First Observation of the Hadronic Transition $\Upsilon(4S) \rightarrow \eta b(1P)$ and New Measurement of the $b(1P)$ and $\eta b(1S)$ Parameters

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Tamponi, U.; Mussa, R.; Abdesselam, A.; Aihara, H.; Arinstein, K.; and Joffe, D., "First Observation of the Hadronic Transition $\Upsilon(4S) \rightarrow \eta b(1P)$ and New Measurement of the $b(1P)$ and $\eta b(1S)$ Parameters" (2015). Faculty Publications. 3594. https://digitalcommons.kennesaw.edu/facpubs/3594
First observation of the hadronic transition $\Upsilon(4S) \to \eta h_b(1P)$ and new measurement of the $h_b(1P)$ and $\eta_b(1S)$ parameters


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Hadron transitions between the lowest mass quarkonium levels can be described using the QCD multipole expansion (ME) [5–10]. In this approach, the heavy quarks expand (ME) [5–10]. In this approach, the heavy quarks

The bottomonium system, comprising bound states of $b$ and $\bar{b}$ quarks, has been studied extensively in the past [1, 2]. The recent observations of unexpected hadronic transitions from the $J^{PC} = 1^{-+}$ states above the $B\bar{B}$ meson threshold, $\Upsilon(4S)$ and $\Upsilon(5S)$, to lower mass bottomonia have opened new pathways to the elusive spin-singlet states, the $h_b(nP)$ and $\eta_b(nS)$ [3–4], and challenged theoretical descriptions, showing a large violation of the selection rules that apply to transitions below the threshold.

Using a sample of $771.6 \times 10^6 \, \Upsilon(4S)$ decays collected by the Belle experiment at the KEKB $e^+e^-$ collider, we observe for the first time the transition $\Upsilon(4S) \to \eta_b(1P)$ with the branching fraction $\mathcal{B}[\Upsilon(4S) \to \eta_b(1P)] = (2.18 \pm 0.11 \pm 0.18) \times 10^{-5}$ and we measure the $h_b(1P)$ mass $M_{h_b(1P)} = (9899.3 \pm 0.4 \pm 1.0) \, \text{MeV}/c^2$, corresponding to the hyperfine splitting $\Delta M_{HF}(1P) = (0.6 \pm 0.4 \pm 1.0) \, \text{MeV}/c^2$. Using the transition $h_b(1P) \to \gamma \eta(1S)$, we measure the $\eta(1S)$ mass $M_{\eta(1S)} = (9400.7 \pm 1.7 \pm 1.6) \, \text{MeV}/c^2$, corresponding to $\Delta M_{HF}(1S) = (59.6 \pm 1.7 \pm 1.6) \, \text{MeV}/c^2$, the $\eta(1S)$ width $\Gamma_{\eta(1S)} = (8_{-5}^{+6} \pm 5) \, \text{MeV}/c^2$ and the branching fraction $\mathcal{B}[h_b(1P) \to \gamma \eta(1S)] = (56 \pm 8 \pm 4)\%$.

PACS numbers: 14.40.Pq,112.38.Qk,12.38.Qk,12.39.Hg,13.20.Gd
deed, the ratio of branching fractions
\[ \mathcal{R}^S_{\pi \pi S}(n, m) = \frac{\mathcal{B}[\Upsilon(nS) \rightarrow \eta \Upsilon(mS)]}{\mathcal{B}[\Upsilon(nS) \rightarrow \pi^+ \pi^- \Upsilon(mS)]]} \]

is measured to be small for low-lying states: \( \mathcal{R}^S_{\pi \pi S}(2, 1) = (1.64 \pm 0.23) \times 10^{-3} \) and \( \mathcal{R}^S_{\pi \pi S}(3, 1) < 2.3 \times 10^{-3} \) [14].

Above the \( BB \) threshold, BaBar observed the transition \( \Upsilon(4S) \rightarrow \eta \Upsilon(1S) \) with the unexpectedly large branching fraction of \( (1.96 \pm 0.28) \times 10^{-4} \), corresponding to \( \mathcal{R}^S_{\pi \pi S}(4, 1) = 2.41 \pm 0.42 \) [16]. This apparent violation of the heavy quark spin-symmetry was explained by the contribution of \( B \) meson loops or, equivalently, by the presence of a four-quark \( BB \) component inside the \( \Upsilon(4S) \) wave function [17, 18]. At the \( \Upsilon(5S) \) energy, the anomaly is even more striking. The spin-flips processes \( \Upsilon(5S) \rightarrow \pi \pi \eta \) are found not to be suppressed with respect to the spin-symmetry preserving reactions \( \Upsilon(5S) \rightarrow \pi \pi \Upsilon(1S, 2S) \) [3], and all the \( \pi \pi \) transitions show the presence of new resonant structures [19, 20] that cannot be explained as conventional bottomonium states.

Further insight into the mechanism of the hadronic transitions above the threshold can be gained by searching for the \( E1M1 \) transition \( \Upsilon(4S) \rightarrow \eta h_b(1P) \), which is predicted to have a branching fraction of the order of \( 10^{-3} \) [21].

In this Letter, we report the first observation of the \( \Upsilon(4S) \rightarrow \eta h_b(1P) \) transition and measurement of the \( h_b(1P) \) and \( \eta h_b(1S) \) resonance parameters. Following the approach used for the observation of the \( h_b(1P, 2P) \) production in e+e− collisions at the \( \Upsilon(5S) \) energy [3] — by studying the inclusive \( \pi^+ \pi^- \) missing mass in hadronic events — we investigate the missing mass spectrum of \( \eta \) mesons in the \( \Upsilon(4S) \) data sample. The missing mass is defined as \( M_{\text{miss}}(\eta) = \sqrt{(P_{\pi^+ \pi^-} - P_\eta)^2} \), where \( P_{\pi^+ \pi^-} \) and \( P_\eta \) are the four-momenta of the colliding e+e− pair and the \( \eta \) meson, respectively.

The large sample of reconstructed \( h_b(1P) \) events allows us to measure its mass and, via the \( h_b(1P) \rightarrow \gamma \eta h_b(1S) \) transition, the mass and width of the \( \eta h_b(1S) \). The latter are especially important since there is a 3.2σ discrepancy between the \( \eta h_b(1S) \) mass measurement by Belle using \( h_b(1P, 2P) \rightarrow \gamma \eta h_b(1S) \) transitions [4] and by BaBar and CLEO using \( \Upsilon(2S, 3S) \rightarrow \gamma \eta h_b(1S) \) [22, 23].

This analysis is based on the 711 fb−1 sample collected at the centre-of-mass energy of \( \sqrt{s} = 10.580 \) GeV/c² by the Belle experiment [25, 26] at the KEKB asymmetric-energy e+e− collider [27, 28], corresponding to 771.6 × 10⁶ \( \Upsilon(4S) \) decays. Monte Carlo (MC) samples are generated using EvtGen [30]. The detector response is simulated with GEANT3 [31]. Separate MC samples are generated for each run period to account for the changing detector performance and accelerator conditions.

Candidate events are requested to satisfy the standard Belle hadronic selection [32], to have at least three charged tracks pointing towards the primary interaction vertex, a visible energy greater than 0.2√s, a total energy deposition in the electromagnetic calorimeter (ECL) between 0.1√s and 0.8√s, and a total momentum balanced along the z axis. Continuum e+e− → q̄q events (where \( q \in \{u, d, s, c\} \)) are suppressed by requiring \( R_2 \), the ratio of the 2nd to 0th Fox-Wolfram moment [30], to be less than 0.3. The \( \eta \) candidates are reconstructed in the dominant \( \eta \rightarrow \gamma \gamma \) channel. The \( \eta \) candidates are selected from energy deposits in the ECL that have a shape compatible with an electromagnetic shower, and are not associated with charged tracks. We investigate the absolute photon energy calibration using three calibration samples: \( \pi^0 \rightarrow \gamma \gamma, \eta \rightarrow \gamma \gamma \), and \( D^{*0} \rightarrow D^0 \gamma [4] \). Comparing the peak position and the widths of the three calibration signals in the MC sample and in the data, as a function of the photon energy \( E \), we determine the photon energy correction \( F_{\text{ph}}(E) \) and the resolution fudge factor \( F_{\text{res}}(E) \). We observe \( F_{\text{ph}}(E) < 0.1\% \) and \( F_{\text{res}}(E) \approx (+5 \pm 3)\% \) in the signal region, and apply the corresponding correction to the MC samples. An energy threshold, ranging from 50 MeV to 95 MeV, is applied as a function of the polar angle to reject low energy photons arising from the beam-related backgrounds. To reject photons from \( \pi^0 \) decays, \( \gamma \gamma \) pairs having invariant mass within 17 MeV/c² of the nominal \( \pi^0 \) mass [33] are identified as \( \pi^0 \) candidates and the corresponding photons are excluded from the \( \eta \) reconstruction process. The angle \( \theta \) between the photon direction and that of the \( \Upsilon(4S) \) in the \( \eta \) rest frame peaks at \( \cos\theta \approx 1 \) for the remaining combinatorial background. We thus require \( \cos\theta < 0.94 \) for the \( \eta \) selection. All the selection criteria are optimized using the MC simulation by maximizing the figure of merit \( f = N_{\text{sig}}/\sqrt{N_{\text{sig}} + N_{\text{bkg}}} \), where \( N_{\text{sig}} \) and \( N_{\text{bkg}} \) are the signal and background yields in the signal region, respectively. The \( \eta \) peak in the \( \gamma \gamma \) invariant mass distribution, after the selection is applied, can be fit by a Crystal Ball (CB) [35] probability density function (PDF) with a resolution of 13 MeV/c². Thus, \( \gamma \gamma \) pairs with an invariant mass within 26 MeV/c² of the nominal \( \eta \) mass \( m_\eta \) [34] are selected as a signal sample, while the candidates in the regions 39 MeV/c² < \( |M(\gamma \gamma) - m_\eta| < 52 \) MeV/c² are used as control samples. To improve the \( M_{\text{miss}}(\eta) \) resolution, a mass-constrained fit is performed on the \( \eta \) candidates in both the signal and control regions. The resulting \( M_{\text{miss}}(\eta) \) distribution is shown in the inset of Fig. 1. The \( \Upsilon(4S) \rightarrow \eta h_b(1P) \) and \( \Upsilon(4S) \rightarrow \eta \Upsilon(1S) \) peaks in \( M_{\text{miss}}(\eta) \) are modeled with a CB PDF, whose Gaussian core resolutions are fixed according to the MC simulation. The parameters of the non-Gaussian tails, which account for the effects of the soft Initial State Radiation (ISR), are calculated assuming the next-to-leading order formula for the ISR emission probability [37] and by modeling the \( \Upsilon(4S) \) as a Breit-Wigner resonance with \( \Gamma = (20.5 \pm 2.5) \) MeV/c² [34]. The \( M_{\text{miss}}(\eta) \) spectrum is fitted in two separate
ηperimental result by BaBar \cite{16}. All the upper limits
pre-
the 90% Credibility Level (CL) upper limit
B
M
subtracted
the sideband samples. Figure 1 shows the background-
mizing the credibility level of the fit and is validated using
polynomial. The polynomial order is determined maxi-

In the first (second) interval, the combinatorial back-
S
per one. The transition Υ(4
the fits are 1% in the lower interval and 19% in the up-
larger than that used for the fit. The credibility levels of
S
No evidence of Υ(4
agreement with the available theoretical prediction \cite{21}.
B
contain
efficiency and
R
for the fit. The credibility levels of
S
where
N
η
the fits are 1% in the lower interval and 19% in the up-
one. The transition Υ(4S) \rightarrow ηh_b(1P) is observed
with a statistical significance of 11σ, calculated using
the profile likelihood method \cite{38}, and no signal is ob-
served in the γγ-mass control regions. The h_b(1P) yield
is N_{h_b(1P)} = 112469 \pm 5537. From the position of
the peak, we measure M_{h_b(1P)} = (9899.3 \pm 0.4 \pm 1.0) MeV/c^2
(hereinafter the first error is statistical and the second is
systematic). We calculate the branching fraction of the
transition as

\[ B[Υ(4S) \rightarrow ηh_b(1P)] = \frac{N_{h_b(1P)}}{N_{Υ(4S)} \epsilon_{h_b(1P)} B[η \rightarrow γγ]}, \]

where \( N_{Υ(4S)} = (771.6 \pm 10.6) \times 10^4 \) is the number of
Υ(4S), \( \epsilon_{h_b(1P)} = (16.96 \pm 1.12) \% \) is the reconstruction
accuracy and \( B[η \rightarrow γγ] = (39.41 \pm 0.21) \% \) \cite{34}. We ob-
tain \( B[Υ(4S) \rightarrow ηh_b(1P)] = (2.18 \pm 0.11 \pm 0.18) \times 10^{-3} \), in
agreement with the available theoretical prediction \cite{21}.
No evidence of Υ(4S) \rightarrow ηΥ(1S) is present, so we set
the 90% Credibility Level (CL) upper limit \( B[Υ(4S) \rightarrow ηΥ(1S)] < 2.7 \times 10^{-4} \), in agreement with the previous ex-
perimental result by BaBar \cite{16}. All the upper limits pre-
sented in this work are obtained using the CLs technique
\cite{39,40} and include systematic uncertainties. Using our
measurement of \( M_{h_b(1P)} \), we calculate the corre-
ponding 1P hyperfine splitting, defined as the difference be-
tween the χ_{h_b(1P)} spin-averaged mass \( m^{\mathrm{av}}_{\chi_{h_b(1P)}} \) and the
h_b(1P) mass, and obtain \( ∆M_{HF}(1P) = (+0.6 \pm 0.4 \pm 1.0) \)
MeV/c^2; the systematic error includes the uncertainty on
the value of \( m^{\mathrm{av}}_{\chi_{h_b(1P)}} \) \cite{34}.

As validation of our measurement, we study the η \rightarrow π^+π^−π^0 mode. The π^0 candidate is reconstructed from
a γγ pair with invariant mass within 17 MeV/c^2 of the
nominal π^0 mass \cite{34} while the π ± candidates tracks are
required to be associated with the primary interaction
vertex and not identified as kaons by the particle iden-
tification algorithm. We observe an excess in the signal
region with statistical significance of 3.5σ and measure
\( B[Υ(4S) \rightarrow ηh_b(1P)]_{η \rightarrow π^+π^-π^0} = (2.3 \pm 0.6) \times 10^{-3} \),
which is in agreement with the result from the γγ mode.

The contributions to the systematic uncertainty in our
measurements are summarized in Table 4. To estimate
them, we first vary — simultaneously — the fit ranges
within ±100 MeV/c^2 and the order of the background
polynomial between 7 (4) and 14 (8) in the upper (lower)
interval. The average variation of the fitted parameters
when the fitting conditions are so changed is adopted
as the fit-range/model systematic uncertainty. Similarly,
we vary the bin width between 0.1 and 1 MeV/c^2 and
we treat the corresponding average variations as the bin-
width systematic error. The ISR modeling contribution
is due to the Υ(4S) width uncertainty \cite{34}. The pres-

\[ \frac{N_{Υ(4S)} \epsilon_{h_b(1P)} B[η \rightarrow γγ]}{2 \times 10^{-4}} \]

\[ \frac{N_{Υ(4S)} \epsilon_{h_b(1P)} B[η \rightarrow γγ]}{2 \times 10^{-4}} \]

\[ \frac{N_{Υ(4S)} \epsilon_{h_b(1P)} B[η \rightarrow γγ]}{2 \times 10^{-4}} \]

\[ \frac{N_{Υ(4S)} \epsilon_{h_b(1P)} B[η \rightarrow γγ]}{2 \times 10^{-4}} \]
TABLE I. Systematic uncertainties in the determination of $\mathcal{B}[^3S_1(4S) \to \eta h_b(1P)]$, in units of %, and on $M_{h_b(1P)}$, in units of MeV/c^2.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\mathcal{B} M_{h_b(1P)}$</th>
<th>$\eta b(1P)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit range and background PDF order</td>
<td>$\pm$2.4 ±0.1</td>
<td></td>
</tr>
<tr>
<td>Bin width</td>
<td>$\pm$2.5 ±0.1</td>
<td></td>
</tr>
<tr>
<td>ISR modeling</td>
<td>$\pm$2.8 ±0.7</td>
<td></td>
</tr>
<tr>
<td>Peaking backgrounds</td>
<td>$\pm$0.5 ±0.4</td>
<td></td>
</tr>
<tr>
<td>$\gamma$ energy calibration</td>
<td>$\pm$1.2 ±0.3</td>
<td></td>
</tr>
<tr>
<td>Reconstruction efficiency</td>
<td>$\pm$6.6 ±1.1</td>
<td></td>
</tr>
<tr>
<td>$N_T(4S)$</td>
<td>$\pm$1.4 ±0.1</td>
<td></td>
</tr>
<tr>
<td>Beam energy</td>
<td>$\pm$0.0 ±0.4</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B}[^3P_0 \to \gamma \gamma]$</td>
<td>$\pm$0.5 ±1.0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>$\pm$5.2 ±1.0</td>
<td></td>
</tr>
</tbody>
</table>

The study of the $\eta b(1S)$ decay is performed by reconstructing the transitions $Y(4S) \to \eta h_b(1P) \to \gamma \gamma \eta b(1S)$. To extract the signal, we measure the number of $Y(4S) \to \eta h_b(1P)$ events $N_{h_b(1P)}$ as a function of the variable $\Delta M_{\text{miss}} = M_{\text{miss}}(\eta \gamma) - M_{\text{miss}}(\eta)$, where $M_{\text{miss}}(\eta \gamma)$ is the missing mass of the $\eta \gamma$ system. The signal transition will produce a peak in $N_{h_b(1P)}$ at $m_{\eta b(1S)} - m_{h_b(1P)}$. The radiative photon arising from the $h_b(1P)$ decay is reconstructed with the same criteria used in the $\eta \gamma \gamma$ selection, and the $h_b(1P)$ yield in each $\Delta M_{\text{miss}}$ bin is measured with the fitting procedure described above. To assure the convergence of the $M_{\text{miss}}(\eta)$ fit in each $\Delta M_{\text{miss}}$ interval, the $h_b(1P)$ mass is fixed to 9899.3 MeV/c^2, the range is reduced to (9.80,9.95) GeV/c^2 and the order of the background PDF polynomial is decreased to seven. The $h_b(1P)$ yield as function of $\Delta M_{\text{miss}}$, shown in Fig. 2, exhibits an excess at $\Delta M_{\text{miss}} = M_{\eta b(1S)} - M_{h_b(1P)}$ with a statistical significance of 9σ. The $\eta b(1S)$ peak is described by the convolution of a double-sided CB PDF, whose parameters are fixed according to the MC simulation, and a non-relativistic Breit-Wigner PDF that accounts for the natural $\eta b(1S)$ width. The background is described by an exponential. We measure $M_{\eta b(1S)} - M_{h_b(1P)} = (−496.6 ± 1.7 ± 1.2)$ MeV/c^2, $\Gamma_{\eta b(1S)} = (8.5 ± 5)$ MeV/c^2 and the number of $Y(4S) \to \eta h_b(1P) \to \eta \gamma \eta b(1S)$ events $N_{\eta b(1S)} = 33116 ± 4741$. The credibility level of the fit is 50%. We calculate the branching fraction of the radiative transition as

$$\mathcal{B}[^3P_0 \to \gamma \gamma] = \frac{N_{\eta b(1S)} \mathcal{B}[^3P_0 \to \gamma \gamma \eta b(1S)]}{N_{h_b(1P)} \mathcal{B}[^3P_0 \to \gamma \gamma \eta b(1S)]},$$

where $\mathcal{B}[^3P_0 \to \gamma \gamma] = 1.887 ± 0.053$ is the ratio of the reconstruction efficiencies for $Y(4S) \to \eta h_b(1P)$ and $Y(4S) \to \eta h_b(1P) \to \eta \gamma \eta b(1S)$. We obtain $\mathcal{B}[^3P_0 \to \gamma \gamma] = (56 ± 8 ± 4)\%$. To estimate the systematic

![FIG. 2. $\Delta M_{\text{miss}}$ distribution. The blue solid line shows our best fit, while the red, dashed line represents the background component.](image-url)
uncertainties reported in Table II we adopt the protocols discussed earlier. Uncertainties related to the $M_{\text{miss}}(\eta)$

TABLE II. Systematic uncertainties in the determination of the $\eta_{b}(1S)$ mass and width, in units of MeV/c² and on $B = B[h_{b}(1P) \rightarrow \gamma\eta_{b}(1S)]$, in units of %.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta M_{\text{miss}}$</th>
<th>$\Gamma_{\eta_{b}(1S)}$</th>
<th>$B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\text{miss}}(\eta)$ fit range</td>
<td>$\pm 0.8$</td>
<td>$\pm 3.0$</td>
<td>$\pm 2.8$</td>
</tr>
<tr>
<td>$M_{\text{miss}}(\eta)$ bin width</td>
<td>$\pm 0.0$</td>
<td>$\pm 0.1$</td>
<td>$\pm 0.0$</td>
</tr>
<tr>
<td>$M_{\text{miss}}(\eta)$ polynomial order</td>
<td>$\pm 0.1$</td>
<td>$\pm 1.9$</td>
<td>$\pm 1.6$</td>
</tr>
<tr>
<td>$M_{h_{b}(1P)}$</td>
<td>$\pm 0.0$</td>
<td>$\pm 0.8$</td>
<td>$\pm 1.1$</td>
</tr>
<tr>
<td>$\Delta M_{\text{miss}}$ fit range</td>
<td>$\pm 0.0$</td>
<td>$\pm 0.7$</td>
<td>$\pm 2.2$</td>
</tr>
<tr>
<td>$\Delta M_{\text{miss}}$ bin width</td>
<td>$\pm 0.8$</td>
<td>$\pm 2.8$</td>
<td>$\pm 5.2$</td>
</tr>
<tr>
<td>$\gamma$ energy calibration</td>
<td>$\pm 0.5$</td>
<td>$\pm 0.3$</td>
<td>$\pm 1.2$</td>
</tr>
<tr>
<td>Reconstruction efficiency ratio</td>
<td>-</td>
<td>-</td>
<td>$\pm 2.8$</td>
</tr>
</tbody>
</table>

Total | $\pm 1.2$ | $\pm 4.7$ | $\pm 7.2$ |

fit are determined by changing the fit range, the bin width, the background-polynomial order and the fixed values of $M_{h_{b}(1P)}$ used in the fits. Similarly, the uncertainties arising from the $\Delta M_{\text{miss}}$ fit are studied by repeating it with different ranges and binning. The calibration uncertainty accounts for the errors on the photon energy calibration factors. The uncertainty due to the ratio of the reconstruction efficiencies arises entirely from the single-photon reconstruction efficiency. The $\eta_{b}(1S)$ annihilates into two gluons, while the $h_{b}(1P)$ annihilates predominantly into three gluons, but the MC simulation indicates no significant difference in the $R_{2}$ shape. Therefore, the continuum suppression cut does not contribute to the uncertainty arising from the reconstruction efficiency ratio. We calculate the $\eta_{b}(1S)$ mass as $M_{\eta_{b}(1S)} = M_{h_{b}(1P)} + \Delta M_{\text{miss}} = (9400.7 \pm 1.7 \pm 1.6$ MeV/c². Assuming $m_{\Upsilon}(1S) = (9460.30 \pm 0.26$ MeV/c²) [34], we calculate $\Delta M_{HF}(1S) = (59.6 \pm 1.7 \pm 1.6$ MeV/c²).

A summary of the results presented in this work is shown in Table III. We report the first observation of a single-meson transition from spin-triplet to spin-singlet bottomonium states, $\Upsilon(4S) \rightarrow \eta_{h_{b}(1P)}$. This process is found to be the strongest known transition from the $\Upsilon(4S)$ meson to lower bottomonium states. A new measurement of the $h_{b}(1P)$ mass is presented. The corresponding $1P$ hyperfine splitting is compatible with zero, which can be interpreted as evidence of the absence of sizable long range spin-spin interactions. Exploiting the radiative transition $h_{b}(1P) \rightarrow \gamma\eta_{b}(1S)$, we present a new measurement of the mass difference between the $h_{b}(1P)$ and the $\eta_{b}(1S)$ and, assuming our measurement of $M_{h_{b}(1P)}$, we calculate $M_{\eta_{b}(1S)}$. Our result is in agreement with the value obtained with the $\Upsilon(5S) \rightarrow \pi^{\pm}\pi^{-}h_{b}(1P) \rightarrow \pi^{+}\pi^{-}\gamma\eta_{b}(1S)$ process [34] but exhibits a discrepancy with the M1-based measurements [23,24]. From the theoretical point of view, our result is in agreement with the predictions of many potential models and lattice calculations [41], including the recent lattice result in Ref. [42]. Our measurement of $B[h_{b}(1P) \rightarrow \gamma\eta_{b}(1S)]$ agrees with the theoretical predictions [43,44]. All the direct measurements presented in this work are independent of the previous results reported by Belle [8], which were obtained by reconstructing different transitions and using a different data sample. Furthermore, all the results except for $\Delta M_{HF}(1S)$ and $\Delta M_{HF}(1P)$ are obtained within the analysis described herein and are uncorrelated with the existing world averages.

TABLE III. Summary of the results of the searches for $\Upsilon(4S) \rightarrow \eta_{h_{b}(1P)}$ and $h_{b}(1P) \rightarrow \gamma\eta_{b}(1S)$.

<table>
<thead>
<tr>
<th>Observable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B[\Upsilon(4S) \rightarrow \eta_{h_{b}(1P)}]$</td>
<td>$(2.18 \pm 0.11 \pm 0.18) \times 10^{-5}$</td>
</tr>
<tr>
<td>$B[h_{b}(1P) \rightarrow \gamma\eta_{b}(1S)]$</td>
<td>$(56 \pm 8 \pm 4) %$</td>
</tr>
<tr>
<td>$M_{h_{b}(1P)}$</td>
<td>$(9899.3 \pm 0.4 \pm 1.0$ MeV/c²</td>
</tr>
<tr>
<td>$M_{\eta_{b}(1S)} - M_{h_{b}(1P)}$</td>
<td>$(-498.6 \pm 1.7 \pm 1.2$ MeV/c²</td>
</tr>
<tr>
<td>$\Gamma_{\eta_{b}(1S)}$</td>
<td>$(816.5 \pm 5$ MeV/c²</td>
</tr>
<tr>
<td>$M_{\eta_{b}(1S)}$</td>
<td>$(9400.7 \pm 1.7 \pm 1.6$ MeV/c²</td>
</tr>
<tr>
<td>$\Delta M_{HF}(1S)$</td>
<td>$(+59.6 \pm 1.7 \pm 1.6$ MeV/c²</td>
</tr>
<tr>
<td>$\Delta M_{HF}(1P)$</td>
<td>$(+0.6 \pm 0.4 \pm 1.0$ MeV/c²</td>
</tr>
</tbody>
</table>

We thank the KEKB group for excellent operation of the accelerator; the KEK cryogenics group for efficient solenoid operations; and the KEK computer group, the NII, and PNPL/EMSL for valuable computing and SINET4 network support. We acknowledge support from MEXT, JSPS and Nagoya’s TLPRC (Japan); ARC and DIISR (Australia); FWF (Austria); NSFC (China); MSMT (Czechia); CZF, DFG, and VS (Germany); DST (India); INFN (Italy); MOE, MSIP, NRF, GSDC of KISTI, and BK21Plus (Korea); MNISW and NCN (Poland); MES (particularly under Contract No. 14.A12.31.0006), RFAAE and RFBR under Grant No. 14-02-01220 (Russia); ARRS (Slovenia); IKERBASQUE and UPV/EHU (Spain); SNSF (Switzerland); NSC and MOE (Taiwan); and DOE and NSF (USA).