Observation of $\Upsilon(2S) \to \gamma \eta_b(1S)$ decay

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We report the observation of $\Upsilon(2S) \to \gamma b\bar{b}(1S)$ decay based on analysis of the inclusive photon spectrum of 24.7 fb$^{-1}$ of $e^+e^-$ collisions at the $\Upsilon(2S)$ center-of-mass energy collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider. We measure a branching fraction of $B(\Upsilon(2S) \to \gamma b\bar{b}(1S)) = (6.1^{+0.6+0.9}_{-0.7-0.5}) \times 10^{-4}$, and derive an $b\bar{b}(1S)$ mass of 9394.8$^{+2.7+1.2}_{-3.1-2.7}$ MeV/$c^2$, where the uncertainties are statistical and systematic, respectively. The significance of our measurement is greater than 7 standard deviations, constituting the first observation of this decay mode.

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iterative fashion. A subset of ~5% of the total \( \Upsilon(2S) \) data is used as the background sample for optimizing the selection. To avoid potential bias, these events are discarded from the final analysis. Large Monte Carlo (MC) samples of simulated \( \Upsilon(2S) \rightarrow \gamma \eta_b(1S) \) events are used as the signal input, assuming the branching fraction from [2]. Particle production and decays are simulated using the EVTGEN [10] package, with PHOTOS [17] for modeling final-state radiation effects, and PYTHIA [18] for inclusive \( b\bar{b} \) decays. The interactions of the decay products with the Belle detector are modeled with the GEANT3 [19] simulation toolkit.

This analysis studies radiative bottomonium transitions based on the energy spectrum of the photons in each event. Photon candidates are formed from clusters of energy deposited in crystals grouped in the ECL. Clusters are required to include more than a single crystal. The ratio of the energy deposited in the innermost \( 3 \times 3 \) array of crystals compared to the complete \( 5 \times 5 \) array centered on the most energetic crystal is required to be greater than or equal to 0.925. Clusters must be isolated from the projected path of charged tracks in the CDC, and the associated electromagnetic shower must have a width of less than 6 cm. Due to increased beam-related backgrounds in the forward endcap region, and insufficient energy resolution in the backward one, we consider only clusters in the ECL barrel region for this analysis.

The inclusive photon sample is drawn from events passing a standard Belle definition for hadronic decays. This requires at least three charged tracks, a visible energy greater than 20% of the CM beam energy \( \sqrt{s} \), and a total energy deposition in the ECL between 0.2\( \sqrt{s} \) and 0.8\( \sqrt{s} \).

We consider the cosine of the angle \( \theta_T \) between the photon and the thrust axis calculated in the \( e^+e^- \) CM frame as a discriminant. In a given event, the thrust axis is calculated based on all charged particle tracks and photons except the candidate photon. For continuum background events the photon direction tends to be (anti-) aligned along the thrust axis, whereas the distribution for signal events is isotropic. Therefore to reduce this background we require \( |\cos \theta_T| < 0.85 \).

To remove backgrounds from \( \pi^0 \rightarrow \gamma\gamma \) decays, each photon candidate is sequentially paired with all remaining photon candidates in the event, and vetoed if the resulting invariant mass \( M_{\gamma\gamma} \) is consistent with that of a \( \pi^0 \) \( (m_{\pi^0}) \) [20]. In order to improve purity and reduce combinatorial background, a requirement on the minimum energy of the second photon \( (E_{\gamma,2}) \) is applied. We require \( E_{\gamma,2} > 60 \) MeV, and \( |M_{\gamma\gamma} - m_{\pi^0}| > 15 \) MeV/\( c^2 \).

The resulting spectrum of photon energies in the CM frame \( (E^*_\gamma) \) is shown in Fig. 1. Below 200 MeV there are three prominent peaks related to \( \Upsilon(2S) \rightarrow \gamma \chi_{bJ}(1P) \) transitions. The region of interest for this analysis is \( 300 < E^*_\gamma < 800 \) MeV, where six components are expected. Photons from the \( \Upsilon(2S) \rightarrow \gamma \eta_b(1S) \) signal transition will produce a peak in this distribution near 600 MeV. Direct production of \( \Upsilon(1S) \) via initial-state radiation (ISR), \( e^+e^- \gamma_{ISR} \rightarrow \Upsilon(1S) \), results in a second peak at \( E^*_\gamma \sim 547 \) MeV. A series of three peaks due to \( \chi_{bJ=0,1,2}(1P) \rightarrow \gamma \Upsilon(1S) \) [21] transitions are centered at ~391, ~424, and ~442 MeV. These peaks are Doppler-broadened because the \( \chi_{bJ}(1P) \) states originate from \( \Upsilon(2S) \rightarrow \gamma \chi_{bJ}(1P) \) decays, and are therefore not at rest in the CM frame to which we boost the photon energy for this analysis. As such, they also overlap one another. These peaking features are all found above a very large, smooth, inclusive photon background that diminishes as energy increases.

The lineshape parameters and efficiencies are determined from the MC samples. The \( \eta_b(1S) \) and \( \chi_{bJ}(1P) \) transitions are described by a variation on the Crystal Ball function [22]: a bifurcated Gaussian with individual power-law tails on either side. We assume a natural width for the \( \eta_b(1S) \) of \( \Gamma_{\eta_b(1S)} = 10^{+5}_{-4} \) MeV [20]. A Gaussian with a low-side power-law tail [22] is used to model the ISR-produced \( \Upsilon(1S) \) signal. The underlying background lineshape is parameterized by an exponential function with a sixth-order polynomial. This was selected based on the best fit of 1.7 fb\(^{-1}\) of continuum background data collected at an energy 30 MeV below the \( \Upsilon(2S) \) resonance.

With the above selection criteria our efficiency \( (\epsilon) \) for the peaking processes ranges from 26 to 32%, depending on the mode (Table I). Photon energy resolution in the
CM frame varies from approximately 8 to 12 MeV. Both quantities increase with energy.

The photon energy scale and resolution are verified with multiple independent control samples. The Belle $\Upsilon(2S)$ data were collected in two separate time periods with different operating characteristics. We apply an energy scale adjustment in order to ensure correspondence of the $\chi_{bJ}(1P) \rightarrow \gamma \Upsilon(1S)$ transition energies in both of the periods. To account for differences between MC simulation and data, we fit the energy spectrum with the MC-determined lineshapes for the $\Upsilon(2S) \rightarrow \gamma \chi_{bJ}(1P)$ and $\chi_{bJ}(1P) \rightarrow \gamma \Upsilon(1S)$ transitions, allowing the energy scale and resolution to vary in order to reproduce the expected $E_\gamma^*$ values [2] of the $\chi_{bJ}(1P)$ peaks in data. We linearly extrapolate the measured energy scale shift and resolution broadening to the $\eta_b(1S)$ energy region, and correct the expected signal lineshape accordingly.

We perform a binned maximum-likelihood fit to data in the region of $300 < E_\gamma^* < 804$ MeV including all six peaking components and the exponential background. The yields, energy peak values, and background polynomial coefficients are allowed to vary. In $\chi_{bJ}(1P) \rightarrow \gamma \Upsilon(1S)$ transitions we find the $J = 0$ component, known to be suppressed compared to the $J = 1$ and 2 transitions, to be absorbed into the other nearby peaks. We fix the $J = 0$ peak position in the fit, and measure a yield consistent with zero. The results of the fit are shown in Fig. 2 and summarized in Table I Branching fractions are calculated by dividing the yield by the MC-determined efficiency and number of $\Upsilon(2S)$ events ($(149.6 \pm 3.4) \times 10^6$ with the optimization sample excluded). The value for $\chi_{bJ}(1P)$ modes includes the $\Upsilon(2S) \rightarrow \gamma \chi_{bJ}(1P)$ transition. The goodness of fit is given by a $\chi^2$ per degrees of freedom of 261.5/237, giving a p-value of 0.132.

We consider three categories of systematic uncertainties in this analysis: those related to energy calibration, fit parametrization, and all other uncertainties. These are listed in Table I and are summed in quadrature.

As verification of the energy calibration, we consider a complementary method based on the photon energy in the laboratory frame, similar to previous Belle studies [3, 4]. We derive $E_\gamma$-dependent corrections to the photon energy according to the comparison between MC and data for $D^{*0} \rightarrow D^0(K^{\pm} \pi^{\mp})\gamma$, inclusive $\eta \rightarrow \gamma \gamma$, and exclusive $\chi_{b1,2}(1P) \rightarrow \gamma \Upsilon(1S)(\mu^+\mu^-)$ decays. After applying these corrections, only a small remaining resolution broadening, taken as a systematic uncertainty, is required to the related $E_\gamma^*$ values to best reproduce the $\chi_{bJ}(1P) \rightarrow \gamma \Upsilon(1S)$ transitions in data. The $\eta_b(1S)$ results obtained by these two independent methods agree closely (within 0.2 MeV), providing confidence in our assessment of the energy calibration.

Measurement of the ISR peak position is used to estimate the uncertainty of the $\eta_b(1S)$ transition energy. For this purpose, we adopt the symmetrized combination of the statistical uncertainty from the fit and contributions from the world average $\Upsilon$ mass uncertainties [20]. This value is greater than the maximal difference obtained by repeating the analysis under both energy calibration methods and while varying the derived calibration parameters within $\pm 1\sigma$, providing the most conservative bound on this uncertainty.

Alternative parameterizations of the $\eta_b(1S)$ transition lineshape are considered by refitting the data using a Breit-Wigner functional form, including the case with additional $E_{\gamma}^3$ corrections suggested for some quarkonium transitions [10]. The latter leads to a $+2.6$ MeV shift in interpretation of the $\eta_b(1S)$ transition energy. The fit is repeated with higher-order $E_{\gamma}^3$ contributions considered, but their relative strength cannot be resolved in this anlaysis, and lead to a small additional systematic uncertainty. We account for uncertainty in the natural $\eta_b(1S)$ width by refitting the data according to MC samples generated with the nominal value varied by $\pm 1\sigma$ [20]. By comparing $\chi^2$ goodness-of-fit results under a variety of different assumed values in this range, we verify that our data are consistent with this nominal value. We vary the background shape by changing the degree of the polynomial in the exponential to five and seven, and refitting the data. We also repeat the fit with the background shape fixed to the parameters determined by using only the ISR and $\eta_b(1S)$ sidebands: $300 < E_\gamma^* < 500$ MeV and $650 < E_\gamma^* < 800$ MeV. The fit is repeated with a $\chi_{b0}(1P)$ yield fixed to the expected value, and the difference in results from its effect on the background shape is taken as a systematic uncertainty. The systematic effects of fitting with a finer binning of 1 MeV and with an extended range to 900 MeV are also considered.

We assign an overall photon reconstruction efficiency uncertainty of 2.8% based on previous Belle studies of photons in a similar energy range [23]. The uncertainty on the number of $\Upsilon(2S)$ events was determined from a study of hadronic decays to be 2.3% [14]. Derived quantities related to masses and expected CM energies use the world average values and their associated uncertainties [20].

The corrected peak $E_\gamma^*$ values of the $\chi_{b1,2}(1P)$ transitions are in good agreement with the world average values (in parentheses) [20]: $423.1 \pm 0.1$ (423.0 $\pm 0.5$) MeV and $442.1 \pm 0.2$ (441.6 $\pm 0.5$) MeV, where the experimental uncertainties are statistical only. For the $\chi_{b1,2}(1P) \rightarrow \gamma \Upsilon(1S)$ branching fractions, we measure $(2.45 \pm 0.02 \pm 0.09)\%$ and $(1.17 \pm 0.01^{+0.05}_{-0.04})\%$. These values are consistent with the average of the most recent directly measured values from CLEO [24] and BaBar [7, 25]: $(2.40 \pm 0.08)\%$ and $(1.33 \pm 0.05)\%$. A significant peak from ISR $\Upsilon(1S)$ events is observed with a corrected $E_\gamma^*$ value of $547.2^{+0.6+1.2}_{-2.3-1.2}$ MeV, in agreement with the expectation of $547.2 \pm 0.4$ MeV [20]. The measured ISR signal yield is $(29.2^{+29+5.4}_{-3.2-0.9}) \times 10^5$ events. This corresponds to the expectation of $(27 \pm 3) \times 10^5$ events based on the second-order calculation from [20] and our photon
efficiency and ECL angular coverage.

We measure $(28.8^{+2.6+4.2}_{-2.2-2.0}) \times 10^3 \, \Upsilon(2S) \rightarrow \gamma \eta_b(1S)$ events, equivalent to a branching fraction of $(6.1^{+0.6+0.9}_{-0.7-0.5}) \times 10^{-4}$. This is in agreement with the most recent lattice QCD calculation of $(5.4 \pm 1.8) \times 10^{-4}$ [12]. This value is compatible with the previous BaBar measurement of $(3.9 \pm 1.5) \times 10^{-4}$ [3]. We measure a transition energy of $E^\gamma_b = 660.1^{+2.4}_{-2.0} \pm 3.4$ MeV, to be compared with 609.3$^{+5.0}_{-4.9}$ MeV in the similar decay mode in BaBar. If we consider a transition line shape proportional to $E^\gamma_b$, unlike previous analyses of the M1 radiative transition [2,4], the interpretation of the data produces a mass measurement of $m_{\eta_b(1S)} = 9394.9^{+2.7+4.5}_{-3.1-2.7}$ MeV/$c^2$. This is in agreement with the current world average value of 9399.0 ± 2.3 MeV/$c^2$ [20]. This is between previous Belle $h_b$-based measurements [2,4] and those from radiative $\Upsilon$ decays [2,4], consistent with the former at the level of 1.2$\sigma$, and 0.7$\sigma$ for the latter. The statistical significance of this measurement is estimated to be 8.4$\sigma$, determined from the difference in the likelihood between the results with and without an $\eta_b(1S)$ component included. Even after considering yield-related systematic uncertainties, the signal significance exceeds 7$\sigma$. This result represents the first significant observation of the $\Upsilon(2S) \rightarrow \gamma \eta_b(1S)$ decay mode. We look forward to additional dedicated bottomonium data samples from the Belle II experiment to mitigate energy scale uncertainties and provide greater ability to interpret radiative M1 transition line shape effects.

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FIG. 2: (a) The inclusive photon spectrum. The solid black curve indicates the total fit to the data. The dashed gray curve indicates the exponential background component. The peak due to the $\chi_{bJ}(1P) \rightarrow \gamma \Upsilon(1S)$ transitions is clearly visible. (b) The inclusive photon spectrum after subtraction of the background component of the fit. The black curve indicates the total fit to the data, and the gray curves indicate the individual signal components. The $\chi_{b1,2}(1P) \rightarrow \gamma \Upsilon(1S)$ transitions at $\sim 424$ and $\sim 442$ MeV are dominant. (c) Same as (b), with the scale chosen to highlight the ISR and $\eta_b(1S)$ signal peaks, appearing at $\sim 547$ and $\sim 600$ MeV, respectively.
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