Charmonium Decays at BESIII

Jielei Zhang (on behalf of the BESIII Collaboration)

*College of Physics and Electronic Engineering,
 Xinyang Normal University, Xinyang 464000, China
 zhangjielei@ihep.ac.cn*

Published 3 May 2018

The BESIII Experiment at the Beijing Electron Positron Collider (BEPCII) has accumulated the largest e^+e^- collisions data sets in the τ -charm region in the world. Using the data sets of 448.1 million $\psi(3686)$ events and 1.3 billion J/ψ events, the branching fractions and the angular distributions of J/ψ and $\psi(3686)$ decay to $\Lambda\bar{\Lambda}$, $\Sigma^0\bar{\Sigma}^0$, $\Sigma(1385)^0\bar{\Sigma}(1385)^0$ and $\Xi^0\bar{\Xi}^0$ are measured. The branching fractions of $\psi(3686) \rightarrow \gamma\chi_{cJ}$ are reported with improved precision. The higher-order multipole amplitudes in $\psi(3686) \rightarrow \gamma\chi_{c1,2}$ with $\chi_{c1,2} \rightarrow \gamma J/\psi$ are measured, as a byproduct the $\eta_c(2S) \rightarrow \gamma J/\psi$ transition is searched. The Dalitz decays of $\psi(3686) \rightarrow e^+e^-\chi_{cJ}$ and $\chi_{cJ} \rightarrow e^+e^-J/\psi$ are observed and the branching fractions are measured. h_c radiative decays $h_c \rightarrow \gamma\eta'(\eta)$ are observed for the first time. Improved measurement of $\eta_c \rightarrow \phi\phi$ and search for $\eta_c \rightarrow \omega\phi$ are reported.

Keywords: Charmonium; Decay; BESIII.

1. Introduction

The BESIII detector at the BEPCII double-ring e^+e^- collider is designed for the studies of physics in the τ -charm energy region. The peak luminosity of BEPCII is $1.0 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ at 3773 MeV, which has been achieved at April, 2016. The decays of charmonium is a field with rich physics. It plays an important role in exploring the effective field theory of quantum chromodynamics (QCD) at low energy. The BESIII detector has accumulated 448.1 million $\psi(3686)$ and 1.3 billion J/ψ events. With these world largest J/ψ and $\psi(3686)$ data sets, many charmonium decays are observed for the first time or measured with the highest precision. In this proceeding, several recent results related to charmonium decays are reported.

2. Measurements of J/ψ and $\psi(3686)$ decay to $B\bar{B}$

The decays of the charmonium J/ψ and $\psi(3686)$ into baryon anti-baryon pairs ($B\bar{B}$) in e^+e^- annihilation have been extensively studies to test the perturbative quantum

This is an Open Access article published by World Scientific Publishing Company. It is distributed under the terms of the Creative Commons Attribution 4.0 (CC-BY) License. Further distribution of this work is permitted, provided the original work is properly cited.

chromodynamics (QCD) ¹, 12% rule, isospin symmetry and helicity selection rule. The angular distribution of baryons from $e^+e^- \rightarrow J/\psi(\psi(3686)) \rightarrow B\bar{B}$ is expected to be

$$\frac{dN}{d\cos\theta} = 1 + \alpha\cos^2\theta, \quad (1)$$

where θ is the angle between the baryon and the beam direction in the e^+e^- center-of-mass system. The α is expected to be positive in most of models.

The measurements of J/ψ and $\psi(3686)$ decay to $\Lambda\bar{\Lambda}$, $\Sigma^0\bar{\Sigma}^0$, $\Sigma(1385)^0\bar{\Sigma}(1385)^0$ and $\Xi^0\bar{\Xi}^0$ are performed ^{2,3}. The measured branching fractions and α are summarized in Tables 1 and 2.

Table 1. The branching fractions for $J/\psi(\psi(3686)) \rightarrow B\bar{B}$ (in units of 10^{-4}). The first uncertainties are statistical, and the second systematic.

Decay Mode	$\mathcal{B}(J/\psi \rightarrow)$	$\mathcal{B}(\psi(3686) \rightarrow)$
$\Lambda\bar{\Lambda}$	$19.43 \pm 0.03 \pm 0.33$	$3.97 \pm 0.02 \pm 0.12$
$\Sigma^0\bar{\Sigma}^0$	$11.64 \pm 0.04 \pm 0.23$	$2.44 \pm 0.03 \pm 0.11$
$\Sigma(1385)^0\bar{\Sigma}(1385)^0$	$10.71 \pm 0.09 \pm 0.82$	$0.69 \pm 0.05 \pm 0.05$
$\Xi^0\bar{\Xi}^0$	$11.65 \pm 0.04 \pm 0.43$	$2.73 \pm 0.03 \pm 0.13$

Table 2. The measured α values for $J/\psi(\psi(3686)) \rightarrow B\bar{B}$. The first uncertainties are statistical, and the second systematic.

Decay Mode	$J/\psi \rightarrow$	$\psi(3686) \rightarrow$
$\Lambda\bar{\Lambda}$	$0.469 \pm 0.026 \pm 0.008$	$0.82 \pm 0.08 \pm 0.02$
$\Sigma^0\bar{\Sigma}^0$	$-0.449 \pm 0.020 \pm 0.008$	$0.71 \pm 0.11 \pm 0.04$
$\Sigma(1385)^0\bar{\Sigma}(1385)^0$	$-0.64 \pm 0.03 \pm 0.10$	$0.59 \pm 0.25 \pm 0.25$
$\Xi^0\bar{\Xi}^0$	$0.66 \pm 0.03 \pm 0.05$	$0.65 \pm 0.09 \pm 0.14$

To test 12% rule, the ratio of $\psi(3686)$ to J/ψ decay to these channels are calculated, which are $(20.43 \pm 0.11 \pm 0.58)\%$, $(20.96 \pm 0.27 \pm 0.92)\%$, $(6.44 \pm 0.47 \pm 0.64)\%$, and $(23.43 \pm 0.26 \pm 1.09)\%$ for $\Lambda\bar{\Lambda}$, $\Sigma^0\bar{\Sigma}^0$, $\Sigma(1385)^0\bar{\Sigma}(1385)^0$ and $\Xi^0\bar{\Xi}^0$, respectively. All the ratios are not in agreement with 12%.

To test isospin symmetry, the ratios of the branching fractions are calculated based on the measurements between the neutral mode and the corresponding charged modes taking into account the cancelation of the common systematic uncertainties. All ratios are within 1σ of the expectation of isospin symmetry.

3. Branching fraction measurements of $\psi(3686) \rightarrow \gamma\chi_{cJ}$

For charmonium states that are above the ground state but below threshold for strong decay into heavy flavored mesons, like the $\psi(3686)$, electromagnetic decays

are important decay modes. The first charmonium states discovered after the J/ψ and $\psi(3686)$ were the χ_{cJ} states, which were found in radiative transitions of the $\psi(3686)$. These states, which are the triplet $1P$ states of the $c\bar{c}$ system, had been theoretically predicted along with the suggestion that they could be produced by $E1$ transitions from the $\psi(3686)$ resonance. Radiative transitions are sensitive to the inner structure of hadrons, and experimental progress and theoretical progress are important for understanding this structure. The development of theoretical models is also important for predicting the properties of missing charmonium states, in order to help untangle charmonium states above the open-charm threshold from the mysterious XYZ states.

The branching fractions of $\psi(3686) \rightarrow \gamma\chi_{c0,1,2}$ are measured with improved precision to be $(9.389 \pm 0.014 \pm 0.332)\%$, $(9.905 \pm 0.011 \pm 0.353)\%$ and $(9.621 \pm 0.013 \pm 0.272)\%$ ⁴, respectively. The branching fractions for $\psi(3686) \rightarrow \gamma\chi_{cJ}$ agree with CLEO within one standard deviation, except for $\psi(3686) \rightarrow \gamma\chi_{c1}$ which differs by 1.3 standard deviations. For comparison with models, experimental results have become accurate enough to become sensitive to fine details of the potential, e.g. relativistic effects, screening effects, and higher partial waves.

4. Measurements of higher-order multipole amplitudes in $\psi(3686) \rightarrow \gamma\chi_{c1,2}$ with $\chi_{c1,2} \rightarrow \gamma J/\psi$

The electric-dipole ($E1$) amplitudes are known to be dominant in $\psi(3686) \rightarrow \gamma\chi_{c1,2}$ and $\chi_{c1,2} \rightarrow \gamma J/\psi$. However, higher multipole amplitudes, such as magnetic quadrupole ($M2$) and electric-octupole ($E3$), are allowed for in these transitions, and can provide information on the anomalous magnetic moment κ of the charm quark and on the admixture of S - and D -wave states.

By assuming $m_c = 1.5 \text{ GeV}/c^2$ and ignoring the mixing of S - and D -wave states, the contributions $b_2^{1,2}$ and $a_2^{1,2}$ corrected to first order in $E_{\gamma_{1,2}}/m_c$ are predicted to be $b_2^1 = 0.029(1+\kappa)$, $a_2^1 = -0.065(1+\kappa)$, $b_2^2 = 0.029(1+\kappa)$ and $a_2^2 = -0.096(1+\kappa)$, respectively. The ratio b_2^1/b_2^2 and a_2^1/a_2^2 are predicted to be (1.000 ± 0.015) and (0.676 ± 0.071) , respectively. Higher-order multipole amplitudes can be obtained by investigating the angular distributions of the particles in the final states.

Nonpure $E1$ transition for the decay $\psi(3686) \rightarrow \gamma_1\chi_{c1,2} \rightarrow \gamma_1\gamma_2 J/\psi$ is observed with significance 24.3σ and 13.4σ for χ_{c1} and χ_{c2} channels ⁵, respectively. The measured results are $a_2^1 = -0.0740 \pm 0.0033 \pm 0.0034$ and $b_2^1 = 0.0229 \pm 0.0039 \pm 0.0027$ for χ_{c1} and $a_2^2 = -0.120 \pm 0.013 \pm 0.004$, $b_2^2 = 0.017 \pm 0.008 \pm 0.002$, $a_2^3 = -0.013 \pm 0.009 \pm 0.004$ and $b_2^3 = -0.014 \pm 0.007 \pm 0.004$ for χ_{c2} , respectively. Figure 1 shows the comparison of the results with previous measurements with $m_c = 1.5 \text{ GeV}/c^2$ and $\kappa = 0$. Our results are consistent but with higher precision than those measured by CLEO-c. The ratios of $M2$ contributions of χ_{c1} to χ_{c2} , which are independent of m_c and κ at the leading order, are determined to be $b_2^1/b_2^2 = 1.35 \pm 0.72$ and $a_2^1/a_2^2 = 0.617 \pm 0.083$, which are consistent with the theoretical predictions mentioned previously.

Based on the measurements, the product branching fractions for $\psi(3686) \rightarrow \gamma\chi_{c0,1,2} \rightarrow \gamma\gamma J/\psi$ to be $(15.8 \pm 0.3 \pm 0.6) \times 10^{-4}$, $(351.8 \pm 1.0 \pm 12.0) \times 10^{-4}$ and $(199.6 \pm 0.8 \pm 7.0) \times 10^{-4}$, respectively. The search for $\eta_c(2S) \rightarrow \gamma J/\psi$ is a byproduct and no statistically significant signal is observed, and the upper limit is set to be $\mathcal{B}(\psi(3686) \rightarrow \gamma\eta_c(2S)) \times \mathcal{B}(\eta_c(2S) \rightarrow \gamma J/\psi) < 9.7 \times 10^{-6}$ at the 90% C.L.

5. Observation of $\psi(3686) \rightarrow e^+e^-\chi_{cJ}$ and $\chi_{cJ} \rightarrow e^+e^-J/\psi$

Study of electromagnetic (EM) Dalitz decays, in which a virtual photon is internally converted into an e^+e^- pair, plays an important role in revealing the structure of hadrons and the interactions between photons and hadrons. Such decays are widely observed in the light-quark meson sector. However, the analogous transitions in charmonium decays have not yet been studied. Although the potential quark model has successfully described the low-lying charmonium states with high precisions, there are still puzzling discrepancies in the decay branching fractions $\mathcal{B}(\psi(3686) \rightarrow \gamma\chi_{cJ})$ between the experimental results⁶ and the various theoretical predictions. Therefore, it is of great interest to measure the EM transition $\psi(3686) \rightarrow e^+e^-\chi_{cJ}$ and $\chi_{cJ} \rightarrow e^+e^-J/\psi$. The EM Dalitz decays in charmonium transitions have access to the EM transition form factors (TFFs) of these charmonium states. The q^2 -dependence of charmonium TFFs can provide additional information on the interactions between the charmonium states and the electromagnetic field, where q^2 is the square of the invariant mass of the e^+e^- pair, and serve as a sensitive probe to their internal structures.

The EM Dalitz decays $\psi(3686) \rightarrow e^+e^-\chi_{cJ}$ and $\chi_{cJ} \rightarrow e^+e^-J/\psi$ are observed for the first time⁷. Figure 2 shows the distributions of the invariant masses $M(\gamma J/\psi)$

Fig. 1. Normalized M2 and E3 amplitudes from this analysis compared with previous experimental results and theoretical predictions with $m_c = 1.5 \text{ GeV}/c^2$ and $\kappa = 0$. The y axis shows the number of signal events of each experiments.

and $M(e^+e^-J/\psi)$, where clear χ_{cJ} signals are seen. The measured branching fractions are $\mathcal{B}(\psi(3686) \rightarrow e^+e^-\chi_{cJ}) = (11.7 \pm 2.5 \pm 1.0) \times 10^{-4}$, $(8.6 \pm 0.3 \pm 0.6) \times 10^{-4}$, $(6.9 \pm 0.5 \pm 0.6) \times 10^{-4}$ for $J = 0, 1, 2$, and $\mathcal{B}(\chi_{cJ} \rightarrow e^+e^-J/\psi) = (1.51 \pm 0.30 \pm 0.13) \times 10^{-4}$, $(3.73 \pm 0.09 \pm 0.25) \times 10^{-3}$, $(2.48 \pm 0.08 \pm 0.16) \times 10^{-3}$ for $J = 0, 1, 2$, respectively. The measured q^2 distributions are consistent with those of the signal MC simulation based on the assumption of a point-like meson.

6. Observation of h_c radiative decays $h_c \rightarrow \gamma\eta'(\eta)$

Charmonium has played an important role for our understanding of QCD, which is the fundamental theory that describes the strong interactions between quarks and gluons. At low energies, QCD remains of high interest both experimentally and theoretically. All charmonium states below the open-charm $D\bar{D}$ threshold have been observed experimentally and can be well described by potential models⁸. However, knowledge is still sparse on the P -wave spin-singlet state, $h_c(^1P_1)$. So far, only a few decay modes of h_c have been observed, in particular, the radiative transition $h_c \rightarrow \gamma\eta_c$ (with a branching fraction $\mathcal{B} \approx 50\%$) and one hadronic decay $h_c \rightarrow 2(\pi^+\pi^-)\pi^0$ ($\mathcal{B} \approx 2\%$). Searches for the new h_c decay modes, such as $h_c \rightarrow \gamma\eta(\eta')$, are useful for providing constraints to theoretical models in the charmonium region. The ratio of the branching fraction $\mathcal{B}(h_c \rightarrow \gamma\eta)$ over $\mathcal{B}(h_c \rightarrow \gamma\eta')$ can also be used to study the $\eta - \eta'$ mixing angle, which is important to test SU(3)-flavor symmetries in QCD.

Using the data sample of 448.1 million $\psi(3686)$ events, the radiative decay process $h_c \rightarrow \gamma\eta'$ and $\gamma\eta$ are observed with a statistical significance of 8.4σ and 4.0σ ⁹, respectively, for the first time. The corresponding branching fractions of $h_c \rightarrow \gamma\eta'$ and $h_c \rightarrow \gamma\eta$ are measured to be $(1.52 \pm 0.27 \pm 0.29) \times 10^{-3}$ and $(4.7 \pm 1.5 \pm 1.4) \times 10^{-4}$, respectively, where the first errors are statistical and the second are systematic. The ratio of the branching fraction $\mathcal{B}(h_c \rightarrow \gamma\eta)$ over $\mathcal{B}(h_c \rightarrow \gamma\eta')$ is $R_{h_c} = \frac{\mathcal{B}(h_c \rightarrow \gamma\eta)}{\mathcal{B}(h_c \rightarrow \gamma\eta')} = (30.7 \pm 11.3(\text{stat.}) \pm 8.7(\text{sys.}))\%$, where the common systematic errors between $\mathcal{B}(h_c \rightarrow \gamma\eta)$ and $\mathcal{B}(h_c \rightarrow \gamma\eta')$ cancel out. Although

Fig. 2. Data distributions of (left) $M(\gamma J/\psi)$ and (right) $M(e^+e^-J/\psi)$. The red solid curve is the overall fit result, the green long-dashed curve is for the background (left) $\psi(3686) \rightarrow \gamma\chi_{c0}, \chi_{c0} \rightarrow e^+e^-J/\psi$ and (right) $\psi(3686) \rightarrow e^+e^-\chi_{c0}, \chi_{c0} \rightarrow \gamma J/\psi$, the blue dashed curve is for QED background, and the pink dashed-dotted curve in right plot is for the backgrounds from $\psi(3686)$ decays.

the uncertainty is large, the $\eta - \eta'$ mixing angle can be extracted from R_{h_c} to test SU(3)-flavor symmetries in QCD, following the methods used for equivalent decays of the J/ψ and ψ' mesons.

7. Improved measurements of $\eta_c \rightarrow \phi\phi, \omega\phi$

The η_c decays into vector meson pairs is highly suppressed at leading order in QCD due to the helicity selection rule (HSR), and it is observed by MARKIII with a product branching fraction with $J/\psi \rightarrow \gamma\eta_c$ of $(1.02 \pm 0.25 \pm 0.14) \times 10^{-4}$, and the result is confirmed by BES and BESIII experiments. However, the measured branching fraction is much larger than the theoretical calculations in different scenario.

An amplitude analysis is performed to extract the $\eta_c \rightarrow \phi\phi$ yield¹⁰. The amplitude formulas are constructed with the helicity covariant method and the η_c resonance is parameterized with the Breit-Wigner function multiplied by a damping factor. The branching fraction $\mathcal{B}(\eta_c \rightarrow \phi\phi)$ is determined to be $(2.5 \pm 0.3_{-0.7}^{+0.3} \pm 0.6) \times 10^{-3}$, where the first uncertainty is statistical, the second is systematic, and the third is from the uncertainty of $\mathcal{B}(J/\psi \rightarrow \gamma\eta_c)$. The measured $\mathcal{B}(\eta_c \rightarrow \phi\phi)$ is close to the predictions of the 3P_0 quark model and the meson loop effects. No significant signal for the double Okubo-Zweig-Iizuka suppressed decay of $\eta_c \rightarrow \omega\phi$ is observed, and the upper limit on the branching fraction is determined to be $\mathcal{B}(\eta_c \rightarrow \omega\phi) < 2.5 \times 10^{-4}$ at the 90% confidence level.

8. Summary

With the large J/ψ and $\psi(3686)$ data sets collected with BESIII detector, the BESIII Collaboration has reported many charmonium decays, which provide important information on charmonium production and decay properties. There are still many analysis ongoing and can be expected to be published in near future. More J/ψ and $\psi(3686)$ events are planed to be collected at the BESIII detector and more results for charmonium decays are promising.

References

1. S.J. Brodsky, G.P. Lepage, *Phys. Rev. D* **24**, 2848 (1981); J. Bolz, P. Kroll, *Eur. Phys. J. C* **2**, 545 (1998); R.G. Ping, H.C. Chiang, B.S. Zou, *Phys. Rev. D* **66**, 054020 (2002).
2. BESIII Collab. (M. Ablikim *et al.*), *Phys. Rev. D* **95**, 052003 (2017).
3. BESIII Collab. (M. Ablikim *et al.*), *Phys. Lett. B* **770**, 217 (2017).
4. BESIII Collab. (M. Ablikim *et al.*), *Phys. Rev. D* **96**, 032001 (2017).
5. BESIII Collab. (M. Ablikim *et al.*), *Phys. Rev. D* **95**, 072004 (2017).
6. Particle Data Group Collab. (C. Patrignani *et al.*), *Chin. Phys. C* **40**, 100001 (2016).
7. BESIII Collab. (M. Ablikim *et al.*), *Phys. Rev. Lett.* **118**, 221802 (2017).
8. T. Barnes, S. Godfrey and E. S. Swanson, *Phys. Rev. D* **72**, 054026 (2005).
9. BESIII Collab. (M. Ablikim *et al.*), *Phys. Rev. Lett.* **116**, 251802 (2016).
10. BESIII Collab. (M. Ablikim *et al.*), *Phys. Rev. D* **95**, 092004 (2017).