

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, the J/ψ mesons, has marked a milestone in particle physics. Charmonium is now interpreted as the 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, confirm or reject models, and test various aspects of quantum chromodynamics (QCD) [1, 2].

Under the predictions 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]. This yields the widely-known “12% rule”: $Q_h = \mathcal{B}_{\psi(3686) \rightarrow h} / \mathcal{B}_{J/\psi \rightarrow h} \simeq \mathcal{B}_{\psi(3686) \rightarrow e^+ e^-} / \mathcal{B}_{J/\psi \rightarrow e^+ e^-} \simeq 13.3\%$ [4], 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 [5], it fails severely in the case of vector-pseudoscalar meson final states, such as $\rho\pi$ [6]. With the recent experimental results on J/ψ and $\psi(3686)$ two-body decays, such as the vector-tensor channel [7], the pseudoscalar-pseudoscalar channel [8], baryon-antibaryon mode [9], and multi-body decays such as $\phi\pi^+\pi^-$, $p\bar{p}\pi^0$ [10], 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, $\psi(3686) \rightarrow \phi K_S^0 K_S^0$, 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 obeys the 12% rule is still an open question.

The BESIII detector [11] records symmetric e^+e^- collisions provided by the BEPCII [12] storage ring in the center-of-mass (CM) energy range from 2.00 to 4.95 GeV, with a peak luminosity of $1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ 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 [5]. With these huge data sets, BESIII has the unique opportunity to measure charmonium decays with very low branching fractions (BF).

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In this proceeding, we present the first observation and BF measurement of the charm-
 onium decay $\psi(3686) \rightarrow \phi K_S^0 K_S^0$ [13], which provides an additional test of the 12% rule in the
 decay $\psi(3686) \rightarrow \phi K_S^0 K_S^0$.

2 First observation of $\psi(3686) \rightarrow \phi K_S^0 K_S^0$

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 [14], we search for the new decay mode $\psi(3686) \rightarrow \phi K_S^0 K_S^0$ for the first time. To
 select candidate events for $\psi(3686) \rightarrow \phi K_S^0 K_S^0$, the ϕ and K_S^0 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_S^0 candidates, as well as on the χ^2 of a kinematic fit, which enforces
 conservation of energy and momentum, the one-dimensional distribution of $M_{\pi^+ \pi^-}$ for the K_S^0
 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_S^0 candidates is shown in Fig. 1(b). To account for the
 backgrounds which do not contain a $K_S^0 K_S^0$ pair, a sideband method is applied, where the
 2D $M(K_S^0)$ distribution is divided into a signal region (marked as Sig) and four background
 regions (marked as B_i).

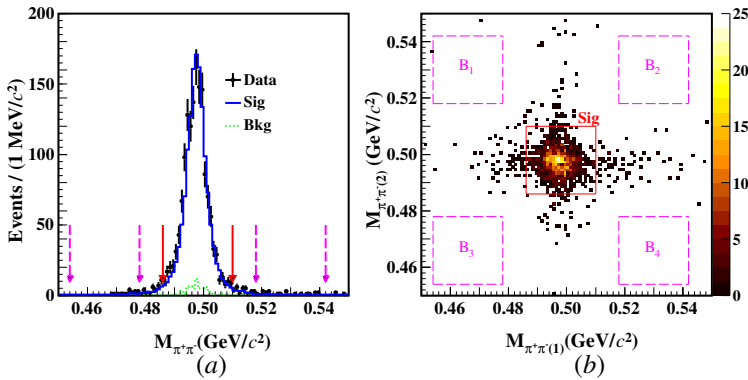


Figure 1. (a) The distribution of $M_{\pi^+ \pi^-}$. The black points with error bars are data. The blue solid curve represents the signal MC. The green dashed curve represents the inclusive MC. The pair of red arrows shows the signal region, and the two pairs of pink dashed arrows show the sideband 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_S^0 signal region. A fit to the $M_{K^+ K^-}$
 distributions was performed, where the signal is described with the MC signal shape con-
 volved with a parameter-floating Gaussian function and the background is modeled with a
 first-order polynomial function. The fit results indicated an extremely low background level,
 quantified at 10^{-3} . Given that the signal magnitude is around 10^3 , this analysis yields a
 background rate as minimal as 10^{-6} , which allows us to obtain the signal events directly by
 counting the number of events in the 2D K_S^0 signal region without considering any significant
 background contributions. The number of net $\psi(3686) \rightarrow \phi K_S^0 K_S^0$ candidate events is given
 by $N_{\text{net}}^{\psi(3686)} = N_{\text{sig}}^{\psi(3686)} - N_{\text{bkg}}^{\psi(3686)}$, where $N_{\text{sig}}^{\psi(3686)}$ is determined by counting the events left

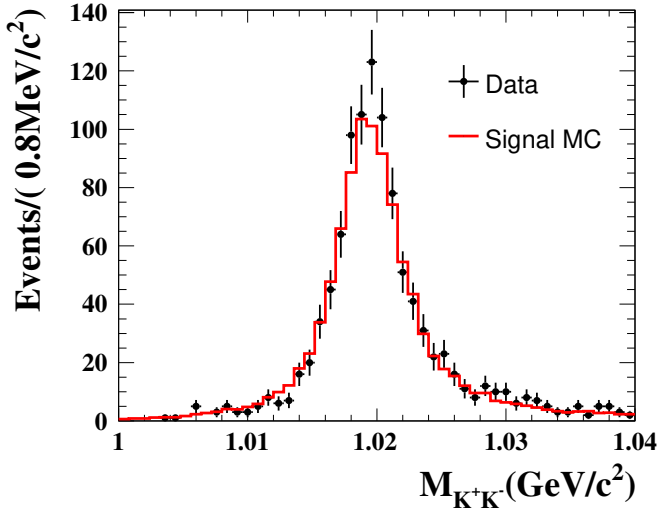


Figure 2. The $M_{K^+K^-}$ distribution for the accepted candidates in the 2D K_S^0 signal region for the $\psi(3686)$ data. The black points with error bars are data. The red solid curve is the signal MC.

in the 2D K_S^0 signal region and $N_{\text{bkg}}^{\psi(3686)}$ is estimated with the mean value of the background events in the sideband regions defined in Fig. 1(b), *i.e.*, $N_{\text{bkg}}^{\psi(3686)} = \sum B_i/4$ (with $i = 1, 2, 3, 4$).

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 to this off-resonance data samples, and the obtained values of signal yields N_{net} for each energy point are listed in Table 1. A scale factor $f_c = \frac{\mathcal{L}_{\psi(3686)}}{\mathcal{L}_{\text{cont.}}} \times \frac{s_{\text{cont.}}^n}{s_{\psi(3686)}^n}$ is considered to account for the energy dependence of the cross section, where $\mathcal{L}_{\psi(3686)}$ [14] and $\mathcal{L}_{\text{cont.}}$ are the integrated luminosities for the $\psi(3686)$ and continuum data samples, and $s_{\psi(3686)}$ and $s_{\text{cont.}}$ are the squares of the corresponding CM energies. We use $n = 1$ in the nominal result, which corresponds to a $1/s$ dependence for the continuum cross section. 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.

2.2 Interference between $\psi(3686)$ and continuum Amplitudes

To accurately determine the total BF of $\psi(3686) \rightarrow \phi K_S^0 K_S^0$, we account for the interference between the continuum process and the $\psi(3686)$ decay. The phase angles between the continuum processes and the $\psi(3686)$ are estimated using energy scan data sets around the $\psi(3686)$, 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 [15]:

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

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.

Table 1. The continuum background estimation for each data set, where: E_{CM} is the center-of-mass energy; $\mathcal{L}_{\text{cont.}}$ is the integrated luminosity; N_{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 $N_{\text{cont.}}$ is the continuum contribution predicted at the $\psi(3686)$.

$E_{\text{CM}}(\text{GeV})$	$\mathcal{L}_{\text{cont.}}(\text{pb}^{-1})$	N_{net}	f_c	$N_{\text{cont.}}$
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

Fit 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 isospin symmetry with the decay of $\psi(3686) \rightarrow \phi K^+ K^-$ [4]. The interference contribution, denoted as N_{inter} , is estimated by scaling the continuum contribution according to the ratio of cross sections for the interference and continuum processes, formulated as $N_{\text{inter}} = \frac{\sigma_{\text{inter}}}{\sigma_{\text{cont}}} \times N_{\text{cont.}}$. The cross section values, σ_{inter} and $\sigma_{\text{cont.}}$, are obtained from the fit.

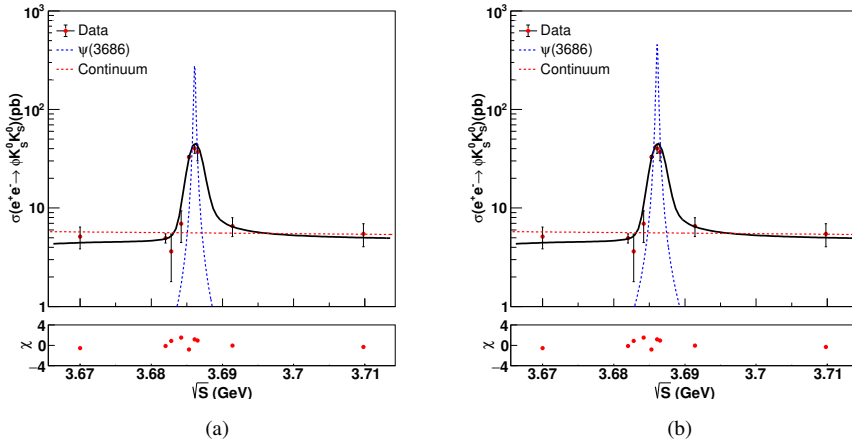


Figure 3. The dressed cross sections of $e^+e^- \rightarrow \phi K_S^0 K_S^0$ as a function of CM energy for (a) constructive solution with $\phi = (83 \pm 11)^\circ$ and (b) destructive solution with $\phi = -(85 \pm 9)^\circ$. The two fits have the same fit quality of $\chi^2/\text{ndf} = 9.88/6$. 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.

2.3 Branching fraction measurement

The BF of $\psi(3686) \rightarrow \phi K_S^0 K_S^0$ is determined by the following formula:

$$\mathcal{B}_{\psi(3686) \rightarrow \phi K_S^0 K_S^0} = \frac{N_{\text{net}}^{\psi(3686)} - \overline{N}_{\text{cont.}} - N_{\text{inter}}}{N_{\psi(3686)} \cdot \varepsilon \cdot \mathcal{B}_{\phi \rightarrow K^+ K^-} \cdot \mathcal{B}_{K_S^0 \rightarrow \pi^+ \pi^-}^2}, \quad (2)$$

where $N_{\text{net}}^{\psi(3686)} - \overline{N}_{\text{cont.}} - N_{\text{inter}}$ is the net number of $\psi(3686) \rightarrow \phi K_S^0 K_S^0$, $N_{\psi(3686)} = (448.1 \pm 2.9) \times 10^6$ is the total number of $\psi(3686)$ events [14], $\mathcal{B}_{\phi \rightarrow K^+ K^-}$ and $\mathcal{B}_{K_S^0 \rightarrow \pi^+ \pi^-}$ are the BFs of $\phi \rightarrow K^+ K^-$ and $K_S^0 \rightarrow \pi^+ \pi^-$ quoted from the PDG [4], and ε stands for the detection efficiency for $\psi(3686) \rightarrow \phi K_S^0 K_S^0$. By substituting each number into Eq. 2, the BF of $\psi(3686) \rightarrow \phi K_S^0 K_S^0$ 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 $\mathcal{B}(J/\psi \rightarrow \phi K_S^0 K_S^0) = (5.9 \pm 1.5) \times 10^{-4}$ [4], the ratio between the two BFs is determined to be $Q_{\phi K_S^0 K_S^0} = (6.0 \pm 1.6) \%$, which is suppressed relative to the 12% rule.

3 Summary and outlook

Using $(448.1 \pm 2.9) \times 10^6$ $\psi(3686)$ events accumulated by the BESIII detector, the decay $\psi(3686) \rightarrow \phi K_S^0 K_S^0$ 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 $\mathcal{B}(J/\psi \rightarrow \phi K_S^0 K_S^0)$, 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 [5] offer an opportunity to improve the precision of Q_h and will lead to a better understanding of the phenomenon.

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