Observation of $B \rightarrow \phi K$


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We report the observation of the decay mode $B \rightarrow \phi \phi K$ based on an analysis of 78 fb$^{-1}$ of data collected with the Belle detector at KEKB. This is the first example of a $b \rightarrow s \bar{s} s \bar{s}$ transition. The branching fraction for this decay is measured to be $\mathcal{B}(B^+ \rightarrow \phi \phi K^+) = (2.6^{+1.7}_{-0.9} \pm 0.3) \times 10^{-6}$ for a $\phi \phi$ invariant mass below 2.85 GeV/$c^2$. Results for other related charmonium decay modes are also reported.

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We report the observation of the decay mode $B \rightarrow \phi \phi K$, the first example of a $b \rightarrow s \bar{s} s$ transition. In the Standard Model (SM), this decay channel requires the creation of an additional final $s \bar{s}$ quark pair than in $b \rightarrow s \bar{s}$ processes, which have been previously observed in modes such as $B \rightarrow \phi K$. In addition to improving our understanding of charmless $B$ decays, the $\phi K$ state may be sensitive to glueball production in $B$ decays, where the glueball decays to $\phi \phi$ [1]. In addition, with sufficient statistics, the decay $B \rightarrow \phi \phi K$ could be used to search for a possible non-SM $CP$-violating phase in the $b \rightarrow s$ transition [2]. Direct $CP$ violation could be enhanced to as high as the 40% level if there is sizable interference between transitions due to non-SM physics and decays via the $\eta_b$ resonance.

We use a 78 fb$^{-1}$ data sample collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider [3] operating at the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58$ GeV). The sample contains $85.0 \times 10^6$ produced $B\overline{B}$ pairs. The Belle detector is a large-solid-angle magnetic spectrometer consisting of a three-layer silicon vertex detector, a 50-layer central drift chamber (CDC), a system of aerogel threshold Čerenkov counters (ACC), time-of-flight scintillation counters (TOF), and an array of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to identify $K^0_L$ and muons. The detector is described in detail elsewhere [4].

We select well measured charged tracks that have impact parameters with respect to the nominal interaction point (IP) that are less than 0.2 cm in the radial direction and less than 2 cm along the beam direction ($z$). Each track is identified as a kaon or a pion according to the information recorded in the CsI(Tl) calorimeter are rejected. Candidate $\phi$ mesons are reconstructed via the $\phi \rightarrow K^+K^-$ decay mode; we require the $K^+K^-$ invariant mass to be within $\pm 20$ MeV/$c^2$ ($\pm 4.5$ times the full width) of the $\phi$ mass [5]. For the $B^0(\overline{B}^0) \rightarrow \phi K^0_S$ decay mode, we use $K_S^0 \rightarrow \pi^+\pi^-$ candidates in the mass window $482$ MeV/$c^2 < M(\pi^+\pi^-) < 514$ MeV/$c^2$ ($\pm 4\sigma$), where the distance of closest approach between the two daughter tracks is less than 2.4 cm, the magnitude of the impact parameter of each track in the radial direction exceeds 0.02 cm, and the flight length is greater than 0.22 cm. The difference in the angle between the pion-pair vertex direction from the IP and its reconstructed flight direction in the $x-y$ plane is required to be less than 0.03 radians.

To isolate the signal, we form the beam-constrained mass, $M_{bc} = \sqrt{E_{beam}^2 - |\vec{P}_{recon}|^2}$, and the energy difference $\Delta E = E_{recon} - E_{beam}$. Here $E_{beam}$ is the
beam energy, and $E_{\text{recon}}$ and $F_{\text{recon}}$ are the reconstructed energy and momentum of the signal candidate in the $T(4S)$ center-of-mass frame. The signal region for $\Delta E$ is $\pm 30$ MeV which corresponds to $\pm 1.1 \sigma$ where $\sigma$ is the resolution determined from a Gaussian fit to the Monte Carlo (MC) simulation. The signal region for $M_{bc}$ is $5.27 \text{ GeV}/c^2 < M_{bc} < 5.29 \text{ GeV}/c^2$. The beam-constrained mass resolution is $2.8 \text{ MeV}/c^2$, which is mostly due to the beam energy spread of KEKB.

The major background for the $B \rightarrow \phi \phi K$ process is from continuum $e^+e^- \rightarrow q\bar{q}$ production, where $q$ is a light quark ($u$, $d$, $s$, or $c$). Several event topology variables are used to discriminate the continuum background, which tends to be collimated along the original quark direction, from the more isotropic $B \bar{B}$ events. Five modified Fox-Wolfram moments, the $S_1$ variable [6] and the cosine of the thrust angle are combined into a Fisher discriminant [7]. We form probability density functions (PDFs) for this Fisher discriminant and for the cosine of the $B$ decay angle with respect to the $z$ axis ($\cos \theta_B$) both for signal MC and sideband. The PDFs are multiplied together to form signal and background likelihoods, $L_S$ and $L_{BG}$. The likelihood ratio $LR \equiv L_S/(L_S+L_{BG})$ is then required to be greater than 0.1. This requirement retains 97% of the signal while removing 55% of the continuum background.

Figure 1(a) shows the $\phi \phi$ invariant mass spectrum for events in the $B^{\pm} \rightarrow \phi \phi K^{\pm}$ signal region, where a clear $\eta_c$ peak and some excess in the lower mass region are evident.

To extract signal yields, we apply an unbinned, extended maximum likelihood (ML) fit to the events with $|\Delta E| < 0.2 \text{ GeV}$ and $M_{bc} > 5.2 \text{ GeV}/c^2$. The extended likelihood for a sample of $N$ events is $L = e^{-(N_S+N_B)} \prod_{i=1}^{N} \left(N_S P_i^S + N_B P_i^B \right)$, where $P_i^S(B)$ describes the probability for candidate event $i$ to belong to the signal (background), based on its measured $M_{bc}$ and $\Delta E$ values. The exponential factor in the likelihood accounts for Poisson fluctuations in the total number of observed events $N$. The signal yield $N_S$ and the number of background events $N_B$ are obtained by maximizing $L$. The statistical errors correspond to unit changes in the quantity $\chi^2 = -2 \ln L$ around its minimum value. The significance of the signal is defined as the square root of the change in $\chi^2$ when constraining the number of signal events to zero in the likelihood fit; it reflects the probability for the background to fluctuate to the observed event yield.

The probability $P$ for a given event $i$ is calculated as the product of independent PDFs for $M_{bc}$ and $\Delta E$. The signal PDFs are represented by a Gaussian for $M_{bc}$ and a double Gaussian for $\Delta E$. The background PDF for $\Delta E$ is a linear function; for the $M_{bc}$ background we use a phase-space-like function with an empirical shape [8]. The parameters of the PDFs are determined from high-statistics MC samples for the signal and sideband data for the background.

For $M(\phi \phi) < 2.85 \text{ GeV}/c^2$, the region below the charm threshold, the ML fit gives an event yield of $7.3_{-2.5}^{+3.2}$ with a significance of 5.1 standard deviations ($\sigma$). Projections of the $\Delta E$ distribution (with $5.27 \text{ GeV}/c^2 < M_{bc} < 5.29 \text{ GeV}/c^2$ and of the $M_{bc}$ distribution (with $|\Delta E| < 30 \text{ MeV}$) are shown in Figs. 2(a,b). As a consistency check, a ML fit to the projected $\Delta E$ distribution (Fig. 2(b)) only gives a signal yield of $7.5_{-2.7}^{+3.3}$ with a 4.8$\sigma$ statistical significance. Figure 1(b) shows a scatter plot of the two $K^+ K^-$ invariant masses for events in the $B$ meson signal region with $M(K^+ K^- K^+ K^-) < 2.85 \text{ GeV}/c^2$ with the $\phi$ mass requirements relaxed. Here there is a clear concentration in the overlap region of the two $\phi$ bands. There is no event excess in the $\phi$ mass sidebands, which leads us to conclude that the observed signal is entirely due to $B^{\pm} \rightarrow \phi \phi K^{\pm}$. Using a signal efficiency of 3.3%, obtained from a large-statistics MC that uses three-body phase space to model the $B^{\pm} \rightarrow \phi \phi K^{\pm}$ decays, we determine the branching fraction for charmless $B^{\pm} \rightarrow \phi \phi K^{\pm}$ with $M_{\phi \phi} < 2.85 \text{ GeV}/c^2$ to be

$$B(B^{\pm} \rightarrow \phi \phi K^{\pm}) = (2.6^{+1.1}_{-0.9} \pm 0.3) \times 10^{-6},$$

where the first error is statistical and the second is systematic.

Contributions to the systematic error include the uncertainties due to the tracking efficiency (5.4%), particle identification efficiency (5%), and the modeling of the likelihood ratio cut (2%). The error due to the modeling of the likelihood ratio cut is determined using $B^- \rightarrow D^0(K^- \pi^+ \pi^- \pi^+)\pi^-$ events in the same data sample; these events have the same number of final-state particles and an event topology that is similar to the $B^{\pm} \rightarrow \phi \phi K^{\pm}$ signal. The uncertainty due to the MC $M_{\phi \phi}$ modeling (4%) accounts for the $M_{\phi \phi}$ dependence of
Events / (2 MeV/c²)  

2 4 6  

1 2 3  

We determine an upper limit of 5% on the possible contamination by non-resonant background. We assume that the signal and the shape parameters of the background are the same as the signal. Assuming isospin symmetry, we obtain a 90% confidence level (CL) upper limit of 3.7 signal events, which corresponds to

\[ B(B^\pm \rightarrow f_1(2220)K^\pm) \times B(f_1(2220) \rightarrow \phi \phi) < 1.2 \times 10^{-6}. \]

We select \( B^\pm \rightarrow \eta_c K^\pm \), \( \eta_c \rightarrow \phi \phi \) candidates by requiring 2.94 GeV/c² < \( M_{\phi \phi} \) < 3.02 GeV/c². A clear signal is evident in Figures 2(c,d), and the fitted yield of \( N_S = 7.0_{-2.3}^{+3.0} \) events has a significance of 8.8σ. The corresponding branching fraction is

\[ B(B^\pm \rightarrow \eta_c K^\pm) \times B(\eta_c \rightarrow \phi \phi) = (2.2^{+1.0}_{-0.7} \pm 0.5) \times 10^{-6}. \]

In addition to the previously listed sources of systematic error, here the error also includes the possible contamination from charmless \( B^\pm \rightarrow \phi \phi K^\pm \) decays, which is estimated to be less than 1.2 events. Using the measured branching fraction \( B(B^\pm \rightarrow \eta_c K^\pm) = (1.25 \pm 0.42) \times 10^{-3} \) [10], we determine the \( \eta_c \rightarrow \phi \phi \) branching fraction to be

\[ B(\eta_c \rightarrow \phi \phi) = (1.8^{+0.8}_{-0.6} \pm 0.7) \times 10^{-3}, \]

which is smaller than the current world average value of \( (7.1 \pm 2.8) \times 10^{-3} \) [5].

Since the \( J/\psi \) and \( \eta_c \) charmonium resonances also decay to \( 2(K^+ K^-) \), the decay chains \( B \rightarrow \) charmonium + \( K \) with charmonium \( \rightarrow 2(K^+ K^-) \) can provide consistency checks of the \( B \rightarrow \phi \phi K \) analysis. To select \( B \rightarrow 2(K^+ K^-) \) candidates, we apply tighter particle identification and continuum suppression requirements than in the case of \( B \rightarrow \phi \phi K \) in order to reduce the larger combinatoric background. Figure 3(a) shows the invariant mass distribution of any two pairs of \( K^+ K^- \), \( M_{4K} \), between 2.8 GeV/c² and 3.2 GeV/c² for the events in the \( B \) signal region. Significant contributions from both \( \eta_c \) and \( J/\psi \) intermediate states are seen.

To identify the signals from \( \eta_c \) and \( J/\psi \) intermediate states, we require that the invariant mass of \( 2(K^+ K^-) \) satisfy 2.94 GeV/c² < \( M_{4K} < 3.02 \) GeV/c² and 3.06 GeV/c² < \( M_{4K} < 3.14 \) GeV/c², respectively. We use signal yields from ML fits to determine branching fractions. Figures 2(e–h) show the \( M_{bc} \) and \( \Delta E \) projection plots with the fitted curves superimposed. Table I summarizes the signal yields, efficiencies, statistical significances, and the branching-fraction products. By requiring the invariant mass of one of the \( K^+ K^- \) pairs to correspond to a \( \phi \) meson, we also measure the decays of \( B^\pm \rightarrow \eta_c(J/\psi)K^\pm \) and \( \eta_c(J/\psi) \rightarrow \phi K^+ K^- \). The results are included in Table I.
TABLE II: Measured branching fractions of secondary charmonium decays and the world averages [5]. The branching fractions for modes with $K^+K^-$ pairs include contributions from $\phi \rightarrow K^+K^-$. 

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield (this work)</th>
<th>Efficiency (%)</th>
<th>Significance (σ)</th>
<th>$B \times 10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \rightarrow \phi K^+$ ($M_\phi &lt; 2.85 \text{ GeV/c}^2$)</td>
<td>7.3 $^{+2.4}_{-1.9}$</td>
<td>3.3</td>
<td>5.1</td>
<td>2.6 $^{+0.3}_{-0.3}$ ± 0.3</td>
</tr>
<tr>
<td>$B \rightarrow \phi K^+$ ($M_\phi &gt; 2.85 \text{ GeV/c}^2$)</td>
<td>8.7 $^{+2.9}_{-2.2}$</td>
<td>2.2</td>
<td>5.3</td>
<td>2.3 $^{+0.8}_{-0.8}$ ± 0.3</td>
</tr>
<tr>
<td>$B^+ \rightarrow J/\psi (2220)K^+$, $J/\psi (2220) \rightarrow \phi$</td>
<td>&lt; 3.7 $^{+0.9}_{-0.3}$</td>
<td>3.5</td>
<td>.</td>
<td>&lt; 1.2</td>
</tr>
<tr>
<td>$B^+ \rightarrow \eta_0 K^+$, $\eta_0 \rightarrow \phi$</td>
<td>7.0 $^{+1.0}_{-0.3}$</td>
<td>3.7</td>
<td>8.8</td>
<td>2.2 $^{+0.7}_{-0.8}$ ± 0.5</td>
</tr>
<tr>
<td>$B^+ \rightarrow \eta_0 K^+$, $\eta_0 \rightarrow \phi K^+$</td>
<td>14.3 $^{+4.4}_{-4.0}$</td>
<td>4.6</td>
<td>7.7</td>
<td>3.6 $^{+0.8}_{-0.8}$ ± 0.4</td>
</tr>
<tr>
<td>$B^0 \rightarrow \eta_0 K^+$, $\eta_0 \rightarrow 2(K^+K^-)$</td>
<td>14.6 $^{+2.1}_{-2.1}$</td>
<td>9.6</td>
<td>6.7</td>
<td>1.8 $^{+0.6}_{-0.6}$ ± 0.4</td>
</tr>
<tr>
<td>$B^0 \rightarrow J/\psi K^+$, $J/\psi \rightarrow \phi K^+$</td>
<td>9.0 $^{+1.0}_{-0.6}$</td>
<td>4.4</td>
<td>5.3</td>
<td>2.4 $^{+0.8}_{-1.0}$ ± 0.3</td>
</tr>
<tr>
<td>$B^0 \rightarrow J/\psi K^+$, $J/\psi \rightarrow 2(K^+K^-)$</td>
<td>11.0 $^{+1.3}_{-0.8}$</td>
<td>9.2</td>
<td>4.8</td>
<td>1.4 $^{+0.4}_{-0.4}$ ± 0.2</td>
</tr>
</tbody>
</table>

TABLE I: Signal yields, efficiencies including secondary branching fractions, statistical significances and branching fractions of $B \rightarrow \phi\phi K$ and related decays. The branching fractions for modes with $K^+K^-$ pairs include contributions from $\phi \rightarrow K^+K^-$. 

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$B$ (PDG)</th>
<th>$B$ (this work)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_c \rightarrow \phi \phi$</td>
<td>$(1.8^{+0.6}_{-0.8} \pm 0.7) \times 10^{-3}$</td>
<td>$(7.1 \pm 2.8) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\eta_c \rightarrow \phi K^+$</td>
<td>$(2.9^{+0.9}_{-0.8} \pm 1.1) \times 10^{-3}$</td>
<td>$(9.8 \pm 2.2) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\eta_c \rightarrow 2(K^+K^-)$</td>
<td>$(1.4^{+0.5}_{-0.6} \pm 0.6) \times 10^{-3}$</td>
<td>$(2.1 \pm 1.2) %$</td>
</tr>
<tr>
<td>$J/\psi \rightarrow \phi K^+$</td>
<td>$(2.4^{+0.6}_{-0.8} \pm 0.3) \times 10^{-3}$</td>
<td>$(7.4 \pm 1.1) \times 10^{-4}$</td>
</tr>
<tr>
<td>$J/\psi \rightarrow 2(K^+K^-)$</td>
<td>$(1.4^{+0.5}_{-0.4} \pm 0.2) \times 10^{-3}$</td>
<td>$(7.0 \pm 1.0) \times 10^{-4}$</td>
</tr>
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</table>

Using the known branching fractions $B(B^\pm \rightarrow J/\psi K^\pm) = (1.01 \pm 0.05) \times 10^{-3}$ [5] and $B(B^\pm \rightarrow \eta_c K^\pm)$, we obtain the secondary branching fractions for $J/\psi$ and $\eta_c$ decays to $2(K^+K^-)$ and $\phi K^+K^-$ listed in Table II.

Our measured branching fractions for $\eta_c \rightarrow \phi \phi$ and $\eta_c \rightarrow 2(K^+K^-)$ are smaller than those of previous experiments [5], while those for $J/\psi$ decays are consistent. The decay $\eta_c \rightarrow 2(K^+K^-)$ proceeds dominantly through $\eta_c \rightarrow \phi K^+K^- \rightarrow \phi K^+K^-$. This is the first measurement of $\eta_c \rightarrow \phi K^+K^-$. The decay of $\eta_c \rightarrow \phi \phi$ with $\phi \rightarrow K^+K^-$ makes up approximately $1/3$ of the branching fraction of $\eta_c \rightarrow \phi K^+K^-$. In summary, we have observed the charmed three-body decay $B \rightarrow \phi\phi K$, which is the first example of a $b \rightarrow s\bar{s}s\bar{s}$ transition. The branching fraction $B(B^\pm \rightarrow \phi\phi K^\pm) = (2.6^{+1.1}_{-0.9} \pm 0.3) \times 10^{-6}$ for $M_{\phi\phi} < 2.85 \text{ GeV/c}^2$, is measured with significances of $5.1 \sigma$. No signal is observed for the decay $B \rightarrow f_1(2220)K^\pm$ with $f_1(2220) \rightarrow \phi$. The corresponding upper limit at 90% C.L. is $B(B^\pm \rightarrow f_1(2220)K^\pm) \times B(f_1(2220) \rightarrow \phi) < 1.2 \times 10^{-6}$. We have also observed significant signals for $B^\pm \rightarrow \eta_c K^\pm$ with $\eta_c \rightarrow \phi \phi$, with $\eta_c \rightarrow \phi K^+K^-$, and with $\eta_c \rightarrow 2(K^+K^-)$, as well as a signal for $B^\pm \rightarrow J/\psi K^\pm$ with $J/\psi \rightarrow \phi K^+K^-$. We report the first measurement of $\eta_c \rightarrow \phi K^+K^-$ with a branching fraction of $B(\eta_c \rightarrow \phi K^+K^-) = (2.9^{+0.9}_{-0.8} \pm 1.1) \times 10^{-3}$. Our measured branching fractions for $\eta_c \rightarrow \phi \phi$ and $2(K^+K^-)$ are smaller than those of previous experiments.

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