Observation of $B_s^0 \rightarrow J/\psi f_0(980)$ and Evidence for $B_s^0 \rightarrow J/\psi f_0(1370)$
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We report the first observation of \( B_s^0 \to J/\psi f_0(980) \) and first evidence for \( B_s^0 \to J/\psi f_0(1370) \), which are CP eigenstate decay modes. These results are obtained from 121.4 fb\(^{-1} \) of data collected at the \( \Upsilon(5S) \) resonance with the Belle detector at the KEKB \( e^+e^- \) collider. We measure the branching fractions \( B(B_s^0 \to J/\psi f_0(980); f_0(980) \to \pi^+\pi^-) = (1.16^{+0.31}_{-0.19}(\text{stat.})^{+0.15}_{-0.17}(\text{syst.})^{+0.26}_{-0.18}(N_{\phi(1020)}^a)) \times 10^{-4} \) with a significance of 8.4\( \sigma \), and \( B(B_s^0 \to J/\psi f_0(1370); f_0(1370) \to \pi^+\pi^-) = (0.34^{+0.14}_{-0.11}(\text{stat.})^{+0.03}_{-0.02}(\text{syst.})^{+0.08}_{-0.05}(N_{\phi(1020)}^a)) \times 10^{-4} \) with a significance of 4.2\( \sigma \). The last error listed is due to uncertainty in the number of produced \( B_s^{(*)} \) pairs.

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The \( b \to c\bar{c}s \) process \( B_s^0 \to J/\psi \phi \), which has a relatively large branching fraction, has been used to extract the \( B_s^0 \) decay width difference \( \Delta \Gamma \) and CP-violating phase \( \beta_s \) from time-dependent angular analyses [1]. The parameter \( \beta_s \) is expected to be small in the Standard Model and can be sensitive to New Physics (NP). The same \( b \to c\bar{c}s \) process can also produce the decay \( B_s^0 \to J/\psi f_0(980) \) [2], which is another promising channel for accessing the CP violation parameter, with the clear advantage that no angular analysis is required because the \( J^P = 0^+ \) quantum numbers of the \( f_0(980) \) restrict the \( J/\psi \) and \( f_0(980) \) to be in a relative P-wave in contrast to a vector-vector channel such as \( B_s \to J/\psi \phi \) in which three partial waves are allowed.

A recent study [3] also shows that measurement of the branching fraction \( B(B_s^0 \to J/\psi f_0(980)) \) can be used to estimate the background from \( B_s^0 \to J/\psi f_0(980) \), \( f_0 \to K^-K^+ \) decays and the corresponding bias in the \( B_s \to J/\psi \phi \), \( \phi \to K^-K^+ \) analysis of \( \beta_s \), the CP violation parameter relevant to NP searches. Leading-order light-cone QCD predicts that \( B(B_s^0 \to J/\psi f_0(980)) = (3.1 \pm 2.4) \times 10^{-4} \) [4]. The ratio \( \mathcal{R}_{f_0/\phi} = \frac{\Gamma(B_s^0 \to J/\psi f_0(980))}{\Gamma(B_s^0 \to J/\psi \phi)} \) is expected to lie in the range \( 0.2 \lesssim \mathcal{R}_{f_0/\phi} \lesssim 0.5 \), based on scaling from the measurements of \( D_s \) decays to \( f_0 \) and \( \phi \) mesons [2, 5]. Using the value \( B(B_s^0 \to J/\psi \phi) = (1.3 \pm 0.4 \pm 0.2) \times 10^{-3} \) [6], we obtain \( 1.3 \times 10^{-4} \lesssim B(B_s^0 \to J/\psi f_0(980); f_0(980) \to \pi^+\pi^-) \lesssim 3.2 \times 10^{-4} \).

We study \( B_s^0 \to J/\psi f_0(980) \) in fully reconstructed \( B_s^0 \to J/\psi \pi^+\pi^- \) final states using a 121.4 fb\(^{-1} \) data sample collected at the \( \Upsilon(5S) \) resonance with the Belle detector at the KEKB collider [7]. \( B_s^0 \) mesons can be produced in three \( \Upsilon(5S) \) decays: \( \Upsilon(5S) \to B_s^0 B_s^0 \), \( B_s^+ B_s^- \) and \( B_s^0 \bar{B}_s^0 \) where the \( B_s^* \) mesons decay to \( B_s^0 \gamma \). The number of \( B_s^{(*)} \) pairs in the sample is measured to be \( N_{B_s^{(*)}B_s^{(*)}} = (7.1 \pm 1.3) \times 10^6 \) using inclusive \( D_s \) production modes described in [8, 9]. Using fully reconstructed \( B_s^0 \to D_s^- \pi^+ \) decays as described in [10], we determine the fraction of \( B_s^* \) pairs among all \( B_s^{(*)} \) events to be \( f_{B_s^*} = 87.0 \pm 1.7 \)\% in the sample. The number of \( B_s^0 \) mesons in the dominant \( B_s^-B_s^0 \) production mode is thus \( N_{B_s^0} = 2N_{B_s^{(*)}B_s^{(*)}} f_{B_s^*} = (1.24 \pm 0.23) \times 10^7 \).

The Belle detector [11] is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector, a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-
like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside the coil is instrumented to detect $K_L^0$ mesons and identify muons (KLM).

Charged tracks are required to originate within 0.5 cm in the radial direction and within 5 cm along the beam direction with respect to the interaction point in the cylindrical geometry of the Belle detector. Electrons or charged pions are identified by combining information from the ECL or TOF, the CDC $(dE/dx)$, and the ACC [11]. Muon candidates are identified through their track penetration depth and hit patterns in the KLM system. For both electrons and muons, the identification efficiency is nearly 100%. For a pion from $B^0_d \to J/\psi\phi(980)$, the momentum-averaged identification efficiency is about 96% with a 22% kaon misidentification probability.

Two oppositely charged leptons $l^+l^-$ ($l = e$ or $\mu$) and any bremsstrahlung photons lying within 50 mrad of an $e^+$ or $e^-$ track are combined to form a $J/\psi$ candidate. The invariant mass is required to lie in the ranges $-0.150 \text{ GeV}/c^2 < M_{\text{in}} < 0.036 \text{ GeV}/c^2$ or $-0.060 \text{ GeV}/c^2 < M_{\mu\mu} - m_{J/\psi} < 0.036 \text{ GeV}/c^2$, where $m_{J/\psi}$ denotes the $J/\psi$ mass, and $m_{\mu\mu}$ or $M_{\mu\mu}$ is the reconstructed invariant mass for $e^+e^-(\gamma)$ or $\mu^+\mu^-$, respectively. We combine the $J/\psi$ candidate and a $\pi^+\pi^-$ pair to form a $B^0_d$ candidate. The $\pi^+\pi^-$ and $J/\psi$ vertex positions are required to be consistent.

Two kinematic variables are computed in the $e^+e^-$ collision rest frame: the energy difference $\Delta E = E_{B^*} - E_{\text{beam}}$, and the beam-energy constrained mass $M_{bc} = \sqrt{(E_{\text{beam}})^2 - (p_B^0)^2}$, where $E_B^*$ and $p_B^0$ are the energy and momentum of the reconstructed $B^*_0$ candidates and $E_{\text{beam}}$ is the beam energy. To improve the $\Delta E$ and $M_{bc}$ resolutions, mass-constrained kinematic fits are applied to $J/\psi$ candidates. After an initial loose selection, 66% of events have multiple candidates. From these we choose the candidate with the $M_{bc}$ value closest to the nominal $B^*_0$ mass. This requirement has an efficiency of 90% for the correctly reconstructed signal in the $\Upsilon(5S) \to B^*_0B^*_0$ channel, according to Monte Carlo (MC) simulations. We then select events that lie inside a $3\sigma$ $M_{bc}$ signal region for $B^*_0B^*_0$ with the criterion $5.4041 \text{ GeV}/c^2 < M_{bc} < 5.4275 \text{ GeV}/c^2$, which completely rejects the small $\Upsilon(5S) \to B^*_0(\gamma)B^*_0$ contribution and retains only candidates from the dominant $\Upsilon(5S) \to B^*_0B^*_0$ production process. We use $\Delta E$ and the $\pi^+\pi^-$ invariant mass $M_{\pi\pi}$ to extract the signal.

To suppress two-jet-like continuum background arising from $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) processes, we require the ratio of the second to zeroth Fox-Wolfram moments [12] to be less than 0.4. This requirement is optimized by maximizing the figure-of-merit $N_{3r}/\sqrt{N_S + N_B}$, where $N_S$ is the expected number of signal events and $N_B$ is the expected number of background events in the $(\Delta E, M_{\pi\pi})$ signal box. Other significant background sources are from $B\bar{B}$ ($B = B_s^0, B_{d^0}^0, B_d^\pm$) events with one $B$ meson decaying to a final state with a $J/\psi$ (denoted $J/\psi X$). We use a sample of simulated $\Upsilon(5S)$ decays, with the most recent $B$ meson pair production rates [13] and all known $B \to J/\psi X$ processes, to estimate this background. The fit region is chosen to be $-0.1 \text{ GeV} < \Delta E < 0.2 \text{ GeV}$ and $M_{\pi\pi} < 2.0 \text{ GeV}/c^2$. Background from $B_{d^0}^0 \to J/\psi\pi^+\pi^-$ peaks near $\Delta E = -0.14 \text{ GeV}$ and lies entirely outside the fit region.

A study of the $J/\psi X$ MC simulation is used to categorize these background components according to their origins and shapes. The expected yields in the fit region from each source are: (a) $B_s^0 \to J/\psi\eta'$, 2.6 events, with $\eta' \to \rho^0\gamma$ in which the photon is lost; (b) $B^+ \to J/\psi K^+$, (c) $B^+ \to J/\psi K^+$, (d) $K^+ \to J/\psi K^+$, (c) other $J/\psi X$ sources, 240.4 events, that do not peak in $\Delta E$ and $M_{\pi\pi}$. There are negligible correlations between $\Delta E$ and $M_{\pi\pi}$ for (b) and (c), which are parameterized by the product of a smooth $\Delta E$ function with a threshold $M_{\pi\pi}$ function for the two-dimensional probability density function (PDF). The $B^+ \to J/\psi K^+$ and $B^+ \to J/\psi\pi^+\pi^-$ background shapes are treated separately. For (a), the shape and yield are obtained from a dedicated MC simulation and the measured branching fraction [14], where a MC-generated two-dimensional PDF is used, since there are correlations between $\Delta E$ and $M_{\pi\pi}$ that are difficult to parameterize analytically. The non-$J/\psi$ background is studied with data from a $J/\psi$ mass ($M_{\Upsilon(\gamma)}$) sideband defined as $2.5 \text{ GeV}/c^2 < M_{\Upsilon(\gamma)} < 3.4 \text{ GeV}/c^2$, with the regions $-0.200 \to -0.080 \text{ GeV}/c^2 < M_{\Upsilon(\gamma)} - m_{J/\psi} < 0.048 \text{ GeV}/c^2$ for $J/\psi \to e^+e^- (\mu^+\mu^-)$ excluded. MC-determined scale factors 0.226 (0.097) for the ratio of the non-$J/\psi$ yield in the $J/\psi$ selection window to the yield in the $J/\psi$ sideband region are used in the $e e (\mu\mu)$ channels. We fix the non-$J/\psi$ background yield to 122.7 in the fit region. The non-$J/\psi$ background shape is obtained by fitting the $J/\psi$ sideband data with relaxed lepton identification requirements to enhance the statistics.

Figure 1 shows the data together with the fitting function. The $M_{\pi\pi}$ distribution in Fig. 1(a) includes a selection on the $\Delta E$ signal region, which has a width of 60 MeV; this is much narrower than the width of the $\Delta E$ fit region, 300 MeV. We find two peaks in the $M_{\pi\pi}$ spectrum of the events in the $\Delta E$ signal region: one for $f_0(980)$ and another around 1.4 GeV/$c^2$. We model the signal $M_{\pi\pi}$ PDF as a coherent sum of a Flatté function [15] for the $f_0(980)$ resonance and a relativistic Breit-Wigner function for a second $f_X$ resonance with mass $m_0(f_X)$ and
width $\Gamma_0(f_X):$

$$P(M_{\pi\pi}) = p_{J/\psi} \left| \frac{p_{J/\psi} \sqrt{M_{\pi\pi} \Gamma_1}}{m_0(f_0)^2 - M_{\pi\pi}^2 - i(g_1 \rho_1 + g_2 \rho_2)} + a e^{i\theta} \frac{p_{J/\psi} \sqrt{M_{\pi\pi} \Gamma(f_X)}}{(M_{\pi\pi}^2 - m_0(f_X)^2 - i m_0(f_X) \Gamma(f_X))^2} \right|^2,$$

where the phase-space factors are $\rho_1 = 2q/M_{\pi\pi}$, $\rho_2 = 2q_K/M_{\pi\pi}$, and the mass-dependent widths are $\Gamma_1 = g_1 \rho_1 m_0$ and $\Gamma(f_X) = \Gamma_0(f_X)(q/g_0)(m_0(f_X)/M_{\pi\pi})$. Here $q$ (or $g_0$) is the pion momentum in the di-pion rest frame where the di-pion mass is $M_{\pi\pi}$ ($m_0$), while $q_K$ is the momentum a kaon would have if the resonance decayed to a kaon pair. The $J/\psi$ momentum in the $B_s^0$ rest frame, $p_{J/\psi}$, is a phase-space factor outside the modulus, and a spin factor inside the modulus for $L = 1$. The Flatté function follows the BES parameterization [16], with the parameters $m_0(f_0) = 965 \pm 10$ MeV/$c^2$, $g_1 = 0.165 \pm 0.018$ GeV$^2/c^4$, and $g_2/g_1 = 4.21 \pm 0.33$. The $\Delta E$ PDF for the signal is parameterized as a sum of two Gaussians with widths calibrated using a control sample of $\Upsilon(5S) \rightarrow B_s^0 \bar{B}_d^0$, $B_s^0 \rightarrow J/\psi K^{*0}(K^+\pi^-)$ in data.

Contributions from the self-cross-feed (SCF) events in which one or two pion tracks from the signal are mis-reconstructed as well as non-resonant $B_s^0 \rightarrow J/\psi\pi^+\pi^-$ events are also considered. The SCF component is fixed to the MC value of 6.0% of the total signal yield in the fit region; the PDF shape is modeled with a non-parametric histogram. For the non-resonant component, the $M_{\pi\pi}$ shape is obtained from a phase-space model and the $\Delta E$ shape is the same as that of the $J/\psi f_0$ signal.

An unbinned extended maximum likelihood fit to the data is performed using the sum of all component PDFs. The parameters allowed to vary in the fit are the total resonant signal yield, which includes the SCF contribution, parameters $a$, $\theta$, $m_0(f_X)$, $\Gamma_0(f_X)$, the yield of the non-resonant component, and the yield of other $J/\psi X$ background. The yield of the $J/\psi(K,\pi)$ background is fixed to the MC expectation.

We obtain $98 \pm 15$ resonant events corresponding to Eq. (1), where $63^{+16}_{-10}$ are from $B_s^0 \rightarrow J/\psi f_0(980)$ and $19^{+6}_{-8}$ are from $B_s^0 \rightarrow J/\psi f_X$, and the rest are from the interfer-ence. The yield for each signal component is calculated using the amplitude squared of that component divided by the coherent sum of all amplitudes squared, with statistical errors obtained from error propagation using the covariance matrix of relevant parameters. The amplitude and phase parameters are determined to be $a = 0.47 \pm 0.10$ and $\theta = 1.63 \pm 0.98$ rad. The fitted mass and width for the $f_X$ component are $m_0 = 1.405 \pm 0.015^{+0.001}_{-0.007}$ GeV/$c^2$ and $\Gamma_0 = 0.054 \pm 0.033^{+0.014}_{-0.003}$ GeV, where the first error is statistical and the second is systematic. These results are consistent with the $f_0(1370)$ parameters listed in the PDG [17]. Henceforth, we refer to this contribution as $B_s^0 \rightarrow J/\psi f_0(1370)$; however, the possibility of other scalar resonance contributions in this region cannot be excluded with the present statistics. The obtained non-resonant yield is $4 \pm 12$, consistent with zero. The yield of other $J/\psi$ background $262 \pm 23$ is consistent with the MC estimate of 240 events. The $J/\psi$ helicity distributions, shown in Fig. 2, are consistent with a longitudinally polarized $J/\psi$ in both $f_0(980)$ and $f_0(1370)$ signal regions, as expected for scalar $\pi \pi$ resonances.

The signal yields, branching fractions, and significances including systematic uncertainties are listed in Table I. The significance is calculated from the log likelihood difference for two parameters in the $f_0(980)$ case and four parameters in the $f_0(1370)$ case, when the corresponding signal amplitude is set to zero.

Contributions to the systematic error are obtained by
TABLE I: Summary of signal yields, significances, and product branching fractions $\mathcal{B}(B_s^0 \to J/\psi f_0(980); F \to \pi^+\pi^-)$, where $F = f_0(980)$ or $f_0(1370)$.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0 \to J/\psi f_0(980)$</td>
<td>$63^{+16}_{-10}$</td>
<td>8.4σ</td>
</tr>
<tr>
<td>$B_s^0 \to J/\psi f_0(1370)$</td>
<td>$19^{+6}_{-4}$</td>
<td>4.2σ</td>
</tr>
</tbody>
</table>

$\mathcal{B}(B_s^0 \to J/\psi f_0; F \to \pi^+\pi^-)$

\[
\begin{align*}
\mathcal{B}(B_s^0 & \to J/\psi f_0(980); f_0(980) \to \pi^+\pi^-) \\
& = (1.16^{+0.31}_{-0.19}\text{(stat.)} \pm 0.12\text{(syst.)}) \times 10^{-4} \\
\mathcal{B}(B_s^0 & \to J/\psi f_0(1370); f_0(1370) \to \pi^+\pi^-) \\
& = (0.34^{+0.11}_{-0.14}\text{(stat.)} \pm 0.03\text{(syst.)}) \times 10^{-4} \\
\end{align*}
\]

FIG. 2: The cosine of the angle $\theta_{\text{hel}}$ between $t^+$ and the direction opposite to that of the $B_s^0$ in the $J/\psi$ rest frame. $\cos(\theta_{\text{hel}})$ is projected in the $\Delta E$ signal region and $f_0(980)$ and $f_0(1370)$ signal regions as 0.80 GeV/$c^2 < M_{\pi\pi} < 1.16$ GeV/$c^2$ (left) and 1.3 GeV/$c^2 < M_{\pi\pi} < 1.5$ GeV/$c^2$ (right). The expected distributions from the fit assuming a longitudinally polarized $J/\psi$, which would result from a $B_s^0 \to J/\psi + \text{scalar decay}$, are superimposed. The curves follow the convention in Fig. 1.

TABLE II: Relative systematic errors (in %) for $\mathcal{B}(B_s^0 \to J/\psi F; F \to \pi^+\pi^-)$.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\mathcal{B}(F = f_0(980))$</th>
<th>$\mathcal{B}(F = f_0(1370))$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta E$ shape</td>
<td>1.0</td>
<td>+0.8, −0.6</td>
</tr>
<tr>
<td>$f_0(980)$ shape</td>
<td>+12.4, −13.6</td>
<td>+8.9, −5.3</td>
</tr>
<tr>
<td>Background parameters</td>
<td>+1.9, −1.7</td>
<td>+1.0, −0.4</td>
</tr>
<tr>
<td>Track reconstruction</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Lepton identification</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>Pion identification</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B}(J/\psi \to \ell\ell)$</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>$f_{B_s^0}\beta_s$</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>$N_{\beta_s^{-1}\beta_s}$</td>
<td>+22.4, −15.5</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>+26.0, −21.1</td>
<td>+24.5, −16.8</td>
</tr>
</tbody>
</table>

varying each fixed parameter by its error and are summarized in Table II. Apart from the $N_{B \beta_s}$ normalization, the largest systematic effect arises from the uncertainties of the Flatté parameters for the $f_0(980)$ lineshape, where the parameters are varied according to errors in [16]. For the signal $\Delta E$ shape, the error on the mean value is determined from the beam energy calibrated with $\Upsilon(5S) \to \Upsilon(1S)+\pi\pi$ and $B_s^0 \to D_s^0\pi$, and the error on the width is determined from the control sample. The yields of the $B_s^0 \to J/\psi q\bar{q}$ and $B^+ \to J/\psi(K^+, \pi^+)$ components are varied according to the experimental errors on their branching fractions. Finally, the non-$J/\psi$ background parameters are varied according to the results of the $J/\psi$ sideband study. Other background shape uncertainties are negligible.

In summary, we report the first observation of $B_s^0 \to J/\psi f_0(980)$ and the first evidence for $B_s^0 \to J/\psi f_0(1370)$. The measured $B_s^0 \to J/\psi f_0(980)$ branching fraction is in agreement with the estimate $1.3 \times 10^{-4} \lesssim \mathcal{B}(B_s^0 \to J/\psi f_0(980); f_0(980) \to \pi^+\pi^-) \lesssim 3.2 \times 10^{-4}$. The signal for $B_s^0 \to J/\psi f_0(1370)$ has a significance of 4.2σ. This mode represents a new CP channel that can be used to study $B_s^0$ mixing properties.

Note added: While preparing the final version of this manuscript, we became aware that the LHCb Collaboration reports similar results for $B_s^0 \to J/\psi f_0(980)$ [18].

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