First Observation of $B_s^0 \to J/\psi \eta$ and $B_s^0 \to J/\psi \eta$'


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0031-9007/12/108(18)/181808(5) 181808-1 © 2012 American Physical Society
We report first observations of $B_s^0 \rightarrow J/\psi \eta(0)$ and $B_s^0 \rightarrow J/\psi \eta'$. The results are obtained from 121.4 fb$^{-1}$ of data collected at the $Y(4S)$ resonance with the Belle detector at the KEKB $e^+e^−$ collider. We obtain the branching fractions $\mathcal{B}(B_s^0 \rightarrow J/\psi \eta) = [5.10 \pm 0.50\,(\text{stat}) \pm 0.25\,(\text{syst}) \pm 0.14(N_{\text{b}}\Delta\Gamma_s)] \times 10^{-4}$, and $\mathcal{B}(B_s^0 \rightarrow J/\psi \eta') = [3.71 \pm 0.61\,(\text{stat}) \pm 0.18\,(\text{syst}) \pm 0.37(N_{\text{b}}\Delta\Gamma_s)] \times 10^{-4}$. The ratio of the two branching fractions is measured to be $\frac{\mathcal{B}(B_s^0 \rightarrow J/\psi \eta)}{\mathcal{B}(B_s^0 \rightarrow J/\psi \eta')} = 0.73 \pm 0.14\,(\text{stat}) \pm 0.02\,(\text{syst})$.

The decays $B_s^0 \rightarrow J/\psi \eta(0)$ are dominated by the $b \rightarrow c\bar{c}\bar{s}$ process shown in Fig. 1. The $J/\psi \eta(0)$ final states are $CP$-even eigenstates; their time distributions can be used to directly measure the $B_s^0$ width difference $\Delta\Gamma_s$ and the $CP$-violating phase $\phi_s$ [1] without an angular analysis. Assuming flavor SU(3) symmetry and factorization, the $B_s^0 \rightarrow J/\psi \eta(0)$ branching fractions relative to the decay $B_d^0 \rightarrow J/\psi K^0$ are estimated to be [2]

$$\frac{\mathcal{B}(B_s^0 \rightarrow J/\psi \eta(0))}{\mathcal{B}(B_d^0 \rightarrow J/\psi K^0)} = \sin^2\phi_p (\cos^2\phi_p) \times \frac{p_s^*}{p_{K^0}^*},$$

where $p^*$ is the momentum of $J/\psi$ in the rest frame of the $B_s^0$ or $B_d^0$. Here $\phi_p = (41.4 \pm 0.5)^\circ$ [3] is the pseudoscalar mixing angle in the flavor basis with $\eta(\eta') = 1/\sqrt{2}[u\bar{u} + d\bar{d}] \cos\phi_p (\sin\phi_p) - (+)s\bar{s} \sin\phi_p (\cos\phi_p)$, and other possible flavor singlet content of the $\eta'$ such as gluonium is neglected. Using this relation and the value $\mathcal{B}(B_d^0 \rightarrow J/\psi K^0) = 8.71 \times 10^{-4}$ [4], we expect $\mathcal{B}(B_s^0 \rightarrow J/\psi \eta(0)) \sim 4.16(4.31) \times 10^{-4}$. The ratio of the two branching fractions $\frac{\mathcal{B}(B_s^0 \rightarrow J/\psi \eta)}{\mathcal{B}(B_s^0 \rightarrow J/\psi \eta')}$ is expected to be $1.04 \pm 0.04$. This ratio estimation does not require flavor SU(3) or the assumption of factorization [5] and can be used to test the $\eta - \eta'$ mixing scheme [5,6]. The only previous experimental result for these decay channels is the 90% confidence level upper limit $\mathcal{B}(B_s^0 \rightarrow J/\psi \eta) < 3.8 \times 10^{-3}$ [7].

FIG. 1. Dominant diagram for the processes $B_s^0 \rightarrow J/\psi \eta(0)$. 

 DOI: 10.1103/PhysRevLett.108.181808

PACS numbers: 13.25.Hw, 14.40.Nd
Candidate $\rho^0 \to \pi^+ \pi^-$ decays are oppositely charged pion pairs satisfying $550\text{MeV}/c^2 < M_{\pi^+ \pi^-} < 900\text{MeV}/c^2$ and a helicity angle requirement $|\cos\theta_{\text{hel}}| < 0.85$ since the $\rho^0$ in $\eta' \to \rho^0 \gamma$ is longitudinally polarized. Here $\theta_{\text{hel}}$ is the helicity angle of $\rho^0$, calculated as the angle between the direction of the $\pi^+$ and the direction opposite to the $\eta'$ momentum in the $\rho^0$ rest frame. We require the reconstructed $\eta'$ invariant mass to satisfy $940\text{MeV}/c^2 < M_{\eta'} < 975\text{MeV}/c^2(3\sigma)$. 

We combine $J/\psi$ and $\eta(1490)$ candidates to form $B^0$ mesons. Signal candidates are identified by two kinematic variables computed in the $Y(5S)$ rest frame: the energy difference $\Delta E = E_B - E_{\text{beam}}$ and the beam-energy-constrained mass $\Delta M = \sqrt{(E_{\text{beam}})^2 - (p_B^2)}$, where $E_B$ and $p_B$ are the energy and momentum of the reconstructed $B^0$ candidate. To improve the $\Delta E$ and $\Delta M$ resolutions, mass-constrained kinematic fits are applied to $J/\psi$, $\pi^0$, and $\eta(1490)$ candidates. We retain $B^0$ meson candidates with $|\Delta E| < 0.4\text{GeV}$ and $\Delta M > 5.25\text{GeV}/c^2$ for further analysis. The candidate that has a minimum sum of $\chi^2$ is selected if there is more than one candidate.

The background is dominated by two-jet-like continuum events of the type $e^+ e^- \to q\bar{q}(q = u, d, s, c)$, together with other $B_\text{meson}$ decay modes ($B = B^0_\text{c}, B^0_\text{b}, B^\pm_\text{s}$). To suppress the continuum background, we require the ratio of second to zeroth Fox-Wolfram moments [12] to be less than 0.4. This requirement is optimized by maximizing a figure of merit $N_S/\sqrt{N_S + N_B}$, where $N_S$ is the expected number of signal events and $N_B$ is the number of background events estimated from Monte Carlo simulation, in the $B^0 \bar{B}^0$ signal region.

Signal and background distributions in $\Delta E$ and $\Delta M$ after all selections are parametrized separately for each $B^0 \to J/\psi \eta(1490)$ subchannel. The signal shapes for the two $\eta'$ (three $\eta'$) subchannels are described with a Crystal Ball function [13] (the sum of a Crystal Ball and a Gaussian function) in $\Delta E$ and a Crystal Ball function in $\Delta M$. The means and widths of the distributions are calibrated with respect to Monte Carlo values using a control sample of $B^+ \to J/\psi K^{*+}(K^{*+} \to K^+ \pi^0)$ decays collected at the $Y(4S)$ resonance. The background shapes for all $\eta(1490)$ subchannels are smooth and described with an exponential function in $\Delta E$ and an ARGUS function [14] in $\Delta M$.

An unbinned, extended maximum likelihood fit is performed simultaneously to the total five two-dimensional $\Delta E - \Delta M$ distributions. The branching fraction of each signal mode is a common parameter shared among the corresponding $\eta(1490)$ subchannels. The parameters $f_{B^0 \bar{B}^0}$ and $f_{B^0 \bar{B}^0}$ are also common to all five subchannels.

In the fit, the total probability density function consists of a signal and background component. The signal component includes contributions from the three $B^0_\text{c}$ pair production channels. The signal normalization for the $B^0_\text{c}$.
TABLE I. A summary of the product of the sub-branching fraction and efficiency for various subchannels. Here \( B_i^0 \) is the production channel parametrized as 
\[
N_{\text{sig}} = 2 \times N_{(i)} \times f_{B_i^0} B(0) \times B_i^0 \to J/\psi \eta^{(i)} / B_i \epsilon_i \text{ for each } \eta^{(i)} \text{ subchannel } i.
\]
The product \( B_i \) is the total branching fraction for a \( J/\psi \) and an \( \eta \) decaying to the reconstructed final states [4], and \( \epsilon_i \) is the reconstruction efficiency obtained from Monte Carlo simulation. The values of the weighted efficiencies \( B_i \epsilon_i \) are listed in Table I. The signal yields in the \( B_s^0 B_s^0 \) and \( B_s^0 B_s^0 \) production channels are obtained in a similar manner, with \( f_{B_s^0} \) replaced by \( f_{B_s^0} \) and \( f_{B_s^0} \); respectively. The floating parameters in the fit are the branching fractions \( B(0) \to J/\psi \eta^{(i)} \); \( f_{B_s^s} \); \( f_{B_s^s} \); and the corresponding background yields and shapes for different \( \eta^{(i)} \) subchannels. This fit procedure was checked with six fully simulated Monte Carlo samples that included both signal and background, each normalized to the data luminosity. The results show that the fitted branching fractions for both modes recover the input values.

The projections of the fit to the 121.4 fb\(^{-1}\) data sample in the \( B_s^0 \) signal region are shown in Figs. 2 and 3. There are good agreements between fit curve and data points in all subchannels’ projections. We obtain a total of 141 \( B_s^0 \) events with a statistical significance of 21.9\( \sigma \) and 86 \( B_s^0 \) events with a statistical significance of 10.3\( \sigma \) in all three \( Y(5S) \to B_s^0 \) channels. The statistical significances are calculated as \( \sqrt{2} \ln(L_{\text{max}}/L_0) \), where \( L_{\text{max}} \) and \( L_0 \) are the maximum likelihood values, while the corresponding signal yield is set to zero for \( L_0 \). The \( B_s^0 \) and \( B_s^0 \) events are observed for the first time. The \( B_s^0 \) pair production fractions are measured to be \( f_{B_s^s} = (90.5 \pm 3.2 \pm 0.1)\% \), with a correlation coefficient \( (\pm 0.72) \). This result is consistent with the value \( f_{B_s^s} = (87.0 \pm 1.7)\% \) [15] obtained from 121.4 fb\(^{-1}\) of data using the \( B_s^0 \to D_s^- \eta^+ \) reconstruction method described in Ref. [16].

The systematic uncertainties due to the signal function mean and width are determined by varying each parameter by its error from the control sample calibration, repeating the fit, and summing the shifts in the branching fraction in quadrature. The lepton and pion identification efficiencies from Monte Carlo calculations are calibrated using \( \gamma \gamma \to l^+ l^- \) and \( D^{*+} \to D^0 \pi^+ (D^0 \to K^- \pi^+) \) control samples in data, respectively. Systematic errors for branching fractions are summarized in Table II. Those on \( f_{B_s^s} \) and \( f_{B_s^s} \) are dominated by the signal shape uncertainty. The large systematic error due to \( N_{B_s^0} \) is quoted separately in the final results.

The ratio of the two branching fractions is also determined, where the systematic error due to \( N_{B_s^0} \) cancels. For this, the statistical errors of the two modes are combined using error propagation. Correlated systematic errors due to calibration, track reconstruction, and particle identification are determined by varying the numerator and denominator simultaneously. Other systematic sources are treated independently.

TABLE II. Relative systematic errors (in %) for \( B(0) \to J/\psi \eta^{(i)} \).

<table>
<thead>
<tr>
<th>Source</th>
<th>( B(0) \to J/\psi \eta^{(i)} )</th>
<th>( B(0) \to J/\psi \eta^{(i)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal shape calibration</td>
<td>+0.4, -0.5</td>
<td>+1.1, -1.3</td>
</tr>
<tr>
<td>Track reconstruction</td>
<td>0.8</td>
<td>1.4</td>
</tr>
<tr>
<td>Electron identification</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Muon identification</td>
<td>1.8</td>
<td>1.7</td>
</tr>
<tr>
<td>Pion identification</td>
<td>0.5</td>
<td>2.1</td>
</tr>
<tr>
<td>( \eta(\pi^0) \to \gamma \gamma ) selection</td>
<td>4.0</td>
<td>2.8</td>
</tr>
<tr>
<td>( B(0) \to ll )</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>( B(0) \to \text{final states} )</td>
<td>0.5</td>
<td>1.2</td>
</tr>
<tr>
<td>Total [without ( N_{B_s^0} )]</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>( N_{B_s^0} )</td>
<td>+22.4, -15.5</td>
<td></td>
</tr>
</tbody>
</table>
In summary, we observe \( B^0_s \rightarrow J/\psi \eta \) and \( B^0_s \rightarrow J/\psi \eta' \) decays for the first time with significances over 10\( \sigma \) by taking advantage of the low background \( e^+ e^- \) environment at Belle. We measure the branching fractions

\[
\mathcal{B}(B^+_s \rightarrow J/\psi \eta) = [5.10 \pm 0.50\text{(stat)} \pm 0.25\text{(syst)}] \times 10^{-4},
\]

\[
\mathcal{B}(B^0_s \rightarrow J/\psi \eta') = [3.71 \pm 0.61\text{(stat)} \pm 0.18\text{(syst)}] \times 10^{-4}.
\]

These branching fractions are consistent with SU(3) expectations using the measured value of \( \mathcal{B}(B^0_{d,s} \rightarrow J/\psi K^0) \) [2]. The ratio of the two branching fractions is measured to be \( \frac{\mathcal{B}(B^0_{s} \rightarrow J/\psi \eta')}{\mathcal{B}(B^0_{d,s} \rightarrow J/\psi K^0)} = 0.73 \pm 0.14\text{(stat)} \pm 0.02\text{(syst)} \). This ratio is smaller than the expected value of 1.04 \pm 0.04 at the 2.1\( \sigma \) level; a significant deviation would indicate additional flavor singlet components in the \( \eta' \) other than \( u\bar{u}, d\bar{d}, s\bar{s} \) pairs or violation of the \( \eta - \eta' \) mixing scheme.

We thank the KEKB group for excellent operation of the accelerator, the KEK cryogenics group for efficient solenoid operations, and the KEK computer group and the NII for valuable computing and SINET4 network support. We acknowledge support from MEXT, JSPS and Nagoya’s TLPSC (Japan); ARC and DIISR (Australia); NSFC (China); MSMT (Czechia); DST (India); INFN (Italy); MEST, NRF, NSDC of KISTI, and WCU (Korea); MNiSW (Poland); MES and RFAAE (Russia); ARRS (Slovenia); SNSF (Switzerland); NSC and MOE (Taiwan); and DOE and NSF (U.S.). J. Li acknowledges support from WCU Grant No. R32-10155.