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Novel observations in charmonium decays

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Four novel observations in charmonium decays are presented in this talk. The first observation is $\psi(3686) \to 3\phi$ decay, which sheds light on the rare decay process of the $\psi(3686)$ resonance into three ϕ mesons, providing valuable insights into the dynamics of charmonium decays. No significant structure is observed in the $\phi\phi$ invariant mass. The second one is the search for $\eta_c(2S) \to \pi^+\pi^-\eta_c$ and $\eta_c(2S) \to \pi^+\pi^- K_S^0 K^\pm\pi^\pm$ decays. This study aims to explore the decay properties of the $\eta_c(2S)$ meson, offering new perspectives on its decay modes and contributing to our understanding of charmonium states. The third one is the $\psi(3686) \to \Omega^- K^+ \bar{X}i^0$ decay. Possible baryon excited states are searched for in this decay, but no evident intermediate state is observed with the current sample size. The fourth observation is the decay of $\chi_{cJ}(J = 0, 1, 2) \to 3(K^+K^-)$.

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1. Introduction

The discovery of the J/ψ and other $c\bar{c}$ bound states had a great impact on the development of the theory of strong interaction within the Standard Model (SM). Although the charmonium state J/ψ has been observed for more than half a century, intensive studies of different decays of various charmonium states are still highly desirable. It includes the other charmonium family members, such as S-wave singlet $\eta_c(1S, 2S)$, P-wave singlet, h_c and triplet $\chi_{cJ}(J = 0, 1, 2)$. Some of them we just have few knowledge. e.g., for h_c and $\eta_c(2S)$, the sum of the measured branching fractions is about 6%. Charmonium resonances lie in between the perturbative and nonperturbative regimes of quantum chromodynamics (QCD). [1–3], which describes the strong interaction. The study of charmonium decays can provide valuable insights to improve the understanding of the inner charmonium structure and test phenomenological mechanisms of nonperturbative QCD

2. Observation of $\psi(3686) \to 3\phi$

In recent years, significant progress has been made in experimental studies of multibody J/ψ and $\psi(3686)$ decays. Previously, the $\psi(3686) \to PPP$, $\psi(3686) \to VPP$, and $\psi(3686) \to VVP$, decays have been extensively studied, as summarized in Ref. [1], where P and V denote pseudoscalar and vector mesons, respectively. To date, no study of $\psi(3686) \to VVV$ has been reported. We present the first observation of the $\psi(3686) \to 3\phi$ decay based on $(2.712 \pm 0.014) \times 10^9$ $\psi(3686)$ events collected by BESIII detector in 2009, 2012, and 2021 [4].

In this analysis, we apply two schemes to select signal events. One is full reconstruction, where we require to find out all 6 charged kaon tracks which can survive kinematic fit. The three K^+K^- pairs result in six combinations to form the three different ϕ candidates. The best combination of three ϕ candidates is selected by minimizing

$$\Delta = \sqrt{\sum_{i=a,b,c} (M^i_{K^+K^-} - m_\phi)^2}, \tag{1}$$

where m_ϕ is the nominal ϕ mass. The three ϕ candidates are randomly labeled by using the Knuth-Durstenfeld shuffle algorithm. The another scheme is partial reconstruction, where we miss one charge kaon track. The detection efficiency is higher relative to the full reconstruction. Figure 1 shows the 3-dimensional scatter plot for both full and partial reconstruction. Clear 3ϕ signal is seen.

The branching fraction of the $\psi(3686) \to 3\phi$ decay is determined to be $(1.46 \pm 0.05 \pm 0.17) \times 10^5$. No obvious intermediate states are found by investigating the Dalitz plot of 3ϕ final states, and the momentum and polar angle distributions for each ϕ candidates.

3. Search for $\eta_c(2S) \to \pi^+\pi^-\eta_c, \pi^+\pi^-K^0_S K^\pm\pi^\mp$

The $\eta_c(2S)$ is the first excited state of the pseudoscalar ground state η_c, lying just below the mass of its vector counterpart $\psi(3686)$. So far, we have only a poor understanding to its property. Few its decay modes are observed. Hadronic transitions between charmonium states offer a good platform to study the dynamics of heavy quarks. Experimental [5] and theoretical [6, 7]

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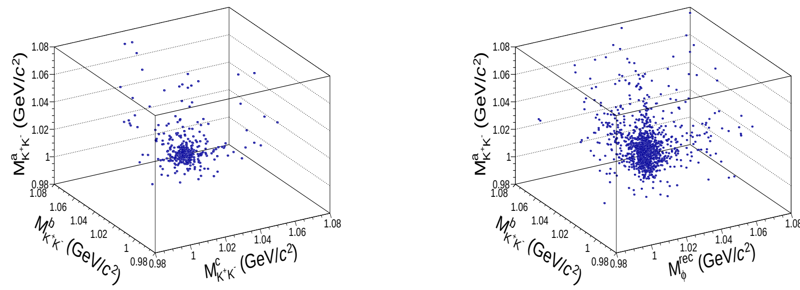

Figure 1: The $M^a_{K^+K^-}$: $M^b_{K^+K^-}$: $M^c_{K^+K^-}$ distributions of the (left) full and (right) partial reconstructed candidates for $\psi(3686) \to 3\phi$.

investigations of these transitions have provided a comprehensive understanding of those processes involving the emission of twopion system within the framework of low-energy chiral dynamics.

The transition amplitude of the $\eta_c(2S) \to \pi^+\pi^-\eta_c$ decay is expected to exhibit the same linear dependence q^2 as the $\psi(3686) \to \pi^+\pi^- J/\psi$ decay [8], where q is the total 4-momentum of the pion pair. However, the two-pion transition between the ${}^1S_0$ charmonium states has not yet been observed. Whether this decay branching fraction may be suppressed due to the contribution of the chromo-magnetic interaction in its decay amplitude [8] needs to be confirmed. In addition, searching for new decay modes of $\eta_c(2S)$ is important to deeply understand its decay properties. we search for $\eta_c(2S) \to \pi^+\pi^-\eta_c$ and present an improved measurement of the branching fraction of $\eta_c(2S) \to \pi^+\pi^- K^0_S K^\pm\pi^\mp$. Here, η_c is reconstructed by $K^+K^-\pi^0$ and $K^0_S K^\pm\pi^\mp$ final states, respectively.

The number of $\eta_c(2S) \to \pi^+\pi^-\eta_c$ signal events is determined from a simultaneous unbinned maximum likelihood fit on the $M(\pi^+\pi^-K^+K^-\pi^0)$ and $M(\pi^+\pi^-K^0_S K^\pm\pi^\mp)$ distributions. Figure 2 shows the fit results for two η_c decay modes. No obvious $\eta_c(2S)$ is found. As a result, the upper limit on $\mathcal{B}(\psi(3686) \to \gamma\eta_c(2S)) \times \mathcal{B}(\eta_c(2S) \to \pi^+\pi^-\eta_c)$ is determined to be 2.21×10^{-5} at the 90% confidential level. In order to investigate the $\eta_c(2S) \to \pi^+\pi^- K^0_S K^\pm\pi^\mp$ decay, we remove

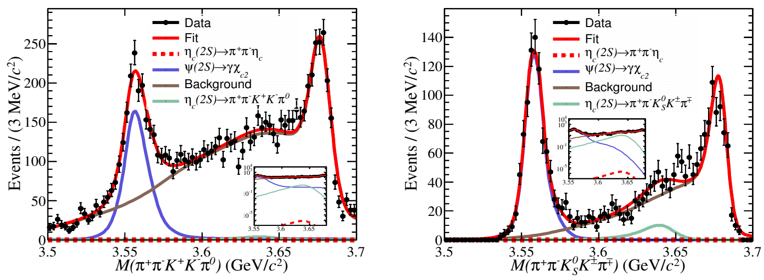

Figure 2: The simultaneous fit to the distributions of $M^{3C}(\pi^+\pi^-K^+K^-\pi^0)$ (left) and (right) $M^{3C}(\pi^+\pi^-K^0_S K^\pm\pi^\mp)$, and the magnified view of the signal region on a logarithmic scale. The black dots with error bars are data, the red dotted lines are the signal.

the η_c mass window requirement. Figure 3 (left) shows the fit results to $M^{3C}(\pi^+\pi^-K^0_S K^\pm\pi^\mp)$ spectrum and the relative pull distribution. Figure 3 (right) shows the zoomed distribution after the

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background subtraction in the $\eta_c(2S)$ signal region. The product branching fraction $\mathcal{B}(\psi(3686) \to \gamma\eta_c(2S))\times\mathcal{B}(\eta_c(2S) \to \pi^+\pi^-K_S^0K^\pm\pi^\mp)$ is determined to be $(9.31\pm0.72)\times10^{-3}$ and the branching fraction of $\eta_c(2S) \to \pi^+\pi^-K_S^0K^\pm\pi^\mp$ is determined to be $(1.33\pm1.1\pm0.4\pm0.95)\times10^{-2}$, where the first and second uncertainties are statistical and systematic, respectively, and the third uncertainty is from the quoted branching fraction of $\psi(3686) \to \gamma\eta_c(2S)$. The obtained result is consistent with our previous measurement [9], but with improved precision.

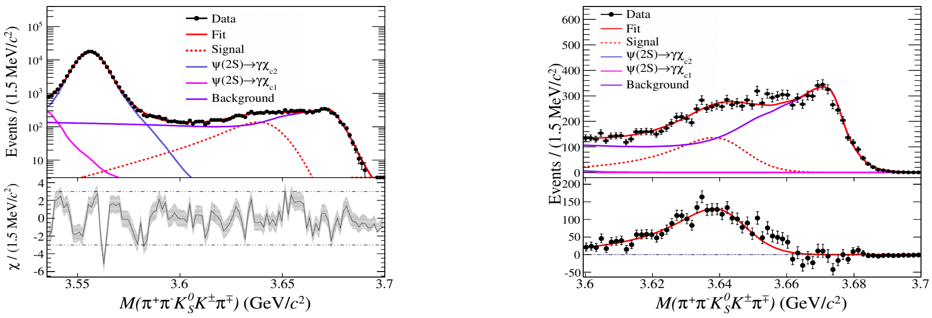

Figure 3: (left) Fit to the distribution of $M^{3C}(\pi^+\pi^-K_S^0K^\pm\pi^\mp)$ and the relative pull distribution. (right) Zoomed $M^{3C}(\pi^+\pi^-K_S^0K^\pm\pi^\mp)$ distribution and background residuals. The black dots with error bars are data, the red dotted lines are the signal, and the red solid lines are the total fit curves.

4. Observation of $\psi(3686) \to \Omega^-K^+\bar{\Xi}^0 + c.c.$

The observation of a decay with three pairs of $s\bar{s}$ in the final state will expand our knowledge of the decay mechanism of charmonium and has the potential to improve our understanding of QCD [10]. Experimental studies of hadronic decays of charmonium states provide important information for investigating many topics involving the strong interaction, such as the color octet and singlet contributions, the violation of helicity conservation, and SU(3) favor symmetry breaking effects [11, 12]. Compared to the two-body final state, the theoretical analysis relevant to three-body decays of charmoniums is more difficult and the available experimental results are rather limited at present [13]. Due to the small production cross sections and the complicated topology of the final states, only a few Ξ^* and $\Omega*$ states have been observed to date, and many of them lack a spin-parity determination. Until now, the most useful measurements have come from diffractive K^-p interactions [10].

The first observation of the decay $\psi(3686) \to \Omega^-K^+\bar{\Xi}^0+c.c.$ is reported and the corresponding branching fraction is measured using total $\psi(3686)$ events. Figure 4 shows the recoil mass of Ω^-K^+ and the fit result for the accepted candidates in $\psi(3686)$ data (left) and the continuum data at 3.773 GeV (right). Due to the limited sample size of the data taken in the vicinity of the $\psi(3686)$, the interference phase between the $\psi(3686)$ decay and the continuum production cannot be determined. Thus in this analysis, we do not consider the interference effect between the $\psi(3686)$ and the continuum process. The measured branching fraction is $\mathcal{B}(\psi(3686) \to^- K^+\bar{\Xi}^0 + c.c.) = (2.78 \pm 0.40 \pm 0.18) \times 10^{-6}$, where the first uncertainty is statistical and the second is systematic.

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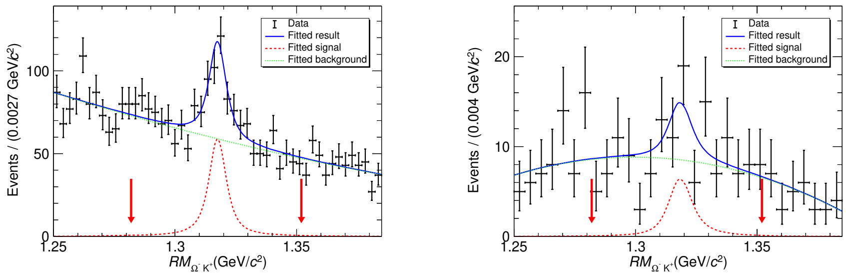

Figure 4: Fits to the $RM_{\Omega^- K^+}$ distributions of the accepted candidates in $\psi(3686)$ data (left) and the continuum data at 3.773 GeV (right). The red arrows mark the $\bar{\Xi}^0$ signal region.

5. Observation of $\chi_{CJ} \to 3(K^+K^-)$

Unlike the vector charmonium states J/ψ and $\psi(3686)$, however, the χ_{cJ} mesons cannot be directly produced in e^+e^- collisions due to parity conservation, and our knowledge about their decays is relatively deficient. These P-wave charmonium mesons are produced abundantly via radiative $\psi(3686)$ decays, with branching fractions of about 9%, thereby offering a good opportunity to study various χ_{cJ} decays. Currently, theoretical studies indicate that the color octet mechanism [14] may substantially influence the decays of the P-wave charmonium states. However, some discrepancies between these theoretical calculations and experimental measurements have been reported in Refs. [15–17]. Therefore, intensive measurements of exclusive χ_{cJ} hadronic decays are highly desirable to understand the underlying χ_{cJ} decay dynamics.

We present the first observation and branching fraction measurements of $\chi_{CJ} \to 3(K^+K^-)$. The distribution of the invariant mass of the $3(K^+K^-)$ combination, $M_{3(K^+K^-)}$, of the accepted candidate events is shown in Fig. 5. Clear $\chi_{c0,1,2}$ signals are observed. The signal yields of $\chi_{CJ} \to 3(K^+K^-)$ are obtained from an unbinned maximum likelihood fit to this distribution. The statistical significances for χ_{cJ} signals are determined to be 8.2σ, 8.1σ, and 12.4σ, respectively. The branching fractions for $\chi_{cJ} \to 3(K^+K^-)$ are measured to be $\mathcal{B}(\chi_{c0} \to 3(K^+K^-)) = (10.7 \pm 1.8 \pm 1.1) \times 10^{-6}$, $\mathcal{B}(\chi_{c0} \to 3(K^+K^-)) = (4.2 \pm 0.9 \pm 0.5) \times 10^{-6}$, and $\mathcal{B}(\chi_{c0} \to 3(K^+K^-)) = (7.2 \pm 1.1 \pm 0.8) \times 10^{-6}$, respectively.

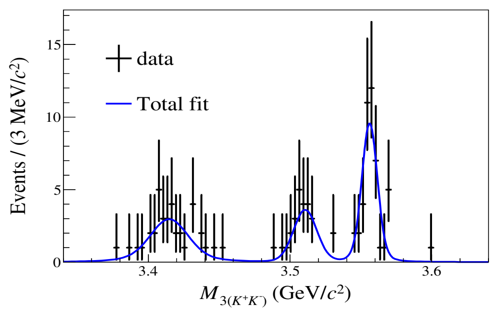

Figure 5: Fit to the $M_{3(K^+K^-)}$ distribution of the accepted candidate events. The points with error bars are data and the blue curve is the overall fit.

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6. Summary

In summary, using the world's largest $\psi(3686)$ sample taken with the BESIII detector, we observe the decay of $\psi(3686) \to 3\phi, \Omega^- K^+ \bar{\Xi}^0 + c.c$ and $\chi_{CJ} \to 3(K^+K^-)$ for the first time. The corresponding branching fractions are measured, and the potential intermediate states are investigated. No obvious intermediate state is found. We also search for $\eta_c(2S) \to \pi^+\pi^-\eta_c$ with $\eta_c \to K^+K^-\pi^0$ and $\eta_c \to K^0_S K^\pm \pi^\mp$. No obvious signal is found, and an upper limit is given. In addition, we present the first observation of $\eta_c(2S) \to \pi^+\pi^- K^0_S K^\pm \pi^\mp$ with a statistical significance of 10σ. The branching fraction is measured and this result is consistent with our previous measurement, but with improved precision.

References

[1] M. Ablikim *et al.* BESIII Collaboration, *Chin. Phys. C* **44**, (2020) 040001.

[2] W. Kwong, J. L. Rosner, and C. Quigg, Annu. Rev. Nucl. Part. Sci. **37**, (1987) 325.

[3] E. Eichten, S. Godfrey, H. Mahlke, and J. L. Rosner, *Rev. Mod. Phys.* **80**, (2008) 1161

[4] M. Ablikim *et al.* BESIII Collaboration, *Chin. Phys. C* **4**8, (2024) 093001.

[5] G. S. Abrams *et al., Phys. Rev. Lett.* **3**4, (1975) 1181.

[6] M. B. Voloshin, *JETP Lett.* **2**1, (1975) 347.

[7] L. S. Brown, and R. N. Cahn, *Phys. Rev. Lett.* **3**5, (1975) 1.

[8] M. B. Voloshin, *Phys. Rev. D* **74**, (2006) 054022.

[9] M. Ablikim *et al.* BESIII Collaboration, *Phys. Rev. D***8**7, (2013) 052005 .

[10] S. Capstick and W. Roberts, Quark models of baryon masses and decays, Prog. Part. *Nucl. Phys.* **4**5 (2000) S241.

[11] D.M. Asner *et al.,* Physics at BES-III, *Int. J. Mod. Phys. A* **2**4 (2009) S1.

[12] A. Rybicki, *Int. J. Mod. Phys. A* **2**4 (2009) 385.

[13] Particle Data collaboration, Review of Particle Physics, Prog. *Theor. Exp. Phys.* (2022) 083C01.

[14] G. T. Bodwin, E. Braaten, and G. P. Lepage, *Phys. Rev. D* **5**1, (1995) 1125; H. W. Huang and K. T. Chao, *Phys. Rev. D* **5**4, (1997) 6850; A. Petrelli, *Phys. Lett. B* **3**80, (1996) 159; J. Bolz, P. Kroll, and G. A. Schuler, *Eur. Phys. J. C* **2**,(1998) 705 .

[15] R. G. Ping, B. S. Zou, and H. C. Chiang, *Eur. Phys. J. A***2**3, (2005) 129.

[16] X. H. Liu and Q. Zhao, *J. Phys. G* **3**8, (2011) 035007.

[17] S. M. H. Wong, *Eur. Phy. J. C* **1**4, (2000) 643.

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