Recent measurements of charmonium decays at BESIII

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Abstract. In this poster, we present the first measurement of the charmonium decay $\psi(3686) \rightarrow \phi K_S^0 K_S^0$, based on an analysis of a data set comprising $(448.1 \pm 2.9) \times 10^6$ $\psi(3686)$ events collected by the BESIII detector operating at the BEPCII collider. Taking the interference between $\psi(3686)$ decay and continuum production into account, clear signals of $\psi(3686) \rightarrow \phi K_S^0 K_S^0$ is observed and the branching fraction of $\psi(3686) \rightarrow \phi K_S^0 K_S^0$ is reported for the first time. Combined with the world average value for $\mathcal{B}(J/\psi \rightarrow \phi K_S^0 K_S^0)$, the 12% rule for this channel is tested with high precision.

1 Introduction

The discovery of the first charmonium state, J/ψ mesons, has marked a milestone in particle physics. Charmonium is now interpreted as non-relativistic bound states of a charm and an anti-charm quark. Experimental measurements of the decays of charmonium particles can provide an ideal laboratory to study the dynamics of strong force physics, validate or falsify models and test various aspects of quantum chromodynamics (QCD) [1, 2].

Under the prediction of Perturbative QCD, both the J/ψ and $\psi(3686)$ decay into light hadron final states with a width proportional to the square of the wave function at the origin [3, 4]. This yields the widely-known "12% rule": $Q_h = \mathcal{B}_{\psi(3686)\rightarrow h}/\mathcal{B}_{J/\psi\rightarrow h} \simeq \mathcal{B}_{\psi(3686)\rightarrow e^+e^-}/\mathcal{B}_{J/\psi\rightarrow e^+e^-} \simeq 13.3\%$ [5], where h denotes any exclusive hadronic decay mode. Although this relation is expected to hold to a reasonably good degree for both inclusive and exclusive decays [6], it fails severely in the case of vector-pseudoscalar meson final states, such as $\rho\pi$ [7]. With the recent experimental results on J/ψ and $\psi(3686)$ two-body decays, such as the vector-tensor channel [8], the pseudoscalar-pseudoscalar channel [9], baryon-antibaryon mode [10], and multi-body decays such as $\phi\pi^+\pi^-$, $p\bar{p}\pi^0$ [11], etc., extensive tests of the 12% rule have been performed. The ratios Q_h for some decay modes are suppressed, some are enhanced, while others obey the 12% rule. For the target channel, $\Psi \rightarrow \phi K_S^0 K_S^0$, the J/ψ decays to the same final states has already been reported, while the result for $\psi(3686)$ is absent. Whether or not this channel holds the 12% rule is still an open questions.

The BESIII detector [13] records symmetric e^+e^- collisions provided by the BEPCII [14] storage ring in the center-of-mass (CM) energy range from 2.00 to 4.95 GeV, with a peak luminosity of 1×10^{33} cm^{-2}s^{-1} achieved at $\sqrt{s} = 3.77$ GeV. BESIII has accumulated the largest data sets in the world at the J/ψ, $\psi(3686)$, and $\psi(3770)$ resonances [6]. With these huge data sets, BESIII has the unique opportunity to measure the charmonium decays with very low branching fraction (BF).

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In this proceeding, we present the first observation and BF measurement of the charmonium decay $\psi(3686) \to \phi K^0_S K^0_S$ [12]. Furthermore, this analysis provides a critical validation of the 12% rule in the decay $\psi(3686) \to \phi K^0_S K^0_S$.

2 First observation of $\psi(3686) \to \phi K^0_S K^0_S$

2.1 Event selection and data analysis

By analyzing $(448.1 \pm 2.9) \times 10^6$ $\psi(3686)$ events collected with the BESIII detector in 2009 and 2012 [15], the $\psi(3686) \to \phi K^0_S K^0_S$ decay is searched for the first time. To select candidate events for $\psi(3686) \to \phi K^0_S K^0_S$, the ϕ and K^0_S mesons are reconstructed using their decays to K^+K^- and $\pi^+\pi^-$, respectively. After applying event selection criteria on the invariant masses of ϕ and K^0_S candidates, as well as on the χ^2 of a kinematic fit, which conserved the energy and momentum, the one-dimensional distribution of $M_{\pi^+\pi^-}$ for the K^0_S candidates in the signal and sideband regions is shown in Fig. 1(a). The two-dimensional (2D) $M_{\pi^+\pi^-}$ distribution for the two K^0_S candidates is shown in Fig. 1(b). To account for the backgrounds which do not contain a $K^0_S K^0_S$ pair, a sideband method is applied, where the 2D $M(K^0_S)$ distribution is devided into signal region (marked as Sig) and background region (marked as B_i).

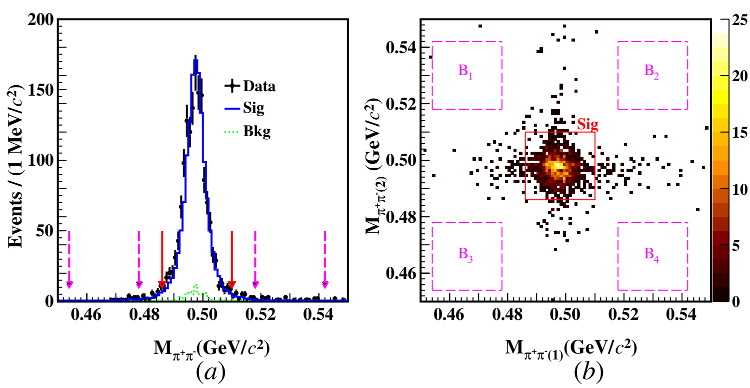


Figure 1. (a) The distribution of $M_{\pi^+\pi^-}$. The black points with error bars are data. The blue solid curve represents the signal MC. The green dashed curve represents the inclusive MC. The pair of red arrows shows the signal region, and the two pairs of pink dashed arrows show the sideband region. (b) The 2D distribution of $M_{\pi^+\pi^-(1)}$ vs. $M_{\pi^+\pi^-(2)}$ (the subscripts 1 and 2 indicate the two $\pi^+\pi^-$ combinations, respectively) in the signal and sideband regions. The red solid rectangle shows the 2D signal region, and the pink dashed rectangles show the 2D sideband regions.

Figure 2 shows the distributions of $M_{K^+K^-}$ in the 2D K^0_S signal region. The background rate can be determined by fitting to the $M_{K^+K^-}$ distributions, which was found to be extremely low, reaching a value of 10^{-6}. Given that the background level is quite low, one can obtain the signal events directly by counting the number of events in the 2D K^0_S signal region without considering any significant background contributions. The number of net $\psi(3686) \to \phi K^0_S K^0_S$ candidate events is given by $N^{\psi(3686)}_{\rm net} = N^{\psi(3686)}_{\rm sig} - N^{\psi(3686)}_{\rm bkg}$, where $N^{\psi(3686)}_{\rm sig}$ is determined by counting the events left in the 2D K^0_S signal region and $N^{\psi(3686)}_{\rm bkg}$ is estimated with the mean value of the background events in the sideband regions defined in Fig. 1(b), *i.e.*, $N^{\psi(3686)}_{\rm bkg} = \sum B_i/4$ (with i = 1, 2, 3, 4). For $N^{\psi(3686)}_{\rm sig}$ and $N^{\psi(3686)}_{\rm bkg}$, the values are determined to be 1023 ± 32 and 0, respectively.

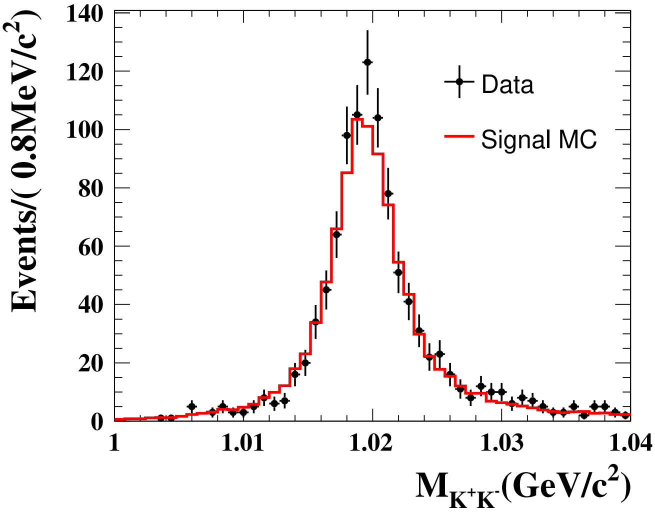


Figure 2. The $M_{K^+K^-}$ distribution for the accepted candidates in the 2D K_S^0 signal region for the $\psi(3686)$ data. The black points with error bars are data. The red solid curve is the signal MC.

Data sets collected at center-of-mass energies ranging from 3.508 GeV to 3.773 GeV are used to estimate the contribution from continuum processes. The same selection criteria and sideband definition are applied on this off-resonance data samples, the obtained values of signal yields $N_{\rm net}$ for each energy point are listed in Table 1. A scale factor $f_c = \frac{\mathcal{L}_{\psi(3686)}}{\mathcal{L}_{\rm cont.}} \times \frac{s^n_{\rm cont.}}{s^n_{\psi(3686)}}$ is considered to account for the energy dependence of the cross section, where $\mathcal{L}_{\psi(3686)}$ [15] and $\mathcal{L}_{\rm cont.}$ are the integrated luminosities for the $\psi(3686)$ and continuum data samples, and $s_{\psi(3686)}$ and $s_{\rm cont.}$ are the squares of the corresponding CM energies. By taking into account the energy-dependence of the cross section, the weighted average contribution for the continuum processes can be determined, using weights proportional to the inverse square of the respective uncertainties.

Table 1. The continuum background estimation for each data set, where: $E_{\rm CM}$ is the center-of-mass energy; $\mathcal{L}_{\rm cont.}$ is the integrated luminosity; $N_{\rm net}$ is the number of signal events in the 2D K_S^0 signal region after subtracting the backgrounds estimated with the sideband method; f_c is the scale factor for each energy point; and $N_{\rm cont.}$ is the continuum contribution.

$E_{\rm CM}$(GeV)	$\mathcal{L}_{\rm cont.}$pb^{-1}	$N_{\rm net}$	f_c	$N_{\rm cont.}$
3.508	183.64	32 ± 6	3.30	106 ± 20
3.510	181.79	28 ± 7	3.34	94 ± 23
3.539	25.50	7 ± 3	24.17	169 ± 72
3.553	42.56	10 ± 3	14.59	146 ± 44
3.554	27.24	1 ± 1	22.81	23 ± 23
3.650	43.88	14 ± 4	14.94	209 ± 60
3.773	2931.80	465 ± 22	0.24	112 ± 5

2.2 Interference effect

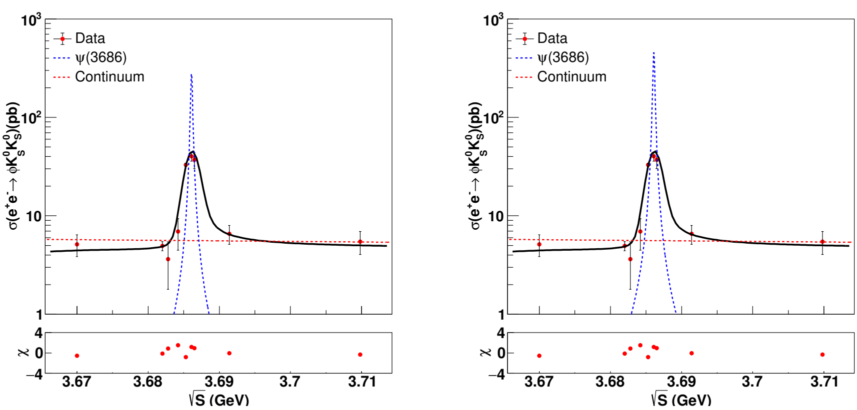
To accurately determine the total BF of $\psi(3686) \rightarrow \phi K^0_S K^0_S$, the contribution from the continuum and its interference with the $\psi(3686)$ decay is carefully accounted for. The phase angles between the continuum processes and the $\psi(3686)$ are estimated using scan data sets of $\psi(3686)$, which range from 3.670 GeV to 3.710 GeV. A least-χ^2 fit is performed to the dressed cross section ($\sigma^{\text{dressed}}(s)$) using the following formula [16]:

$$\sigma^{\text{dressed}}(s) = |A_{\text{cont}}(s) + A_{\text{res}}(s) \times e^{i\varphi}|^2 \tag{1}$$

where $\sqrt{s}$ is the CM energy, $A_{\text{cont}}(s)$ and $A_{\text{res}}(s)$ represent the amplitudes of the continuum process and $\psi(3686)$, respectively, while φ denotes the relative phase between the two amplitudes.

The Fitting results are presented in Fig. 3. By fitting to the cross sections in the vicinity of the $\psi(3686)$, two solutions for the phase angles can be derived, corresponding to a constructive interference of $(83 \pm 11)^\circ$ and a destructive interference of $-(85 \pm 9)^\circ$. The former is determined to be the physical one by the isospin symmetry with the decay of $\psi(3686) \rightarrow \phi K^+ K^-$ [5]. The interference contribution is then estimated by scaling the continuum contribution with the ratio of the cross sections between the interference term and the continuum process.

The BF of $\psi(3686) \rightarrow \phi K^0_S K^0_S$ is measured to be $(3.53 \pm 0.20 \pm 0.21) \times 10^{-5}$, where the first uncertainty is statistical, the second one is systematic. Using the world average of $\mathcal{B}(J/\psi \rightarrow \phi K^0_S K^0_S) = (5.9 \pm 1.5) \times 10^{-4}$ [5], the ratio between the two BFs is determined to be $Q_{\phi K^0_S K^0_S} = (6.0 \pm 1.6)$ %, which is suppressed relative to the 12% rule.



(a) (b)

Figure 3. The dressed cross sections of $e^+e^- \rightarrow \phi K^0_S K^0_S$ as a function of CM energy for (a) constructive solution with $\phi = (83 \pm 11)^\circ$ and (b) destructive solution with $\phi = (-85 \pm 9)^\circ$. The two fits have the same goodness of $\chi^2/\text{ndf} = 9.88/6$. The points with error bars are data, and the red and blue dashed curves represent the continuum contribution and $\psi(3686)$ contribution, respectively. The χ distributions of the two fits are shown in the bottom panel.

3 Summary and outlook

Using $(448.1 \pm 2.9) \times 10^6$ $\psi(3686)$ events accumulated by the BESIII detector, the decay $\psi(3686) \rightarrow \phi K^0_S K^0_S$ is observed for the first time. Taking the interference between $\psi(3686)$

decay and continuum production into account, the BF for this decay is precisely measured. Combined with the world average of $\mathcal{B}(J/\psi \to \phi K^0_S K^0_S)$, the 12% rule for this channel is well tested, and the result shows a significant suppression compared to the expected ratio. The 2.7×10^9 $\psi(3686)$ events recently collected by BESIII [6] offer an opportunity to improve the precision of Q_h and will lead to a better understanding of the phenomenon.

References

[1] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. D **99**, 032006 (2019).

[2] N. Brambilla *et al.* (Quarkonium Working Group), arXiv:hep-ph/0412158.

[3] T. Appelquist and H. D. Politzer, Phys. Rev. Lett. **34**, 43 (1975).

[4] T. Appelquist and H. D. Politzer, Phys. Rev. Lett. **34**, 43 (1975).

[5] R. L. Workman *et al.* (Particle Data Group), PTEP 2022, 083C01 (2022).

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

[7] M. E. B. Franklin *et al.* Phys. Rev. Lett. **51**, 963 (1983).

[8] J. Z. Bai *et al.* (BES Collaboration), Phys. Rev. D **69**, 072001 (2004)

[9] J. Z. Bai *et al.* (BES Collaboration), Phys. Rev. D **67**, 032004 (2003)

[10] T. K. Pedlar *et al.* (CLEO Collaboration), Phys. Rev. D **72**, 051108 (2005).

[11] R. A. Briere *et al.* (CLEO Collaboration), Phys. Rev. Lett. **95**, 062001 (2005). **42**, 023001 (2018).

[12] M. Ablikim*et al.* (BESIII Collaboration) Phys. Rev. D **108**, 052001

[13] M. Ablikim *et al.* (BESIII Collaboration), Nucl. Instrum. Meth. A **614**, 345 (2010).

[14] C. H. Yu et al., in *Proceedings of IPAC2016* , Busan, Korea, 2016, doi:10.18429/JACoW-IPAC2016-TUYA01.

[15] M. Ablikim *et al.* (BESIII Collaboration), Chin. Phys. C

[16] M. Ablikim *et al.* (BESIII Collaboration), Physics Letters B **791**, 375 (2019