Search for bottomonium states in exclusive radiative $\Upsilon(2S)$ decays

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We search for bottomonium states in $T(2S) \to (b\bar{b})\gamma$ decays with an integrated luminosity of 24.7 fb$^{-1}$ recorded at the $T(2S)$ resonance with the Belle detector at KEK, containing $(157.8 \pm 3.6) \times 10^6 T(2S)$ events. The $(b\bar{b})$ system is reconstructed in 26 exclusive hadronic final states comprised of charged pions, kaons, protons, and $K^0_S$ mesons. We find no evidence for the state recently observed around 9975 MeV ($X_{2750}$) in an analysis based on a data sample of $9.3 \times 10^6 T(2S)$ events collected with the CLEO III detector. We set a 90% confidence-level upper limit on the branching fraction $B[T(2S) \to X_{2750} \gamma] \times \sum_i B[X_{2750} \to h_i] < 4.9 \times 10^{-6}$, summed over the exclusive hadronic final states employed in our analysis. This result is an order of magnitude smaller than the measurement reported with CLEO data. We also set an upper limit for the $\eta_b(1S)$ state of $B[T(2S) \to \eta_b(1S)\gamma] \times \sum_i B[\eta_b(1S) \to h_i] < 3.7 \times 10^{-9}$.

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Bottomonium, a bound system of a bottom ($b$) quark and its antiquark ($\bar{b}$), offers a unique laboratory to study strong interactions; since the $b$ quark is heavier than other quarks ($q = u, d, s, c$), the system can be described by non-relativistic quantum mechanics and effective theories [1]. Spin-singlet states permit the study of spin-spin interactions within the $b\bar{b}$ system.

The ground state of the bottomonium family with zero orbital and spin angular momenta, the $\eta_b(1S)$, was discovered by the BaBar Collaboration in 2008 [2]. Evidence for its radially excited spin-singlet partner, the $\eta_b(2S)$, was reported by Belle [3] using a 133.4 fb$^{-1}$ data sample collected near the $T(5S)$ resonance. That analysis used the process $e^+e^- \to T(5S) \to h_b(nP)\pi^+\pi^-$, $h_b \to \eta_b(mS)\gamma$ for $n(\geq m) = 1, 2$. The $\eta_b(2S)$ mass measured in the $h_b(2P) \to \eta_b(2S)\gamma$ transition was $[9999.0 \pm 3.5 \text{(stat)} \pm 2.5 \text{(syst)}] \text{MeV}/c^2$, corresponding to a hyperfine mass splitting between $\Upsilon(2S)$ and $\eta_b(2S)$ states, $\Delta M_{HF}(2S) \equiv M[\Upsilon(2S)] - M[\eta_b(2S)]$, of $[24.3^{+8.3}_{-8.5}] \text{MeV}/c^2$. The BaBar and Belle analyses were based on an inclusive approach, where the final state of the $\eta_b(nS)$ was not reconstructed.
There is a recent claim of the observation of a bottomonium state $X_{c\bar{s}}$ in the radiative decay $\Upsilon(2S) \rightarrow X_{c\bar{s}}\gamma$ with a data sample of $9.3 \times 10^6 \Upsilon(2S)$ decays recorded with the CLEO III detector. The analysis, based on the reconstruction of 26 exclusive hadronic final states, reports a mass of $[9974.6 \pm 2.3 \text{(stat)} \pm 2.1 \text{(syst)}]$ MeV/$c^2$ and assigns this state to the $n_b(2S)$, which corresponds to $\Delta M_{J\text{HF}}(2S) = [48.6 \pm 3.1]$ MeV/$c^2$. This disagrees with most of the predictions for $\Delta M_{J\text{HF}}(2S)$ from unquenched lattice calculations, potential models and a model-independent relation that are compiled in Ref. [5] and therefore suggests a flaw in the theoretical understanding of QCD hyperfine mass splittings. In contrast, the Belle result is consistent with the theoretical expectations in Ref. [6].

In this Letter, we report a search for the states $X_{c\bar{s}}$ in $\Upsilon(2S) \rightarrow X_{c\bar{s}}\gamma$ decays and $\eta_b(1S)$ in $\Upsilon(2S) \rightarrow \eta_b(1S)\gamma$ decays using a data sample with an integrated luminosity of 24.7 fb$^{-1}$ collected at the $\Upsilon(2S)$ peak with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider. The sample contains $157.8(36) \times 10^6 \Upsilon(2S)$ decays [7], about 17 times larger than the one used in Ref. [8]. In addition, 1.7 [89.5] fb$^{-1}$ of data recorded 30 [60] MeV below the $\Upsilon(2S)$ [$\Upsilon(4S)$] resonance energy ("off-resonance") are used to model the $e^+e^- \rightarrow q\bar{q}$ continuum background. It is not possible to reconstruct the $n_b(2S)$ state using exclusive reconstruction of the hadronic final state near the mass found in Ref. [3] because this region suffers from a low photon detection efficiency and high background.

We employ the EvtGen [8] package to generate signal Monte Carlo (MC) events. The radiative decays of the $\Upsilon(2S)$ are generated using the helicity amplitude formalism. Hadronic decays of the $(b\bar{b})$ system are modeled assuming a phase space distribution; to incorporate final state radiation effects, an interface to PHOTOS [11] is added. Inclusive $\Upsilon(2S)$ MC events, produced using PYTHIA [12] with the same luminosity as the data, are investigated for potential peaking backgrounds.

The Belle detector [6] is a large-solid-angle spectrometer that includes a silicon vertex detector, a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprising CsI(Tl) crystals. All these components are located inside a superconducting solenoid coil that provides a 1.5 T magnetic field.

Our event reconstruction begins with the selection of an appropriate number and type of charged particles to reconstruct a subset of the many exclusive hadronic final states of the $(b\bar{b})$ system. We restrict ourselves to the 26 modes reported in Ref. [3]:

- $2(\pi^+\pi^-)$,
- $3(\pi^+\pi^-)$, $4(\pi^+\pi^-)$, $5(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$, $K^+K^-2(\pi^+\pi^-)$, $K^+K^-3(\pi^+\pi^-)$, $K^+K^-4(\pi^+\pi^-)$,
- $2(K^+K^-)$,
- $2(K^+K^-)\pi^+\pi^-$,
- $2(K^+K^-)3(\pi^+\pi^-)$.

We require all charged tracks, except for those from $K^0_s$ decays, to originate from the vicinity of the interaction point (IP) by requiring their impact parameters along and perpendicular to the $z$ axis to be less than 4 cm and 1 cm, respectively. Here, the $z$ axis is defined by the direction opposite the $e^+$ beam. Track candidates are identified as pions, kaons, or protons ("hadrons") based on information from the CDC, the TOF and the ACC. The kaon identification efficiency is 83.1% with a pion misidentification probability of 8.0% - 10.0%.

We then combine a photon candidate with the $(b\bar{b})$ system to form an $\Upsilon(2S)$ candidate. The photon is reconstructed from an isolated (not matched to any charged track) cluster in the ECL that has an energy greater than 22 MeV and a cluster shape consistent with an electromagnetic shower. The energy sum of the $3 \times 3$ array of crystals centered around the most energetic one exceeding 85% of that of the $5 \times 5$ array of crystals. The energy of the signal photon is $30 - 70$ MeV and $400 - 900$ MeV for the $X_{c\bar{s}}$ and $\eta_b(1S)$, respectively. We exclude photons from the backward endcap in the $\eta_b(1S)$ selection to suppress low-energy photons arising from beam-related background.

For the $X_{c\bar{s}}$ selection, the forward endcap region is also excluded as the energy of the photon from the $\Upsilon(2S) \rightarrow X_{c\bar{s}}\gamma$ decay is too low, and lies in a range contaminated with large beam backgrounds. The photon energy resolution in the barrel ECL ranges between 2% at $E_\gamma = 1$ GeV and 3% at $E_\gamma = 100$ MeV.

There is a weak correlation between the signal photon momentum and the thrust axis of the hadrons of the $(b\bar{b})$ system if the latter has spin zero. The same correlation is stronger for continuum events [2], so the cosine of the angle $\theta_T$ between the candidate photon and the thrust axis, calculated in the $e^+e^-$ center-of-mass (CM) frame, is useful in suppressing the continuum background. Since the distribution of this variable is independent of the $(b\bar{b})$-mass region considered, we require $|\cos \theta_T| < 0.8$ for a substantial reduction (60%) of continuum events and a modest loss (20%) of signal.

The signal windows for the difference between the energy of the $\Upsilon(2S)$ candidate and the CM energy ($\Delta E$) and the $\Upsilon(2S)$ momentum measured in the CM frame...
\(P_{\pi^0}^\ast(2S)\) are optimized separately for the \(X_{bb}\) and \(\eta_b(1S)\) mass regions. We perform this optimization using a figure-of-merit \(S/\sqrt{S + B}\), where \(S\) is the expected signal based on MC simulations, and \(B\) is the background estimated from a sum of the \(\Upsilon(4S)\) off-resonance data, scaled to the available \(\Upsilon(2S)\) integrated luminosity, and the inclusive \(\Upsilon(2S)\) MC sample described earlier. The value of \(S\) is calculated by assuming the branching fraction to be \(46.2 \times 10^{-6}\) in the case of the \(X_{bb}\) and \(3.9 \times 10^{-6}\) for the \(\eta_b(1S)\). The \(\Upsilon(2S)\) candidates with \(-40\) MeV \(< \Delta E < 50\) MeV and \(P_{\pi^0}^\ast(2S) < 30\) MeV/c \([-30\) MeV \(< \Delta E < 80\) MeV and \(P_{\pi^0}^\ast(2S) < 50\) MeV/c] are retained for a further study of the putative \(X_{bb} \eta_b(1S)\) state.

For the two-body decay hypothesis, the angle \(\theta_{(b\bar{b})\gamma}\) between the reconstructed \((b\bar{b})\) system and the photon candidate in the CM frame should be close to \(180^\circ\). We apply an optimized requirement on \(\theta_{(b\bar{b})\gamma}\) to be greater than \(150^\circ [177^\circ]\) to select the \(\Upsilon(2S) \rightarrow X_{bb}\gamma \quad \Upsilon(2S) \rightarrow \eta_b(1S)\gamma\) decay candidates. The difference between the invariant mass formed by combining the signal photon with another photon candidate in the event and the nominal \(\pi^0\) mass \([15]\) is computed for each photon pair; the smallest of the magnitudes of these differences is denoted by \(\Delta M_{\pi^0}\) and used for a \(\pi^0\) veto. For the \(\eta_b(1S)\) selection, where the background contribution is dominated by \(\pi^0\)'s coming from the \(\Upsilon(2S)\) decays, we require \(\Delta M_{\pi^0} > 10\) MeV/c\(^2\). We do not apply the \(\pi^0\) veto in the \(X_{bb}\) selection since there is negligible \(\pi^0\) contamination; the background here is dominated by photons coming from beam background. The final selection efficiencies for the individual modes range from 6.1% \([X_{bb} \rightarrow 3(\pi^+\pi^-)]\) to 1.2% \([X_{bb} \rightarrow 2K^0S(3\pi^+\pi^-)]\).

We apply a kinematic fit constrained by energy-momentum conservation to the \(\Upsilon(2S)\) candidates. The resolution of the reconstructed invariant mass of \(\eta_b(1S)\), presented in terms of \(\Delta M \equiv M((b\bar{b})\gamma) - M(b\bar{b})\), is significantly improved by this fit from approximately 14 to 8 MeV/c\(^2\). The improvement in the mass resolution is minimal for the \(X_{bb}\) since the photon has so little energy. The fit \(\chi^2\) value is used to select the best \(\Upsilon(2S)\) candidate in the case of multiple candidates that appear in about 10% of the events satisfying the \(X_{bb}\) selection.

We extract the signal yield by performing an unbinned extended maximum-likelihood fit of the \(\Delta M\) distribution for the selected candidates. The probability density functions (PDFs) for \(\chi_{bJ}(1P)\) and \(X_{bb}\) signals are parameterized by the sum of a Gaussian and an asymmetric Gaussian to take into account low-energy tails. Their parameters (common mean, widths and the relative fraction) are taken from MC simulations. To account for the modest difference in the detector resolution between data and simulations, we use a calibration factor common to the four signal components, i.e., \(\chi_{bJ}(1P)\) with \(J = 0, 1, 2\) and \(X_{bb}\), to smear their core Gaussian components. The choice of the background PDF is particularly important and is determined from the large sample of \(\Upsilon(4S)\) off-resonance data (Fig. 1). The best fit to these data is obtained by using a sum of an exponential and a first-order Chebyshev polynomial for the \(X_{bb}\) region, whose parameters are allowed to vary in the fit. (This is in contrast to Ref. [4], where the single exponential alone was used to describe the background PDF.) The polynomial component is needed to model the background due to final state radiation in the lower \(\Delta M\) region (< 0.15 GeV/c\(^2\)) and the \(\pi^0\) background above that \(\Delta M\) value. Figure 1 shows fits to the \(\Delta M\) distributions for the sum of the 26 modes in the \(X_{bb}\) region. The results of the fit show no evidence of an \(X_{bb}\) signal, with a yield of \(-30 \pm 19\) events. Large yields are found for the \(\chi_{bJ}(1P)\) \((J = 0, 1, 2)\) states and their invariant masses obtained from the fit, 9859.6 ± 0.5, 9892.8 ± 0.2

![Figure 1: (color online). \(\Delta M\) distributions for (top) \(\Upsilon(4S)\) off-resonance and (bottom) \(\Upsilon(2S)\) data events that pass through the selection criteria applied for the [0.03, 0.30] GeV/c\(^2\) region. Points with error bars are the data, (top) the blue solid curve is the result of the fit for the background-only hypothesis, and (bottom) the result of the fit for the signal-plus-background hypothesis, where blue solid and blue dashed curves are total and background components, respectively. The three \(\chi_{bJ}(1P)\) components indicated by the red dotted curves are here considered as part of the signal. The bottom inset shows an expanded view of the \(\Delta M\) distribution in the [0.035, 0.065] GeV/c\(^2\) region.](image-url)
and $9912.0 \pm 0.3$ MeV/$c^2$, are in excellent agreement with the corresponding world-average values [15]. The strong $\chi_{bJ}(1P)$ signals determine the aforementioned data-MC width-calibration factor to be $1.23 \pm 0.05$. The parameters obtained for the background PDF in the $Y(2S)$ sample are consistent with those found in the fit to the $Y(4S)$ off-resonance data, giving us confidence in our background modeling.

The signal PDF for the $\eta_b(1S)$ is a Breit-Wigner function, whose width is fixed to the value obtained in Ref. 3, convolved with a Gaussian of width 8 MeV describing the detector resolution. A first-order Chebyshev polynomial is used for the background in the $\eta_b(1S)$ region, validated with the large sample of $Y(4S)$ off-resonance data (Fig. 2). No signal ($-6 \pm 10$ events) is found for the $\eta_b(1S)$, as shown in the bottom plot of Fig. 2.

![Figure 2](attachment:image.png)

**FIG. 2:** (color online). $\Delta M$ distributions for (top) $Y(4S)$ off-resonance and (bottom) $Y(2S)$ data events that pass through the selection criteria applied for the $[0.45, 0.75]$ GeV/$c^2$ region. Points with error bars are the data, (top) the blue solid curve is the result of the fit for the background-only hypothesis, and (bottom) the result of the fit for the signal-plus-background hypothesis, where blue solid and blue dashed curves are total and background components, respectively.

For a particle of mass near 10 GeV/$c^2$, exclusive decays are distributed across many final states, and thus we use the $\chi_{b0}(1P)$ [spin-zero, as for the $\eta_b(nS)$] decay modes for guidance. The average efficiency for each $(b\bar{b})$ state is calculated from the individual efficiencies $[\varepsilon((b\bar{b}))]$ obtained with MC samples weighted according to the yields $[N_{\chi_{b0}(1P)}^i]$ for each mode in the $\chi_{b0}(1P)$ case, as

$$\varepsilon((b\bar{b})) = \frac{\sum_{i=1}^{26} \varepsilon((b\bar{b})) \times N_{\chi_{b0}(1P)}^i}{N_{\chi_{b0}(1P)}^{\text{tot}}},$$

where $N_{\chi_{b0}(1P)}^{\text{tot}}$ denotes the total sum of the signal yields obtained for the 26 hadronic decays of the $\chi_{b0}(1P)$. Those efficiencies are corrected to take into account the data-MC difference in the hadron identification efficiency. The corrected efficiencies are 2.9% and 3.5% for the $X_{b0}$ and $\eta_b(1S)$, respectively. Very similar results are obtained when using the $\chi_{b1}(1P)$ or $\chi_{b2}(1P)$ state as the proxy instead of the $\chi_{b0}(1P)$.

We estimate the uncertainties on the signal yields due to the signal PDF shapes using $\pm 1\sigma$ variations of the shape parameters that are fixed in the fit. The dominant sources of such additive systematic errors are the $X_{b0}$ [4] and $\eta_b(1S)$ [5] masses. For the upper limit estimates (described below), we conservatively use the fit likelihood, which gives the largest upward variation of the signal yield: 18 and 4 events for the $X_{b0}$ and $\eta_b(1S)$, respectively. The multiplicative systematic uncertainties that do not affect the signal yields are summarized in Table II. The largest contribution arises from the uncertainty in the efficiency estimate. Two sources dominate here: (a) the statistical error in the yield of the different decay modes of the $\chi_{b0}(1P)$, and (b) the effects of possible intermediate states on the signal efficiency (referred to as “decay modeling”). As described earlier, all our signal MC samples are generated with a phase space distribution. Therefore, in order to estimate the contribution from source (b), possible intermediate states such as $\rho^0 \rightarrow \pi^+\pi^-$, $K^*(892)^0 \rightarrow K^+\pi^-$ and $K^*(892)^\pm \rightarrow K^0\pi^\pm$ are considered. Differences in the efficiencies based on the same final-state modes generated with these intermediate resonances can be as large as 9.2%. The other minor sources arise from hadron identification, charged track reconstruction, $K^0$ and photon detection, and the number of $Y(2S)$.

The branching fraction is determined from the number of observed signal events ($n_{\text{sig}}$) as $B = n_{\text{sig}} / [\varepsilon((b\bar{b})) \times N_{Y(2S)}]$, where $\varepsilon((b\bar{b}))$ is evaluated as shown in Eq. II and $N_{Y(2S)}$ is the total number of $Y(2S)$ decays. In the absence of the signal, we obtain an upper limit at 90% confidence level (CL) on the branching fraction ($B_{UL}$) by integrating the likelihood ($L$) of the fit with fixed values of the branching fraction: $\int_0^{B_{UL}} L(B) dB = 0.9 \times \int_0^{B_{UL}} L(B) dB$. Multiplicative systematic uncertainties are included by convolving the likelihood function with a Gaussian function of width equal to the total uncertainty. We estimate $B[Y(2S) \rightarrow \eta_b(1S)] \times \sum_i B[\eta_b(1S) \rightarrow h_i] < 3.7 \times 10^{-6}$ and $B[Y(2S) \rightarrow X_{b\gamma}] \times \sum_i B[X_{b\gamma} \rightarrow h_i] < ...$
TABLE I: Multiplicative systematic uncertainties (in %) considered in the estimation of the $X_{b\bar{b}}$ and $\eta_b(1S)$ upper limits.

| Source                     | $X_{b\bar{b}}$ | $\eta_b(1S)$ |
|----------------------------|----------------|--------------|
| Efficiency calculation     | ±2.5           | ±2.9         |
| Decay modeling             | ±9.2           | ±6.9         |
| Hadron identification      | ±3.7           | ±3.7         |
| Track reconstruction       | ±2.6           | ±2.6         |
| $K_S^0$ detection          | ±0.2           | ±0.2         |
| Photon detection           | ±3.0           | ±3.0         |
| Number of $\Upsilon(2S)$   | ±2.3           | ±2.3         |
| Total                      | ±11.2          | ±9.5         |

4.9 × 10^{-6}.

In summary, we have searched for the $X_{b\bar{b}}$ state reported in Ref. [4], that is reconstructed in 26 exclusive hadronic final states using a sample of $(157.8 \pm 3.6) \times 10^6 \Upsilon(2S)$ decays. We find no evidence for signal and thus estimate a 90% CL upper limit $B[\Upsilon(2S) \to X_{b\bar{b}}\gamma] \times \sum_i B[X_{b\bar{b}} \to h_i] < 4.9 \times 10^{-6}$. This result is an order of magnitude smaller than the branching fraction reported in Ref. [4].

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