< 1.6
$\Xi^0\overline{\Xi}^0$	$1.0^{+2.2}_{-0.8}$	0.0	$2.0^{+3.2}_{-1.2}$	0.0	5.36	$-2.22^{+1.55}_{-3.93} \pm 0.37$	< 1.8

enhancement $X(p\overline{p})$ in the $p\overline{p}$ invariant mass is determined to be a 0^{-+} state. With the inclusion of Julich-FSI effects, the mass, width and product of BRs for the $X(p\overline{p})$ are measured to be: $M = 1832^{+19}_{-5}(\text{stat})^{+18}_{-17}(\text{syst})\pm 19(\text{model})$ MeV/c^2, $\Gamma = 13 \pm 39(\text{stat})^{+10}_{-13}(\text{syst})\pm 4(\text{model})$ MeV/c^2 (a total width of $\Gamma < 76$ MeV/c^2 at the 90% C.L.) and $\text{BR}[J/\psi \to \gamma X(p\overline{p})]\text{BR}[X(p\overline{p}) \to p\overline{p}]= [9.0^{+0.4}_{-1.1}(\text{stat})^{+1.5}_{-5.0}(\text{syst})\pm 2.3(\text{model})]$ $\times 10^{-5}$, respectively.

3.2 Partial wave analysis of $J/\psi \to \gamma\eta\eta$

In accordance with the lattice QCD predictions [21, 22], the lowest mass glueball with $J^{PC} = 0^{++}$ is in the mass region from 1.5 to 1.7 GeV/c^2. However, the mixing of the pure glueball with nearby $q\overline{q}$ nonet mesons makes the identification of the glueballs difficult in both experiment and theory. Radiative J/ψ decay is a gluon-rich process and has long been regarded as one of the most promising hunting grounds

Table 2: Summary of the PWA results, including the masses and widths for resonances, branching ratios of $J/\psi \to \gamma X$, as well as the significance. The first errors are statistical and the second ones are systematic. The statistic significances here are obtained according to the changes of the log likelihood.

Resonance	Mass(MeV/c^2)	Width(MeV/c^2)	$\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$	Significance
$f_0(1500)$	1468^{+14+23}_{-15-74}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$	8.2 σ
$f_0(1710)$	$1795 \pm 6^{+14}_{-25}$	$172 \pm 10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	25.0 σ
$f_0(2100)$	$2081 \pm 13^{+24}_{-36}$	273^{+27+70}_{-24-23}	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$	13.9 σ
$f_2'(1525)$	$1513 \pm 5^{+4}_{-10}$	75^{+12+16}_{-10-8}	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$	11.0 σ
$f_2(1810)$	1822^{+29+66}_{-24-57}	$229^{+52+88}_{-42-155}$	$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$	6.4 σ
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$	7.6 σ

for glueballs. In particular, for a J/ψ radiative decay to two pseudoscalar mesons, it offers a very clean laboratory to search for scalar and tensor glueballs because only intermediate states with $J^{PC} = even^{++}$ are possible.

Based on the sample of 2.25×10^8 J/ψ events collected with the BESIII detector, a full partial wave analysis on $J/\psi \to \gamma\eta\eta$ [23] was performed using the relativistic covariant tensor amplitude method. The results show that the dominant 0^{++} and 2^{++} components are from the $f_0(1710)$, $f_0(2100)$, $f_0(1500)$, $f_2'(1525)$, $f_2(1810)$, $f_2(2340)$. The resonance parameters and branching fractions are also presented in Table 2.

4 Summary

The BESIII experiment has collected the world's largest data samples at the J/ψ, $\psi(3686)$, $\psi(3770)$ and $\psi(4040)$ resonances. Based on these samples, we present the charmonium decays at BESIII. Search for baryonic decays of $\psi(3770)$ and $\psi(4040)$, including $\Lambda\overline{\Lambda}\pi^+\pi^-$, $\Lambda\overline{\Lambda}\pi^0$, $\Lambda\overline{\Lambda}\eta$, $\Sigma^+\overline{\Sigma}^-$, $\Sigma^0\overline{\Sigma}^0$, $\Xi^-\overline{\Xi}^+$ and $\Xi^0\overline{\Xi}^0$ are very helpful for understanding the non-$D\overline{D}$ decays of particles above $D\overline{D}$ threshold. The partial wave analysis of the $p\overline{p}$ mass-threshold enhancement and $\eta\eta$ system in J/ψ radiative decays are very meanful for understanding the nature of the enhancement and finding the promising glueballs.

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