

中國科學院為能物明細完所 Institute of High Energy Physics Chinese Academy of Sciences





Measurement of Charmonium decays at BESIII

Han Miao (on behalf of BESIII Collaboration)

Institute of High Energy Physics

University of Chinese Academy of Sciences

2023.5.30

FPCP 2023, Lyon

CONTENTS

- BEPCII and BESIII
- Results from BESIII
 - Helicity amplitude analysis of $\chi_{cJ} \rightarrow \phi \phi$
 - Evidence for the $\eta_c(2S) \rightarrow \pi^+\pi^-\eta$ decay
 - Observation of $\psi(3770) \rightarrow \eta J/\psi$
 - Observation of the decay $\chi_{cI} \rightarrow \Omega^- \overline{\Omega}^+$
- > Summary

Beijing Electron Positron Collider II (BEPCII)





- 2020: energy upgrade to 2.45 GeV & top-up mode 2004: started BEPCII upgrade, **BESIII construction** 2009 - now: BESIII physics run
- 1989-2004 (BEPC):

 $L_{peak} = 1.0 \times 10^{31} / cm^2 s$

2009-now (BEPCII):

 L_{peak} = 1.1 x10³³/cm²(3/2023)

- \checkmark about 10 billion I/ψ
- \checkmark about 2.7 billion $\psi(3686)$
- \checkmark data sets for the study of R value, exotic states,

charmed hadrons...

- Study of the χ_{cJ} (J = 0, 1, 2) decays helps to test QCD
- Predictions are smaller than measured branching fraction [Phys. Lett. B 93 (1980) 119, Phys. Lett. B 93 (1980) 119, Phys. Lett. B 93 (1980) 119]
- BESIII measured $\chi_{cJ} \rightarrow \phi \phi$ before without amplitude analysis [Phys.Rev.Lett. 107 (2011) 092001]
- The analysis of the ϕ meson polarization: probe hadronic-loop effects in the $\chi_{cJ} \rightarrow \phi \phi$ decay [Phys. Lett. B 93 (1980) 119]
- The ratios of the helicity amplitudes are effective in the discrimination between the proposed models [Phys. Lett. B 611 (2005) 123, Phys. Lett. B 611 (2005) 123, Phys. Lett. B 93 (1980) 119]

Decay channel	$\chi_{c0} o \phi \phi$	$\chi_{c2} o \phi \phi$		
Parameter	x	ω_1	ω_2	ω_4
pQCD	0.293 ± 0.030	0.812 ± 0.018	1.647 ± 0.067	0.344 ± 0.020
${}^{3}P_{0}$	0.515 ± 0.029	1.399 ± 0.580	0.971 ± 0.275	0.406 ± 0.017
$D\bar{D}$ loop	0.359 ± 0.019	1.285 ± 0.017	5.110 ± 0.057	0.465 ± 0.002

Table 1. Numerical results of predictions from pQCD [6], ${}^{3}P_{0}$ [9] and $D\bar{D}$ loop models [10].

- $x = |F_{1,1}^0/F_{0,0}^0|$ for χ_{c0}
- $\omega_1 = |F_{0,1}^2/F_{0,0}^2|, \omega_2 = |F_{1,-1}^2/F_{0,0}^2|, \omega_4 = |F_{1,1}^2/F_{0,0}^2|$ for χ_{c2} ($F_{\lambda_1,\lambda_2}^{J=0,2}$ are the helicity amplitudes)

- Based on 448.1 million $\psi(3686)$ data
- The joint distribution for the sequential decays $e^+e^- \rightarrow \psi(3686) \rightarrow \gamma \chi_{cJ}, \chi_{cJ} \rightarrow \phi \phi$ and $\phi \rightarrow K^+K^$ is constructed in the helicity system
- An unbinned likelihood fit is performed
- Interference is only considered for χ_{c0} due to the much wider width compared with χ_{c1} and χ_{c2}



- > Properties of χ_{c0} :
 - $m_{\chi_{c0}} = 3415.42 \text{ MeV}/c^2$
 - $\Gamma_{\chi_{c0}} = 11.4 \text{ MeV}/c^2$
- For χ_{c0} :
 - $x = |F_{1,1}^0/F_{0,0}^0| = 0.299 \pm 0.003 \pm 0.019$
- > For χ_{c1} (statistical uncertainty only):
 - $u_1 = |F_{1,0}^1/F_{0,1}^1| = 1.05 \pm 0.05$
 - $u_2 = |F_{1,1}^1/F_{1,0}^1| = 0.07 \pm 0.04$

\succ For χ_{c2} :

- $\omega_1 = |F_{0,1}^2/F_{0,0}^2| = 1.265 \pm 0.054 \pm 0.079$
- $\omega_2 = |F_{1,-1}^2/F_{0,0}^2| = 1.450 \pm 0.097 \pm 0.104$
- $\omega_4 = |F_{1,1}^2/F_{0,0}^2| = 0.808 \pm 0.051 \pm 0.009$

Branching fractions

$$\begin{array}{l} \triangleright \ B(\chi_{c0} \to \phi \phi) = (8.59 \pm 0.27 \pm 0.20) \times 10^{-4} \\ \triangleright \ B(\chi_{c1} \to \phi \phi) = (4.26 \pm 0.13 \pm 0.15) \times 10^{-4} \\ \triangleright \ B(\chi_{c2} \to \phi \phi) = (12.67 \pm 0.28 \pm 0.33) \times 10^{-4} \end{array}$$



- > Discussions:
 - For the decay of χ_{c1} , no evidence of identical particle symmetry breaking
 - For the deday of χ_{c0} , consistent with the pQCD prediction
 - For the decay of χ_{c2} , the $D\overline{D}$ loop model ruled out due to the large deviation, while the other models cannot describe the measurements, either.
 - Using about 2.7 billion $\psi(3686)$ accumulated at BESIII now, more attractive results will be reported in future





Evidence for the $\eta_c(2S) \rightarrow \pi^+\pi^-\eta$ **decay**

- Charmonium states play an important role in understanding the strong interaction
- The knowledge about $\eta_c(2S)$ is still limited [Eur. Phys. J. C 71, 1534 (2011)], suffering from the very soft photon from $\psi(3686)$ transition
- The total measured branching fraction of $\eta_c(2S)$ is less than 5%

• $\frac{Br(\eta_c(2S) \to h)}{Br(\eta_c \to h)} \approx \frac{Br(\psi(3686) \to h)}{Br(J/\psi \to h)} = 0.128$, so-called '12% rule' [Phys. Rev. D 44, 1597 (1991)], which is violated

especially in the $\psi \rightarrow \rho \pi$ [Phys. Rev. Lett. 51, 963 (1983)]

Decay Mode	Branching fraction
$\eta_c(2S) \to KK\pi$	$(1.9 \pm 1.2)\%$
$\eta_c(2S) \to KK\eta$	$(5 \pm 4) \times 10^{-3}$
$\eta_c(2S) \to K^+ K^- \pi^+ \pi^- \pi^0$	$(1.4 \pm 1.0)\%$
$\eta_c(2S) \to \gamma \gamma$	$(1.9 \pm 1.3) \times 10^{-4}$

Evidence for the $\eta_c(2S) \rightarrow \pi^+\pi^-\eta$ decay

- Based on 448.1 million $\psi(3686)$ data
- $Br(\psi(3686) \rightarrow \gamma \eta_c(2S)) \times Br(\eta_c(2S) \rightarrow \pi^+ \pi^- \eta) = (2.97 \pm 0.81 \pm 0.26) \times 10^{-6}$
- $Br(\eta_c(2S) \to \pi^+\pi^-\eta) = (42.4 \pm 11.6 \pm 3.8 \pm 30.3) \times 10^{-4}$
- The evidence for the decay η_c(2S) → π⁺π⁻η is found for the first time with a statistical significance of 3.5σ using the 448 million ψ(3686) events
- $\frac{Br(\eta_c(2S) \to \pi^+ \pi^- \eta)}{Br(\eta_c \to \pi^+ \pi^- \eta)} = 0.25 \pm 0.20$
- $\frac{Br(\eta_c(2S) \to h)}{Br(\eta_c \to h)} = 0.30 \pm 0.10$
- Will be measured more precisely using about 2.7 billion ψ(3686)





- The conventional model for $\psi(3770)$, the lowest-mass *D*-wave charmonium state above the $D\overline{D}$ threshold [Phys. Rev. D 17, 3090 (1978)], cannot explain the measured large non- $D\overline{D}$ decay width of the state [Phys. Rev. Lett. 101, 112001 (2008)]
- Various theoretical models are developed for this puzzle
 - ✓ tetra-quark component [Phys. Rev. Lett. 101, 112001 (2008)]
 - ✓ 2S 1D mixing between $\psi(3686)$ [Phys. Rev. D 81, 034011 (2010)]
 - ✓ ψ (3770) or rescattering mechanism with *D* mesons [Phys. Rev. D 85, 114007 (2012)]
- The only well established non- $D\overline{D}$ channel is $\psi(3770) \rightarrow \pi^+\pi^- J/\psi$ [Rev. Mod. Phys. 80, 1161-1193 (2008)]
- CLEO reports the branching fraction $Br(\psi(3770) \rightarrow \eta J/\psi) = (8.7 \pm 3.3 \pm 2.2) \times 10^{-4}$ at a statistical significance of 3.5σ without considering the interference [Phys. Rev. Lett. 96, 082004 (2006)]
- $Br(\psi(3770) \rightarrow \eta J/\psi)$ is usually used as an input for the calculation of charmonium(-like) states [Phys. Rev. D 88, 014010 (2013), Phys. Rev. D 95, 114031 (2017)]

Decay Mode	Branching fraction
$\psi(3770) \to \pi^+\pi^- J/\psi$	$(1.93 \pm 0.28) \times 10^{-3}$
$\psi(3770) \to \pi^0 \pi^0 J/\psi$	$(8.0 \pm 3.0) \times 10^{-3}$
$\psi(3770) \to \eta J/\psi$	$(9 \pm 4) \times 10^{-4}$
$\psi(3770) o \phi\eta$	$(3.1 \pm 0.7) \times 10^{-4}$

- Based on 2.93 fb⁻¹ data @ 3.773 GeV
- The observed signal yield $N^{\rm obs} = 232 \pm 23$

0.79

The Born cross section

 $2931 \pm 15 \ 47.8 \pm 0.1$

N^{obs} $\sigma^{B}(e^{+}e^{-} \to \eta J/\psi) = \frac{1}{L \cdot (1 + \delta^{\text{ISR}}) \cdot (1 + \delta^{\text{VP}}) \cdot \varepsilon \cdot Br(\eta \to \gamma \gamma) \cdot Br(J/\psi \to \mu^{+}\mu^{-})}$ • $\sigma^B(e^+e^- \to \eta J/\psi) = (8.88 \pm 0.87_{\text{stat}} \pm 0.42_{\text{sys}}) \text{ pb } @ 3.773 \text{ GeV}$ Event/0.006(GeV/c[']) 08 08 ent/0.0022(GeV/c Event/0.0022(GeV/c (a) (b) 40 20 20 $\frac{3.3}{M(xx)(GeV/c^2)}$ 0.56 0.58 M'(γγ)(GeV/c²) 0.56 0.58 M'(γγ)(GeV/c²) 3.2 0.48 0.54 0.52 0.54 3.1 0.5 0.52 0.48 0.5 $\sigma^B(\text{pb})$ $(1+\delta^{\text{ISR}}) \cdot (1+\delta^{VP})$ $N^{\rm obs}$ $\mathcal{L} (\mathrm{pb}^{-1})$ $\mathcal{B}(J/\psi \to \mu^+ \mu^-)(\%) \ \mathcal{B}(\eta \to \gamma \gamma)(\%)$ $\varepsilon(\%)$

 5.96 ± 0.03

 39.4 ± 0.2

 232 ± 23 8.88 ± 0.87

- $Br(\psi(3770) \rightarrow \eta J/\psi)$ is obtained by fitting to the dressed cross section of $e^+e^- \rightarrow \eta J/\psi$ from $\sqrt{s} = 3.773$ to 4.60 GeV
- Two treatments of the $\psi(3770)$ resonant decay amplitude:
 - ✓ $\psi(3770)$ is coherent with the other amplitudes:

$$\sigma_{\text{co.}} = |C \cdot \sqrt{\Phi(s)} + e^{i\phi_1} BW_{\psi(3770)} + e^{i\phi_2} BW_{\psi(4040)} + e^{i\phi_3} BW_{Y(4230)} + e^{i\phi_4} BW_{Y(4390)}|^2$$

✓ $\psi(3770)$ is incoherent with the other amplitudes:

$$\sigma_{\text{co.}} = |\mathsf{BW}_{\psi(3770)}|^2 + |C \cdot \sqrt{\Phi(s)} + e^{i\phi_2} \mathsf{BW}_{\psi(4040)} + e^{i\phi_3} \mathsf{BW}_{Y(4230)} + e^{i\phi_4} \mathsf{BW}_{Y(4390)}|^2$$



• Incoherent:

✓ $Br(\psi(3770) \rightarrow \eta J/\psi) = (8.7 \pm 1.0_{stat} \pm 0.8_{sys}) \times 10^{-4}$, close to the result of CLEO

- Coherent:
 - ✓ Four solutions between $Br(\psi(3770) \rightarrow \eta J/\psi) = (11.2 \pm 5.8_{stat} \pm 1.1_{sys}) \times 10^{-4}$ and $(11.6 \pm 1.1_{sys}) \times 10^{-4}$

 $6.0_{\rm stat} \pm 1.1_{\rm sys}) \times 10^{-4}$

• There exists substantial interference effect, especially between $\psi(3770)$ and highly excited vector charmonium(-like) states

Observation of the decay $\chi_{cJ} \rightarrow \Omega^- \overline{\Omega}^+$

- The decays of the *P*-wave charmonium states, χ_{cJ} (J = 0,1,2), to baryon anti-baryon ($B\overline{B}$) have a non-trivial color-octet contribution [Phys. Lett. B 57, 407 (1975), Phys. Lett. B 57, 407 (1975)]
- Multiple models have been developed for χ_{cJ} to $B\overline{B}$, including $p\overline{p}$, $A\overline{A}$, $\Sigma^+\overline{\Sigma}^-$, $\Sigma^0\overline{\Sigma}^0$, while none of them can describe all the final states [Phys. Lett. B 57, 407 (1975), Phys. Rev. D 81, 014017 (2010)]
- For spin 3/2 baryons, only $\chi_{cJ} \rightarrow \Sigma(1385)^{\pm}\overline{\Sigma}(1385)^{\mp}$ has been studied by BESIII Collaboration [Phys. Rev. D 86, 052004 (2012)]
- The decay $\chi_{cJ} \rightarrow \Omega^- \overline{\Omega}^+$ is unique due to the presence of three pairs of strange quarks in the final states

Decay Mode	Branching fraction			
	χ_{c0}	χ_{c1}	χ_{c2}	
$\chi_{cJ} o p\overline{p}$	$(2.21 \pm 0.08) \times 10^{-4}$	$(7.60 \pm 0.34) \times 10^{-5}$	$(7.33 \pm 0.33) \times 10^{-5}$	
$\chi_{cJ} \to \Lambda \overline{\Lambda}$	$(3.59 \pm 0.15) \times 10^{-4}$	$(1.27 \pm 0.08) \times 10^{-4}$	$(1.83 \pm 0.16) \times 10^{-4}$	
$\chi_{cJ} o \Sigma^0 \overline{\Sigma}{}^0$	$(4.68 \pm 0.32) \times 10^{-4}$	$(4.2 \pm 0.6) \times 10^{-5}$	$(3.7 \pm 0.6) \times 10^{-5}$	
$\chi_{cJ} \to \Sigma^+ \overline{\Sigma}^-$	$(4.6 \pm 0.8) \times 10^{-4}$	$(3.6 \pm 0.7) \times 10^{-5}$	$(3.4 \pm 0.7) \times 10^{-5}$	
$\chi_{cJ} \to \Sigma^- \overline{\Sigma}^+$	$(5.1 \pm 0.5) \times 10^{-4}$	$(5.7 \pm 1.5) \times 10^{-5}$	$(4.4 \pm 1.8) \times 10^{-5}$	
$\chi_{cJ} o \Xi^0 \overline{\Xi}{}^0$	$(3.1 \pm 0.8) \times 10^{-4}$	$< 6 \times 10^{-5}$	$< 1.0 \times 10^{-4}$	
$\chi_{cJ} \to \Xi^- \overline{\Xi}^+$	$(4.8 \pm 0.7) \times 10^{-4}$	$(8.0 \pm 2.1) \times 10^{-5}$	$(1.42 \pm 0.32) \times 10^{-4}$	

14

Observation of the decay $\chi_{cJ} \rightarrow \Omega^- \overline{\Omega}^+$

- Based on 2.708 billion $\psi(3686)$ data
- Signal yield is obtained by fitting to the recoil mass spectrum of the radiative photon (RM_{γ})

$$Br(\chi_{cJ} \to \Omega^{-}\overline{\Omega}^{+}) = \frac{N_{\chi_{cJ}}^{obs}}{N_{\psi(3686)} \cdot Br(\psi(3686) \to \gamma \chi_{cJ}) \cdot \varepsilon}$$

- Measured $Br(\chi_{cJ} \to \Omega^- \overline{\Omega}^+)$ is one order of magnitude smaller than other $B\overline{B}$ channels. Useful to investigate the helicity selection rule evading mechanism in χ_{c0} decays
- Used to probe the spin polarization of Ω^- baryon in the charmonium production at the future tau-charm factories [arxiv: 2303.15790]

Mode	$N_{\chi_{cJ}}^{ m obs}$	$\epsilon_{\chi_{cJ}}(\%)$	$Sig.(\sigma)$	$\mathcal{B}(\times 10^{-5})$
χ_{c0}	284 ± 44	3.05	5.6	3.51 ± 0.54
χ_{c1}	277 ± 42	7.02	6.4	1.49 ± 0.23
χ_{c2}	1038 ± 56	8.91	18	4.52 ± 0.24



Summary

- → Helicity amplitude analysis of $\chi_{cJ} \rightarrow \phi \phi$ [JHEP 05, 069 (2023)]
 - Present models is tested by the ratio of helicity amplitudes
 - The branching fractions of $\chi_{cJ} \rightarrow \phi \phi$ is measured
- ► Evidence for the $\eta_c(2S) \rightarrow \pi^+ \pi^+ \eta$ decay [Phys.Rev.D 107 (2023) 5, 052007]
 - The evidence of the decay $\eta_c(2S) \rightarrow \pi^+ \pi^+ \eta$ is found for the first time with a statistical significance of 3.5σ
- ► Observation of $\psi(3770) \rightarrow \eta J/\psi$ [Phys.Rev.D 107 (2023) 9, L091101]
 - The Born cross section of $e^+e^- \rightarrow \eta J/\psi$ is measured at $\sqrt{s} = 3.773 \text{ GeV}$
 - The branching fraction of $\psi(3770) \rightarrow \eta J/\psi$ is measured in two cases associated with interference
- ▷ Observation of the decay $\chi_{cI} \rightarrow \Omega^{-}\overline{\Omega}^{+}$ [Phys.Rev.D 107 (2023) 9, 092004]
 - The decay $\chi_{cI} \rightarrow \Omega^- \overline{\Omega}^+$ is observed and measured for the first time

Outlook

- > BESIII has accumulated about 2.7 billion $\psi(3686)$ data in 2009, 2012 and 2021, the largest dataset around the world now
- The following topics will be further studied at BESIII
 - ✓ The transiton between low-lying charmonium states ($\psi(3686) \rightarrow \eta_c/\eta_c(2S), \psi(3686) \rightarrow \chi_{cJ}...$)
 - $\checkmark\,$ The decays of charonia into light hadrons
 - The precise validation of the calculation of non-perturbative QCD, such QCD sum rules and lattice QCD
 - ✓ Study on the light hadron spectroscopy
 - ✓ Search for the rare decays of charmonia, leptonic, semi-leptonic, invisible...
 - ✓ Constrain the new physics models related with axion, dark matter...

Thank you !

Han Miao (on behalf of BESIII Collaboration)Institute of High Energy PhysicsUniversity of Chinese Academy of Sciences

2023.5.30

FPCP 2023, Lyon