Evidence for $B \to \phi\phi$


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We report evidence for 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. In the standard model (SM), this decay channel requires the creation of an additional final $s\bar{s}$ quark pair than in $b \rightarrow s\bar{s} s$ 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 $\phi \phi K$ state may be sensitive to glueball production in $B$ decays, where the glueball decays to $\phi \phi$ [1]. Furthermore, 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 $\eta_c$ resonance.

We use a 78 fb$^{-1}$ data sample collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ (3.5 on 8 GeV) collider [3] operating at the $Y(4S)$ resonance ($\sqrt{s} = 10.58$ GeV). The sample contains $85.0 \times 10^9$ produced $B\bar{B}$ 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 $K^0_S$ 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 a $K/\pi$ likelihood ratio, $L_K/(L_\pi + L_K)$, where $L_{K(\pi)}$ are likelihoods derived from responses of the TOF and ACC systems and $dE/dx$ measurements in the CDC. We select kaon candidates by requiring $L_K/(L_\pi + L_K) > 0.6$. This requirement has a kaon efficiency varying from $89.6 \pm 1.0\%$ for momentum of 500 MeV to $86.9 \pm 0.4\%$ for momentum of 3 GeV and a mismeasurement rate from pions of 8.5%. Kaon candidates that are electronlike 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 $B^0(B^0) \rightarrow \phi \phi K^0_S$ decay mode, we use $K^0_S \rightarrow \pi^+\pi^-$ 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, \( M_{bc} = \sqrt{E_{\text{beam}}^2 - |\vec{p}_{\text{recon}}|^2} \), and the energy difference \( \Delta E = E_{\text{recon}} - E_{\text{beam}} \). Here \( E_{\text{beam}} \) is the beam energy, 
and \( E_{\text{recon}} \) and \( \vec{p}_{\text{recon}} \) are the reconstructed energy and 
momentum of the signal candidate, in the Y(4S) center-
of-mass frame. The signal region for \( \Delta E \) is \( \pm 30 \) MeV 
which corresponds to \( \pm 3.1 \sigma \), where \( \sigma \) is the 
resolution determined from a Gaussian fit to the Monte Carlo 
(MC) simulation and verified using the decay of \( B^+ \to 
D^0 \pi^+ \) and \( D^0 \to K^+ \pi^- \pi^+ \pi^- \). The signal region for 
\( M_{bc} \) is 5.27 GeV/c\(^2\) < \( M_{bc} \) < 5.29 GeV/c\(^2\). 
The beam-constrained mass resolution is 2.8 MeV/c\(^2\), which is 
mostly due to the beam energy spread of KEKB.

The major background for the \( B \to \phi \phi K \) process is 
from continuum \( e^+ e^- \to qq \) production, where \( q \) is a 
light quark \( (u, d, s, \text{ or } c) \). Several event topology variables 
are used to discriminate the continuum background, 
which tends to be collimated along the original quark 
direction, from the \( B \bar{B} \) events, which are more isotropic 
than the former. Five modified Fox-Wolfram moments, 
the \( S_2 \) variable [6], and the cosine of the thrust angle are 
combined into a Fisher discriminant [7]. We form signal 
and background probability density functions (PDFs) for 
this Fisher discriminant and for the cosine of the \( B \) decay 
angle with respect to the \( z \) axis \( (\cos \theta_B) \) for the signal MC 
and sideband data. The PDFs are multiplied 
together to form signal and background likelihoods, \( L_S \) 
and \( L_{BG} \). The likelihood ratio \( L_R = L_S / (L_S + L_{BG}) \) 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 \( B^+ \to \phi \phi K^+ \) 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 \( |\Delta E| < 0.2 \) GeV and \( M_{bc} > 5.2 \) GeV/c\(^2\). The 
extended likelihood for a sample of \( N \) events is 
\( L = e^{-\left(N_S + N_B\right) \mu \vec{P}^2} \prod_{i=1}^{N_S} N_S \left( \chi_i^2 + N_B \right) P_i^{(B)} \), where \( P_i^{(B)} \) 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 \( P \) 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 \( M(\phi \phi) < 2.85 \) GeV/c\(^2\), the region below the 
charm thresh hold, the ML fit gives an event yield of 
7.3 +3.2 
with a significance of 5.1 standard deviations \( (\sigma) \). Projections of the \( \Delta E \) distribution 
(5.27 GeV/c\(^2\) < \( M_{bc} \) < 5.29 GeV/c\(^2\)) and of the \( M_{bc} \) 
distribution (with \( |\Delta E| < 30 \) MeV) are shown in Figs. 2(a) 
and 2(b). As a consistency check, a ML fit to the 
projected \( \Delta E \) distribution [Fig. 2(b)] gives a signal yield 
of 7.5 +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 the \( \phi \) mass 
requirements relaxed. Here there is a clear concentration 
in the overlap region of the two \( \phi \) bands. To confirm that 
the observed signal is from \( B^+ \to \phi \phi K^+ \), we apply a tighter \( \phi \) mass requirement (\( \pm 10 \) MeV/c\(^2\)), which reduces 
the signal efficiency by 15\%, and obtain a signal 
yield of 5.6 with 4.6\( \sigma \) statistical significance. Using a 
signal efficiency of 3.3\%, obtained from a large-statistics 
MC that uses three-body phase space to model the \( B^+ \to 
\phi \phi K^+ \) decays, we determine the branching fraction for 
charmless \( B^+ \to \phi \phi K^+ \) with \( M_{\phi \phi} < 2.85 \) GeV/c\(^2\) to be 
\( \mathcal{B}(B^+ \to \phi \phi K^+) = (2.6^{+1.1}_{-0.9} \pm 0.3) \times 10^{-6} \),
where the first error is statistical and the second is 
 systematic.

FIG. 1 (color online). (a) \( \phi \phi \) invariant mass spectrum. The 
open histogram corresponds to events from the \( B^+ \to \phi \phi K^+ \) 
signal region and the shaded histogram corresponds to events 
from the \( \Delta E \) sidebands. (b) \( M_{K^+ K^-} \) of one \( \phi \) meson candidate 
versus \( M_{K^+ K^-} \) of the other for the events satisfying \( M_{\phi \phi} < 
2.85 \) GeV/c\(^2\). Dots are for \( \phi \phi K^+ \) and squares for \( \phi \phi K_0 \). 
Each event is plotted twice for combinations. The dashed box shows 
the selected signal region.
quadrature to obtain the final systematic error of relaxed. The sources of systematic error are combined in $B^0(B^0)$ signal candidates. We combine the decays by redoing the fits with the $M^*/0.0030/0.0030$ and an event topology that is similar to the $B^+$ decays. These events have the same number of final-state particles and the shape parameters of the background. We determine an uncertainty due to the tracking efficiency ($2\%$), likelihood ratio cut ($5\%$), identification efficiency ($4\%$), and the modeling of the background, estimated from the sideband, of $0.5$. Using an extended Cousins-Highland method that uses the Feldman-Cousins ordering scheme and takes systematic uncertainties into account [9], we obtain a $90\%$ confidence level (C.L.) upper limit of $3.7$ signal events, which corresponds to

$$B(B^+ \rightarrow \phi \phi K^-) < 1.2 \times 10^{-6}.$$ 

No enhancement is observed in the $M_{\phi \phi}$ region corresponding to the $f^0_1(2220)$ glueball candidate [5], also referred to as $\xi$. Assuming the mass and width of $f^0_1(2220)$ to be $2230$ MeV/$c^2$ and $20$ MeV/$c^2$, we define a signal region of $2.19$ GeV/$c^2 < M_{\phi \phi} < 2.27$ GeV/$c^2$, $5.27$ GeV/$c^2 < M_{bc} < 5.29$ GeV/$c^2$, and $|\Delta E| < 30$ MeV. One event is observed in this region with an expected background, estimated from the sideband, of $0.5$. Using an extended Cousins-Highland method that uses the Feldman-Cousins ordering scheme and takes systematic uncertainties into account [9], we obtain a $90\%$ confidence level (C.L.) upper limit of $3.7$ signal events, which corresponds to

$$B(B^+ \rightarrow f^0_1(2220)K^-) \times B(f^0_1(2220) \rightarrow \phi \phi) < 1.2 \times 10^{-6}.$$ 

We select $B^+ \rightarrow \eta_c K^+$, $\eta_c \rightarrow \phi \phi$ candidates by requiring $2.94$ GeV/$c^2 < M_{\phi \phi} < 3.02$ GeV/$c^2$. This decay has been searched by previous experiments [10]. A clear signal is evident in Figs. 2(c) and 2(d), and the fitted yield of $N_5 = 7.0^{+3.0}_{-1.1}$ events has a significance of $8.8\sigma$. The corresponding product branching fraction is

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

In addition to the previously listed source of systematic errors, here the error also includes the possible contamination from charmless $B^0 \rightarrow \phi \phi K^0$ decays, which is estimated to be less than $1.2$ events. We select a signal region, and the shaded corresponds to events from the $B$ signal region, and the shaded corresponds to events from the $M_{bc}-\Delta E$ sidebands.

![FIG. 2 (color online). Projections of $M_{bc}$ and $\Delta E$ overlaid with the fitted curves for (a),(b) $B^0(B^0) \rightarrow \phi \phi K^- \rightarrow \phi \phi K^-$ with $M_{\phi \phi} < 2.85$ GeV/$c^2$, (c),(d) $B^+ \rightarrow \eta_c K^+$ and $\eta_c \rightarrow \phi \phi$, (e),(f) $B^+ \rightarrow \eta_c K^+$ and $\eta_c \rightarrow 2(K^+ K^-)$, and (g),(h) $B^+ \rightarrow J/\psi K^+$ and $J/\psi \rightarrow 2(K^+ K^-)$.

Contributions to the systematic error include the uncertainties due to the tracking efficiency ($5\%$), 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 $B^- \rightarrow D^0(\rightarrow K^- \pi^+ \pi^- \pi^0)\pi^-$ 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 $B^0 \rightarrow \phi \phi K^0$ signal. The uncertainty due to the MC $M_{\phi \phi}$ modeling ($4\%$) accounts for the $M_{\phi \phi}$ dependence of the detection efficiency. The systematic error in the signal yield ($6\%$) is determined by varying the means and $\sigma$ of the signal and the shape parameters of the background. We determine an upper limit of $5\%$ on the possible contamination by non-resonant $B^+ \rightarrow \phi (K^+ K^-)_{NR} K^+$ or $B^+ \rightarrow 2(K^+ K^-)_{NR} K^+$ decays by redoing the fits with the $\phi$ mass requirement relaxed. The sources of systematic error are combined in quadrature to obtain the final systematic error of $12\%$.

For the $B^0(B^0) \rightarrow \phi \phi K^0_S$ mode, there are only four signal candidates. We combine the $B^0(B^0) \rightarrow \phi \phi K^0_S$ and $B^0(B^0) \rightarrow \phi \phi K^0_S$ modes and perform a ML fit and obtain a signal event yield of $8.7^{+3.0}_{-2.9}$ with $5.3\sigma$ statistical sign-

ificance. Assuming isospin symmetry, we obtain

$$B(B^+ \rightarrow \phi \phi K^-) = (2.3^{+0.8}_{-0.7} \pm 0.3) \times 10^{-6},$$

for $M_{\phi \phi} < 2.85$ GeV/$c^2$.
TABLE I. Signal yields, efficiencies including secondary branching fractions, statistical significances, and branching fractions (or branching fraction products) of $B \to \phi K\Lambda$ and the related decays. The branching fractions for modes with $K^+ K^-$ pairs include contributions from $\phi \to K^+ K^-$. Since the $J/\psi$ and $\eta_c$ charmonium resonances decay to $2(K^+ K^-)$, we also measure branching fractions of the decays $B \to$ charmonium $+ K$ with charmonium $\to 2(K^+ K^-)$. To select $B \to 2(K^+ K^-)K$ candidates, we apply tighter particle identification and continuum suppression requirements than in the case of $B \to \phi K\Lambda$ in order to reduce the larger combinatorial background. Figure 3(a) shows the invariant mass distribution of any two pairs of $K^+ K^-$, $M_{4K}$, between 2.8 GeV/$c^2$ and 3.2 GeV/$c^2$ 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 $2.94 \text{GeV}/c^2 < M_{4K} < 3.02 \text{GeV}/c^2$ and $3.06 \text{GeV}/c^2 < M_{4K} < 3.14 \text{GeV}/c^2$, respectively. We use yield signals from ML fits to determine branching fractions. Figures 2(e)–2(h) show the $M_{bc}$ and $\Delta E$ projection plots with the fitted curves superimposed. Table I summarizes the yield, 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 $B^0 \to \eta_c(J/\psi)K^0$ and $\eta_c(J/\psi) \to \phi K^+ K^-$. The results are included in Table I.

Using the known branching fractions $B(B^+ \to \phi K^+) = (1.01 \pm 0.05) \times 10^{-3}$ [5] and $B(B^0 \to \eta_c K^0)$, 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 $\eta_c \to \phi \phi$ and $\eta_c \to 2(K^+ K^-)$ are smaller than those of previous experiments [5], while those for $J/\psi$ decays are consistent. The decay $\eta_c \to 2(K^+ K^-)$ proceeds dominantly through $\eta_c \to \phi K^+ K^-$ with $\phi \to K^+ K^-$. This is the first measurement of $\eta_c \to \phi K^+ K^-$. The decay of $\eta_c \to \phi \phi$ with $\phi \to K^+ K^-$ makes up approximately $1/3$ of the branching fraction of $\eta_c \to \phi K^+ K^-$. In summary, we have observed evidence for the charmless three-body decay $B \to \phi \phi K$, which is the first example of a $b \to s\pi s\pi s$ transition. The branching fraction $B(B^0 \to \phi \phi K^0) = (2.65 \pm 0.11 \pm 0.3) \times 10^{-6}$ for $M_{4K} < 2.85 \text{GeV}/c^2$, is measured with a significance of $5.1 \sigma$. No signal is observed for the decay $B \to J/\psi K^0$ with $J/\psi \to \phi \phi$. The corresponding upper limit at 90% C.L. is $B(B^0 \to J/\psi K^0) < 1.2 \times 10^{-6}$. We have also observed significant signals for $B^0 \to \eta_c K^0$ with $\eta_c \to \phi \phi$, with $\eta_c \to \phi K^+ K^-$, and with $\eta_c \to 2(K^+ K^-)$, as well as a signal for $B^0 \to J/\psi K^0$ with $J/\psi \to K^+ K^-$. We report the first measurement of $\eta_c \to \phi K^+ K^-$ with a branching fraction of $B(\eta_c \to \phi K^+ K^-) = (2.9 \pm 0.9 \pm 1.1) \times 10^{-3}$. Our measured branching fractions for $\eta_c \to \phi \phi$ and $2(K^+ K^-)$ are smaller than those of previous experiments.

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<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield</th>
<th>Efficiency (%)</th>
<th>Significance ($\sigma$)</th>
<th>$B$ ($\times 10^{-6}$)</th>
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<tbody>
<tr>
<td>$B^0 \to \phi \phi K^0 (M_{4K} &lt; 2.85 \text{GeV}/c^2)$</td>
<td>$7.3^{+5.2}_{-2.5}$</td>
<td>$3.3 \pm 0.3$</td>
<td>5.1</td>
<td>$2.6^{+1.1}_{-0.9} \pm 0.3$</td>
</tr>
<tr>
<td>$B \to \phi K (M_{4K} &lt; 2.85 \text{GeV}/c^2)$</td>
<td>$8.7^{+3.6}_{-2.9}$</td>
<td>$2.2 \pm 0.2$</td>
<td>5.3</td>
<td>$2.3^{+0.9}_{-0.8} \pm 0.3$</td>
</tr>
<tr>
<td>$B^0 \to f_s(2220)K^0$, $f_s(2220) \to \phi \phi$</td>
<td>$&lt;3.7$</td>
<td>$3.6 \pm 0.3$</td>
<td>$&lt;1.2$</td>
<td></td>
</tr>
<tr>
<td>$B \to \eta_c K^0$, $\eta_c \to \phi \phi$</td>
<td>$7.0^{+3.0}_{-2.3}$</td>
<td>$3.7 \pm 0.3$</td>
<td>8.8</td>
<td>$2.2^{+0.5}_{-0.7} \pm 0.5$</td>
</tr>
<tr>
<td>$B^0 \to \eta_c K^0$, $\eta_c \to \phi K^+ K^-$</td>
<td>$14.1^{+5.4}_{-3.7}$</td>
<td>$4.6 \pm 0.4$</td>
<td>7.7</td>
<td>$3.6^{+1.0}_{-0.9} \pm 0.8$</td>
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<tr>
<td>$B^0 \to \eta_c K^0$, $\eta_c \to 2(K^+ K^-)$</td>
<td>$14.6^{+5.6}_{-3.9}$</td>
<td>$9.6 \pm 0.9$</td>
<td>6.6</td>
<td>$1.8^{+0.5}_{-0.6} \pm 0.4$</td>
</tr>
<tr>
<td>$B \to J/\psi K^0$, $J/\psi \to \phi K^+ K^-$</td>
<td>$9.0^{+5.7}_{-3.0}$</td>
<td>$4.4 \pm 0.4$</td>
<td>5.3</td>
<td>$2.4^{+1.0}_{-0.8} \pm 0.3$</td>
</tr>
<tr>
<td>$B^0 \to J/\psi K^0$, $J/\psi \to 2(K^+ K^-)$</td>
<td>$11.0^{+5.3}_{-3.3}$</td>
<td>$9.2 \pm 0.9$</td>
<td>4.8</td>
<td>$1.4^{+0.5}_{-0.4} \pm 0.2$</td>
</tr>
</tbody>
</table>

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 $\phi \to K^+ K^-$.  

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$B$ (this work)</th>
<th>$B$ (PDG)</th>
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<tbody>
<tr>
<td>$\eta_c \to \phi \phi$</td>
<td>$(1.8^{+0.8}_{-0.6} \pm 0.7) \times 10^{-3}$</td>
<td>$(7.1 \pm 2.8) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\eta_c \to \phi K^+ K^-$</td>
<td>$(2.9^{+0.9}_{-0.8} \pm 1.1) \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>$\eta_c \to 2(K^+ K^-)$</td>
<td>$(1.4^{+0.5}_{-0.4} \pm 0.6) \times 10^{-3}$</td>
<td>$(2.1 \pm 1.2) %$</td>
</tr>
<tr>
<td>$J/\psi \to \phi K^+ K^-$</td>
<td>$(2.4^{+1.0}_{-0.8} \pm 0.3) \times 10^{-3}$</td>
<td>$(7.4 \pm 1.1) \times 10^{-4}$</td>
</tr>
<tr>
<td>$J/\psi \to 2(K^+ K^-)$</td>
<td>$(1.4^{+0.5}_{-0.4} \pm 0.2) \times 10^{-3}$</td>
<td>$(7.0 \pm 3.0) \times 10^{-4}$</td>
</tr>
</tbody>
</table>
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