Charmonium results from BESIII

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The resent results from BESIII on charmonium spectroscopy and charmonium decays are presented. It includes 1, first measurements of the transition rates of $\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$, and improved measurements of the mass and width of h_c; 2, observation of $\chi_{cJ} \to VV$, with VV being $\phi\phi$, $\omega\omega$, and $\omega\phi$; 3, improved measurements of the branching fractions of χ_{cJ} decays into two neutral pseudoscalar meson pairs $\chi_{c0,2} \to \pi^0\pi^0$ and $\chi_{c0,2} \to \eta\eta$.

1. Introduction

BEPCII/BESIII [1] is a major upgrade of the BESII experiment at the BEPC accelerator for studies of hadron spectroscopy and τ-charm physics. It has started data-taking since July 2008. Results shown in this paper are based on a data sample of 106M ψ' events.

2. $\chi_{c0,2} \to \pi^0\pi^0$, $\eta\eta$

Charmonium decays provide an ideal laboratory to test QCD theory. Theoretical models based on the color singlet model make predictions well below the data. Recently theoretical models which include the color octet contributions [2] show more promising results, but the uncertainties are still large. The studies of the χ_{cJ} decays to higher mass mesons (η and η') offer the possibility of investigating the contribution of DOZI suppressed decays [3]. Recently CLEO has published new results on the branching fractions $\chi_{c0,2}$ [4]. In this paper, we report the BESIII measurements of $\chi_{c0,2} \to \pi^0\pi^0$, $\eta\eta$.

Candidate events are required to have 5 or 6 photons and zero charged track. The π^0 or η measons are reconstructed from pairs of photons with an invariant mass $0.075 < M(\gamma\gamma) < 0.175$ GeV/c^2 for π^0, $0.458 < M(\gamma\gamma) < 0.608$ GeV/c^2 for η.

The main background to $\chi_{cJ} \to \pi^0\pi^0$ comes from $\psi' \to \gamma\chi_{cJ}$, $\chi_{cJ} \to \gamma J/\psi$, $J/\psi \to \gamma\eta$. Based on the known branching fraction, 48 events are expected in the signal region. The main background to $\chi_{cJ} \to \eta\eta$ are $\psi' \to \pi^0\pi^0 J/\psi$ and $\psi' \to \eta J/\psi$, with $J/\psi \to \gamma\eta$. 233 events are expected in the χ_{cJ} signal region. The MC simulation shows that these backgrounds do not peak at the χ_{c0} or χ_{c2} mass region.

A sample of 100M MC of inclusive ψ' decays is used to investigate other possible backgrounds. In the χ_{cJ} signal region, there is no peaking background is found. The background originating from non-resonance processes is studied by using a continuum data sample collected at a center of mass energy of 3.65 GeV. The estimated contribution to $\chi_{cJ} \to \pi^0\pi^0$ is 384 events, and 48 events to $\chi_{cJ} \to \eta\eta$.

In Fig. 1, left plot shows the radiative photon energy spectrum of $\chi_{cJ} \to \pi^0\pi^0$ candidates. The curve shows the results of a unbinned maximum-likelihood fit with two components, signal and background. The signal shapes of χ_{c0} and χ_{c2} are obtained from MC simulation, the masses and widths of χ_{cJ} are fixed to the known values. The background is described by a 2nd-order Chebychev polynomial. The fit gives a χ_{c0} signal yield of 17443 ± 167, and χ_{c2} signal yield of 4516 ± 80. The selection efficiency, determined from MC simulation, is $(55.6 \pm 0.2)\%$ for $\psi' \to \gamma\chi_{c0}(\chi_{c0} \to \pi^0\pi^0, \pi^0 \to \gamma\gamma)$, and is $(59.8 \pm 0.2)\%$ for $\psi' \to \gamma\chi_{c2}(\chi_{c2} \to \pi^0\pi^0, \pi^0 \to \gamma\gamma)$.

In Fig. 1, right plot shows the photon energy spectrum of $\chi_{cJ} \to \eta\eta$ candidates. The curve shows the results of an unbinned maximum likelihood fit that uses a MC-determined shape to represent signal, a 2nd-order Chebychev function for the background. The fit gives a χ_{c0} signal yield of 2132 ± 60, and a χ_{c2} signal yield of 386 ± 25. The MC-determined efficiency is $(40.3 \pm 0.2)\%$ for $\psi' \to \gamma\chi_{c0}(\chi_{c0} \to \eta\eta, \eta \to \gamma\gamma)$, and is $(43.9 \pm 0.2)\%$ for $\psi' \to \gamma\chi_{c2}(\chi_{c2} \to \eta\eta, \pi^0 \to \gamma\gamma)$

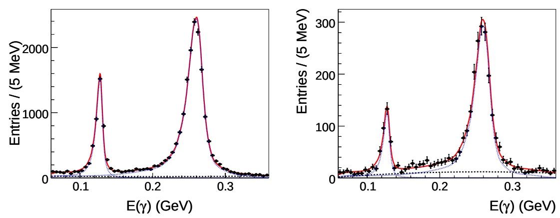

Figure 1. The radiative photon energy for $\psi(2S) \to \gamma\chi_{cJ}$, $\chi_{cJ} \to \pi^0\pi^0$ (Left), $\chi_{cJ} \to \eta\eta$ (Right), The solid curves are the fit results. Dotted line is for signal; dashed line is for background.

The systematic errors on the branching fractions are considered mainly from photon detection efficiency, π^0/η reconstruction, selection efficiency, the signal or background shape, fit range, the total number of ψ'. We assign a systematic error of 7.0% for $\chi_{c0} \to \pi^0\pi^0$, 6.9% for $\chi_{c2} \to \pi^0\pi^0$, 6.9% for $\chi_{c0} \to \eta\eta$, 7.5% for $\chi_{c2} \to \eta\eta$, respectively.

The branching fractions are obtained to be [5] $\mathcal{B}(\chi_{c0} \to \pi^0\pi^0) = (3.23 \pm 0.03 \pm 0.23 \pm 0.14) \times 10^{-3}$; $\mathcal{B}(\chi_{c2} \to \pi^0\pi^0) = (0.88 \pm 0.02 \pm 0.06 \pm 0.04) \times 10^{-3}$; $\mathcal{B}(\chi_{c0} \to \eta\eta) = (3.44 \pm 0.10 \pm 0.24 \pm 0.13) \times 10^{-3}$; $\mathcal{B}(\chi_{c2} \to \eta\eta) = (0.65 \pm 0.04 \pm 0.05 \pm 0.03) \times 10^{-3}$, where the third error is from the uncertainty in the branching fractions of $\psi' \to \gamma\chi_{cJ}$. The results are consistent with CLEO's.

3. $\chi_{cJ} \to VV$ decays

The identical particle symmetry requirements χ_{c1} decays to two identical particles $\omega\omega$, $\phi\phi$ only can occur through D-wave. Therefore, the processes are suppressed. Decays of $\chi_{cJ} \to \omega\phi$ are doubly OZI suppressed. The decay rates should be small. Studies of those decay channels experimentally will test the theoretical models.

$\chi_{cJ} \to \phi\phi$: ϕ measons are reconstructed from the decay of $\phi \to KK$ with an invariant mass $|M_{KK} - M_\phi| < 15$ MeV/c^2. Figure 2 shows the $M(\phi\phi)$ invariant mass, where clear χ_{c0}, χ_{c1}, χ_{c2} signals are seen. The contribution from non-resonance $\chi_{cJ} \to K^+K^-K^+K^-/\ \phi K^+K^-$, as shown in shaded histogram, is estimated from ϕ sideband.

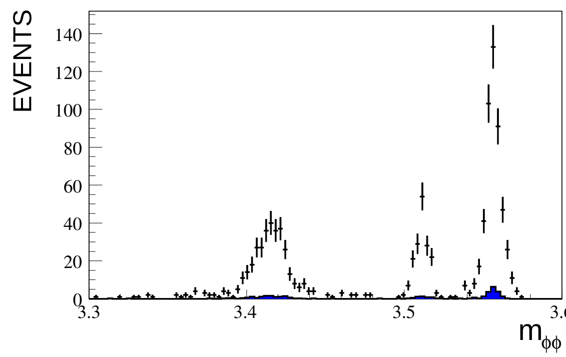

Figure 2. The invariant mass $M(\phi\phi)$ distribution. The data point is for data; the shaded histogram is non-resonance contribution estimated from ϕ sideband.

$\chi_{cJ} \to \omega\omega$: the ω measons are reconstructed from $\pi^+\pi^-\pi^0$. The combination of four photons with minimum $\sqrt{(M^1_{\gamma\gamma} - M_{\pi^0})^2 + (M^2_{\gamma\gamma} - M_{\pi^0})^2}$ is selected for the two π^0 candidates. The ω is selected by minimizing $|M_{\pi\pi\pi} - M_\omega|$, and satisfy $|M_{\pi\pi\pi} - M_\omega| < 0.04$ GeV/c^2. Figure 3 shows the $M(\omega\omega)$ invariant mass, where clear χ_{c0}, χ_{c1}, χ_{c2} signals are seen. The non-resonance background is studied by using the ω sideband.

$\chi_{cJ} \to \omega\phi$: ϕ is reconstructed via the decay $\phi \to KK$, while ω is reconstructed via the decay $\omega \to \pi\pi\pi^0$. The π^0 is selected by minimizing the $\sqrt{(M_{\gamma\gamma} - M_{\pi^0})^2 - (M_{\gamma\gamma\pi\pi} - M_\omega)^2}$. Figure 4 shows the $M(\omega\phi)$ invariant mass, where we see

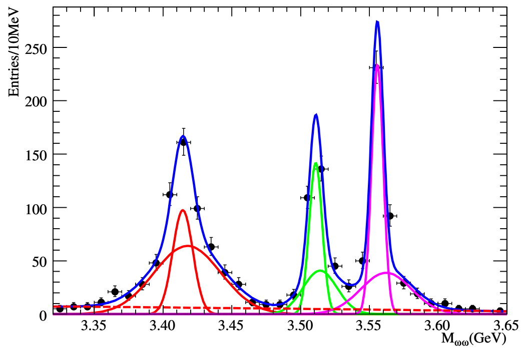

Figure 3. The invariant mass of $M(\omega\omega)$. The curve is the fit results; the dashed line is for background.

χ_{c0}, χ_{c1}, χ_{c2} signals. The non-resonance background is studied by using the ω sideband.

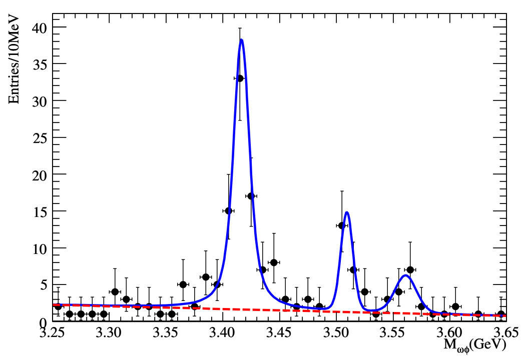

Figure 4. The invariant mass of $M(\omega\phi)$. The curve is the fit results; the dashed line is for background.

Decays of $\chi_{c1} \to \omega\omega$, $\phi\phi$, and $\chi_{cJ} \to \omega\phi$ are observed at BESIII [6].

4. h_c

Charmonium spectroscopy and transition have played an important role to understand the quark-antiquark ($Q\bar{Q}$) interaction of quantum chromodynamics (QCD) in particle physics. The $P-$wave singlet charmonium state $h_c(^1P_1)$ is particularly significant since the triplet-singlet hyperfine splitting $\Delta M_{hf} \equiv \langle M(1^3P_J)\rangle - \langle M(1^1P_1)\rangle$ will provide information on the spin dependence and spatial behavior of the $Q\bar{Q}$ force, where $\langle M(1^3P_J)\rangle = [M(\chi_{c0}) + 3M(\chi_{c1}) + 5M(\chi_{c2})]/9 = 3525.30 \pm 0.04$ MeV$/c^2$. Lattice QCD and relativistic calculations predict the hyperfine splitting ΔM_{hf} less than a few MeV$/c^2$.

The CLEO measurement [7] of h_c mass yields the mass splitting $\Delta M_{hf} = +0.02 \pm 0.19 \pm 0.13$ MeV$/c^2$, which agrees with the expectation of perturbative QCD calculations [8], $m(h_c) > \langle m(1^3P_J)\rangle$, but with large uncertainty to distinguish lattice QCD prediction $m(h_c) < \langle m(1^3P_J)\rangle$ [9]. The measurement of branching fraction $\psi(2S) \to \pi^0 h_c$ is urgent to determine the absolute decay rate of h_c particle produced in $\psi(2S)$ decays, e.g. h_c hadronic decays. A theoretical calculation based on the QCD multipole expansion [10] predicts the branching fraction of $B(\psi(2S) \to \pi^0 h_c) = (4.8 \sim 14.4) \times 10^{-4}$, the total decay width of $\Gamma(h_c) = (0.51 \pm 0.01)$ MeV$/c^2$.

At BESIII, we study distributions of mass recoiling against a detected π^0 to measure $\psi' \to \pi^0 h_c$ both inclusively and in events tagged as $h_c \to \gamma\eta_c$ by detection of the $E1$ transition photon. Combining inclusive and $E1$-tagged yields, we determined for the first time the branching fraction for $\psi' \to \pi^0 h_c$ and that for the $E1$ transition $h_c \to \gamma h_c$, as well as the h_c width. We also measure the product branching ratio for the chain $\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$ and the h_c mass.

Figure 5 top shows the inclusive π^0 recoil mass spectrum. Bottom plot is for the $E1$-tagged selection, where we require one photon in the energy range of $465 - 535$ MeV, and it should not form a π^0 with any other photon in the event. The π^0 recoil mass spectra are fitted by an unbinned maximum likelihood method. The $E1$-tagged fit is used to extract the mass and width of the h_c, which are then fixed for the inclusive fit. For the $E1$-tagged fit, the signal is parameterized by a Breit-Wigner with the mass and width free, convoluted by a detector resolution function determined from MC simulation. The background shape is obtained from the π^0 recoil mass spectrum with no photon in the signal region of 400-600 MeV and at least one photon in the signal-free region (below 400 MeV or above 600 MeV). The fit gives a yield of $E1$-tagged h_c decays of $N^{E1} = 3679 \pm 319$ and h_c parameters $M(h_c) = 3525.40 \pm 0.13$ MeV/c^2 and $\Gamma(h_c) = 0.73 \pm 0.45$ MeV/c^2. In the inclusive fit, the h_c mass and width are fixed and background is described by a 4th-order Chebychev polynomial with all parameters float. The fit result for the inclusive h_c yield is $N = 10353 \pm 1097$, the statistical significance is 9.5σ.

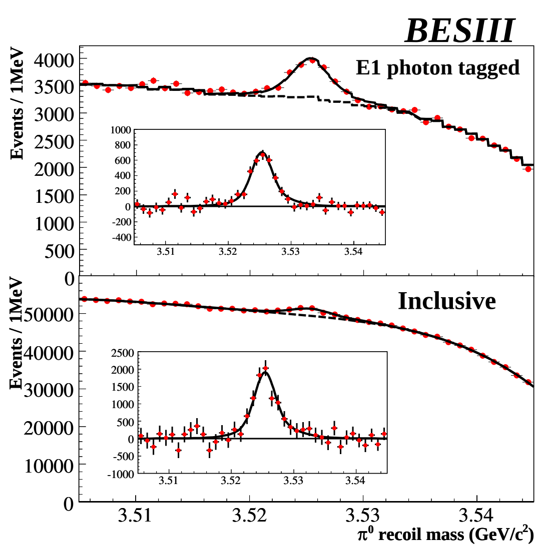

Figure 5. The π^0 recoil mass spectrum for the $E1$-tagged analysis (top), inclusive analysis (bottom) of $\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$. The curves show the results of unbinned maximum likelihood fits. The insets show the background-subtracted spectra.

The systematic uncertainties for the measurements are dominated by the treatment of the background in the recoil mass fits and imperfect modeling of photon and π^0 detection.

We obtain [11] $M(h_c) = 3525.40 \pm 0.13 \pm 0.18$ MeV/c^2; $\Gamma(h_c) = 0.73 \pm 0.45 \pm 0.28$ MeV/c^2; $\mathcal{B}(\psi' \to \pi^0 h_c) = (8.4 \pm 1.3 \pm 1.0) \times 10^{-4}$; $\mathcal{B}(\psi' \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma\eta_c) = (4.58 \pm 0.40 \pm 0.50) \times 10^{-4}$; $\mathcal{B}(h_c \to \gamma\eta_c) = (54.3 \pm 6.7 \pm 5.2)\%$. The results of $\mathcal{B}(h_c \to \gamma\eta_c)$ is close to the theoretical prediction. The branching ratio of $\mathcal{B}(\psi' \to \pi^0 h_c)$ is consistent with the prediction [10], and the total width $\Gamma(h_c)$ is also consistent with the theory prediction. We find the $1P$ hyperfine mass splitting to be $\Delta M_{hf} \equiv < M(1^3P) > - M(1^1P_1) = -0.10 \pm 0.13 \pm 0.18$ MeV/c^2, consistent with no strong spin-spin interaction.

5. Summary

Using 106M ψ' collected at BESIII, we improved the measurements of the branching fractions of $\chi_{cJ} \to \pi^0\pi^0,\ \eta\eta$. The absolute branching fraction ratios $\mathcal{B}(\psi' \to \pi^0 h_c)$ and $\mathcal{B}(h_c \to \gamma\eta_c)$ and width of h_c are measured for the first time. Also, decays of $\chi_{c1} \to \phi\phi$, $\omega\omega$, and $\omega\phi$ are observed as BESIII.

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