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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First observation of the hadronic transition $\Upsilon(4S) \to \eta h_0(1P)$ and new measurement of the $h_0(1P)$ and $\eta(1S)$ parameters


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The bottomonium system, comprising bound states of $b$ and $\bar{b}$ quarks, has been studied extensively in the past. The recent observations of unexpected hadronic transitions from the $J^{PC} = 1^{−−}$ states above the $BB$ 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 $\eta_b(nS)$, and challenged theoretical descriptions, showing a large violation of the selection rules that apply to transitions below the threshold.

Hadronic transitions between the lowest mass quarkonium levels can be described using the QCD multipole expansion (ME). In this approach, the heavy quarks emit two gluons that subsequently transform into light hadrons. The $\pi$ and $\eta$ transitions between the vector states proceed via emission of $E_1E_1$ and $E_1M_2$ gluons, respectively. Therefore, $\eta$ transitions are highly suppressed as they require a spin flip of the heavy quark.
studying the inclusive \( \pi \) us to measure its mass and, via the \( \eta \) mesons in the \( \Upsilon(4s) \) production in
is predicted to have a branching fraction of the order of \( h \) approach used for the observation of the
and \( \eta \) are the four-momenta of the colliding \( \eta \) mesons and charged tracks pointing towards the primary interaction vertex, a visible energy greater than \( 0.2\sqrt{s} \), a total energy deposition in the electromagnetic calorimeter (ECL) between \( 0.1\sqrt{s} \) and \( 0.8\sqrt{s} \), and a total momentum balanced along the \( z \) axis. Continuum \( e^+e^- \rightarrow q\bar{q} \) 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 \( \gamma \) 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 \( D^{*0} \rightarrow D^0 \gamma \). 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 \( F_{\gamma}(E) \) and the resolution fudge factor \( F_{\gamma}(E) \). We observe \( F_{\gamma}(E) \approx 0.1\% \) and \( F_{\gamma}(E) \approx (\pm 5 \pm 3)\% \) 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/c\(^2\) 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 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/c\(^2\). Thus, \( \gamma \gamma \) pairs with an invariant mass within 26 MeV/c\(^2\) of the nominal \( \eta \) mass \( 34 \) are selected as a signal sample, while the candidates in the regions \( 39 \) MeV/c\(^2\) \( 52 \) MeV/c\(^2\) 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 \( \Upsilon(4s) \rightarrow \eta b(1P) \) 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/c\(^2\) \( 33 \). The \( M_{\text{miss}}(\eta) \) spectrum is fitted in two separate
intervals: (9.30, 9.70) GeV/c² and (9.70, 10.00) GeV/c². In the first (second) interval, the combinatorial background is described with a 6th-order (11th) Chebyshev polynomial. The polynomial order is determined maximizing the credibility level of the fit and is validated using the sideband samples. Figure 1 shows the background-subtracted Mmiss(η) distribution, with a bin size 50 times larger than that used for the fit. The credibility levels of the fits are 1% in the lower interval and 19% in the upper one. The transition Υ(4S) → ηh_b(1P) is observed with a statistical significance of 11σ, calculated using the profile likelihood method [38], and no signal is observed in the γγ-mass control regions. The h_b(1P) yield is N_{h_b(1P)} = 112469 ± 5537. From the position of the peak, we measure M_{h_b(1P)} = (9899.3 ± 0.4 ± 1.0) MeV/c² (hereinafter the first error is statistical and the second is systematic). We calculate the branching fraction of the transition as

\[ \mathcal{B}(\Upsilon(4S) \to \eta h_b(1P)) = \frac{N_{h_b(1P)}}{N_{\Upsilon(4S)} e_{\eta h_b(1P)} \mathcal{B}[\eta \to \gamma \gamma]}, \]

where \( N_{\Upsilon(4S)} = (771.6 ± 10.6) \times 10^6 \) is the number of \( \Upsilon(4S) \), \( e_{\eta h_b(1P)} = (16.96 ± 1.12)\% \) is the reconstruction efficiency and \( \mathcal{B}[\eta \to \gamma \gamma] = (39.41 ± 0.21)\% \) [34]. We obtain \( \mathcal{B}(\Upsilon(4S) \to \eta h_b(1P)) = (2.18 ± 0.11 ± 0.18) \times 10^{-3} \), in agreement with the available theoretical prediction [21]. No evidence of \( \Upsilon(4S) \to \eta \Upsilon(1S) \) is present, so we set the 90% Credibility Level (CL) upper limit \( \mathcal{B}(\Upsilon(4S) \to \eta \Upsilon(1S)) < 2.7 \times 10^{-4} \), in agreement with the previous experimental result by BaBar [16]. All the upper limits presented in this work are obtained using the CLs technique [39, 40] and include systematic uncertainties. Using our measurement of \( M_{h_b(1P)} \), we calculate the corresponding 1P hyperfine splitting, defined as the difference between the \( \chi_{bJ}(1P) \) spin-averaged mass \( m^\text{av}_{\chi_{bJ}(1P)} \) and the \( h_b(1P) \) mass, and obtain \( \Delta M_{HF}(1P) = (0.6 ± 0.4 ± 1.0) \) MeV/c²; the systematic error includes the uncertainty on the value of \( m^\text{av}_{\chi_{bJ}(1P)} \) [34].

As validation of our measurement, we study the \( \eta \to \pi^+ \pi^- \pi^0 \) mode. The \( \pi^0 \) candidate is reconstructed from a \( \gamma \gamma \) pair with invariant mass within 17 MeV/c² of the nominal \( \pi^0 \) mass [34] while the \( \pi^\pm \) candidates tracks are required to be associated with the primary interaction vertex and not identified as kaons by the particle identification algorithm. We observe an excess in the signal region with statistical significance of 3.5σ and measure \( \mathcal{B}(\Upsilon(4S) \to \eta h_b(1P))_{\eta \to \pi^+ \pi^- \pi^0} = (2.3 ± 0.6) \times 10^{-5} \), which is in agreement with the result from the \( \gamma \gamma \) mode.

The contributions to the systematic uncertainty in our measurements are summarized in Table I. To estimate them, we first vary — simultaneously — the fit ranges within \( \pm 100 \) MeV/c² 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/c² and we treat the corresponding average variations as the binwidth systematic error. The ISR modeling contribution is due to the \( \Upsilon(4S) \) width uncertainty [34]. The pres-
TABLE I. Systematic uncertainties in the determination of \( \mathcal{B}[\Upsilon(4S) \rightarrow \eta b(1P)] \), in units of \%, and on \( M_{b(1P)} \), in units of MeV/c\(^2\).

<table>
<thead>
<tr>
<th>Source</th>
<th>( \mathcal{B} )</th>
<th>( M_{b(1P)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit range and background PDF order</td>
<td>( \pm 2.4 \pm 0.1 )</td>
<td></td>
</tr>
<tr>
<td>Bin width</td>
<td>( \pm 2.5 \pm 0.1 )</td>
<td></td>
</tr>
<tr>
<td>ISR modeling</td>
<td>( \pm 2.8 \pm 0.7 )</td>
<td></td>
</tr>
<tr>
<td>Peaking backgrounds</td>
<td>( \pm 0.5 \pm 0.4 )</td>
<td></td>
</tr>
<tr>
<td>( \gamma ) energy calibration</td>
<td>( \pm 1.2 \pm 0.3 )</td>
<td></td>
</tr>
<tr>
<td>Reconstruction efficiency</td>
<td>( \pm 6.6 )</td>
<td></td>
</tr>
<tr>
<td>( N_{\Upsilon(4S)} )</td>
<td>( \pm 1.4 )</td>
<td></td>
</tr>
<tr>
<td>Beam energy</td>
<td>( \pm 0.0 \pm 0.4 )</td>
<td></td>
</tr>
<tr>
<td>( \mathcal{B}[\eta \rightarrow \gamma \gamma] )</td>
<td>( \pm 0.5 )</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>( \pm 8.2 \pm 1.0 )</td>
<td></td>
</tr>
</tbody>
</table>

efact of peaking backgrounds is studied using MC samples of inclusive \( BB \) events and bottomonium transitions. While no peaking background due to \( B \) meson decay has been identified, the as-yet-unobserved transitions \( \Upsilon(4S) \rightarrow \gamma \gamma \Upsilon(1^3D_{1,2}) \rightarrow \gamma \gamma \eta \Upsilon(1S) \) can appear in the \( M_{\text{miss}}(\eta) \) spectrum as a CB-shaped peaking structure at \( M_{\text{miss}}(\eta) = 9.877 \) GeV/c\(^2\) with resolution of 10.6 MeV/c\(^2\). We take this effect into account by repeating the fit with and without an additional CB component. No signal is observed and we obtain the upper limit on the product of branching fractions \( \mathcal{B}[\Upsilon(4S) \rightarrow \gamma \gamma \Upsilon(1^3D_{1,2})] \times \mathcal{B}[\Upsilon(1^3D_{1,2}) \rightarrow \eta \Upsilon(1S)] < 0.8 \times 10^{-4} \) (90\% CL). The uncertainty on the photon energy calibration factors is determined by varying both \( \mathcal{S}_{en}(E) \) and \( \mathcal{S}_{res}(E) \) within their errors. The uncertainty on the reconstruction efficiency includes contributions from several sources. Using 121.4 fb\(^{-1}\) collected at the \( \Upsilon(5S) \) energy, the \( \Upsilon(5S) \rightarrow \pi^+ \pi^- \Upsilon(2S) \) transition is reconstructed; comparing the \( R_2 \) shape obtained from this data sample with the simulation provides a \( \pm 3\% \) uncertainty related to the continuum rejection. A \( \pm 1\% \) uncertainty is assigned for the efficiency of the hadronic event selection. The uncertainty on the photon reconstruction efficiency is estimated using \( D \rightarrow K^{\pm} \pi^\pm \pi^0 \) events to be \( \pm 2.8\% \) per photon, corresponding to \( \pm 5.6\% \) per \( \eta \). The number of \( \Upsilon(4S) \) mesons is measured with a relative uncertainty of \( \pm 1.4\% \) from the number of hadronic events after the subtraction of the continuum contribution using off-resonance data. The absolute value of accelerator beam energies are calibrated by fully reconstructed \( B \) mesons. We observe a \( \pm 0.4 \) MeV/c\(^2\) fluctuation of \( M_{b(1P)} \) due to the uncertainty on the \( B \) meson mass \( ^{[34]} \) and a negligible effect on the branching ratio measurement. Finally, we include an uncertainty in the branching fraction due to the uncertainty in \( \mathcal{B}[\eta \rightarrow \gamma \gamma] \) \( ^{[34]} \).

The study of the \( \eta_b(1S) \) is performed by reconstructing the transitions \( \Upsilon(4S) \rightarrow \eta b(1P) \rightarrow \eta \gamma \eta_b(1S) \). To extract the signal, we measure the number of \( \Upsilon(4S) \rightarrow \eta b(1P) \) events \( N_{b(1P)} \) 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 transi-

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 \( M_{\eta_b(1S)} - M_{b(1P)} = (-498.6 \pm 1.7 \pm 1.2) \) MeV/c\(^2\), \( \Gamma_{\eta_b(1S)} = (8^{+9}_{-5} \pm 5) \) MeV/c\(^2\) and the number of \( \Upsilon(4S) \rightarrow \eta b(1P) \rightarrow \gamma \eta \eta_b(1S) \) events \( N_{\eta_b(1S)} = 33116 \pm 4741 \). The credibility level of the fit is 50\%. We calculate the branching fraction of the radiative transition as

\[
\mathcal{B}[b(1P) \rightarrow \gamma \eta_b(1S)] = \frac{N_{\eta_b(1S)} \epsilon_{\eta_b(1P)}}{N_{b(1P)} \epsilon_{\gamma \eta_b(1S)}},
\]

where \( \epsilon_{\gamma \eta_b(1S)} = 1.887 \pm 0.053 \) is the ratio of the reconstruction efficiencies for \( \Upsilon(4S) \rightarrow \eta b(1P) \) and \( \Upsilon(4S) \rightarrow \eta b(1P) \rightarrow \gamma \eta \eta_b(1S) \). We obtain \( \mathcal{B}[b(1P) \rightarrow \gamma \eta_b(1S)] = (56 \pm 8 \pm 4)\% \). To estimate the systematic

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{\( \Delta M_{\text{miss}}(\gamma \gamma) \) distribution. The blue solid line shows our best fit, while the red, dashed line represents the background component.}
\end{figure}
TABLE II. Systematic uncertainties in the determination of the $\eta(1S)$ mass and width, in units of MeV/$c^2$ and on $B = B[\eta_b(1P) \rightarrow \gamma\eta_b(1S)]$ in units of \%.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta M_{\text{miss}} \Gamma_{\eta_b(1S)}$</th>
<th>$B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\text{miss}}(\eta)$ fit range</td>
<td>$\pm 0.8 \pm 3.0 \pm 2.8$</td>
<td></td>
</tr>
<tr>
<td>$M_{\text{miss}}(\eta)$ bin width</td>
<td>$\pm 0.0 \pm 0.1 \pm 0.0$</td>
<td></td>
</tr>
<tr>
<td>$M_{\text{miss}}(\eta)$ polynomial order</td>
<td>$\pm 0.1 \pm 1.9 \pm 1.6$</td>
<td></td>
</tr>
<tr>
<td>$M_{h_b(1P)}$</td>
<td>$\pm 0.0 \pm 0.8 \pm 1.1$</td>
<td></td>
</tr>
<tr>
<td>$\Delta M_{\text{miss}}$ fit range</td>
<td>$\pm 0.0 \pm 0.7 \pm 2.2$</td>
<td></td>
</tr>
<tr>
<td>$\Delta M_{\text{miss}}$ bin width</td>
<td>$\pm 0.8 \pm 2.8 \pm 5.2$</td>
<td></td>
</tr>
<tr>
<td>$\gamma$ energy calibration</td>
<td>$\pm 0.5 \pm 0.3 \pm 1.2$</td>
<td></td>
</tr>
<tr>
<td>Reconstruction efficiency ratio</td>
<td>- - $\pm 2.8$</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$\pm 1.2 \pm 4.7 \pm 7.2$</td>
<td></td>
</tr>
</tbody>
</table>

Uncertainties reported in Table II we adopt the protocols discussed earlier. Uncertainties related to the $M_{\text{miss}}(\eta)$ 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/$c^2$. Assuming $m_{\Upsilon(1S)} = (9460.30 \pm 0.26)$ MeV/$c^2$ [34], we calculate $\Delta M_{HF}(1S) = (59.6 \pm 1.7 \pm 1.6)$ MeV/$c^2$.

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, $\Upsilon(4S) \rightarrow \eta\eta_b(1P)$. 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 $\Upsilon(5S) \rightarrow \pi^+\pi^-h_b(1P) \rightarrow \pi^+\pi^-\gamma\eta_b(1S)$ process [4] but exhibits a discrepancy with the $M_1$-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 $B[\eta_b(1P) \rightarrow \gamma\eta_b(1S)]$ 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.

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