Observation of $\Upsilon(2S) \to \eta\Upsilon(1S)$ and Search for Related Transitions

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We report the first observation of $\Upsilon(2S) \to \eta\Upsilon(1S)$, with a branching fraction $\mathcal{B} = (2.1^{+0.7}_{-0.6}(\text{stat}) \pm 0.3(\text{syst})) \times 10^{-4}$ and a statistical significance 5.3σ. Data were acquired with the CLEO III detector at the CESR e^+e^- symmetric collider. This is the first process observed involving a b-quark spin flip. For related transitions, 90% confidence limits in units of 10^{-4} are $\mathcal{B}(\Upsilon(2S) \to \pi^0\Upsilon(1S)) < 1.8$, $\mathcal{B}(\Upsilon(3S) \to \eta\Upsilon(1S)) < 1.8$, $\mathcal{B}(\Upsilon(3S) \to \pi^0\Upsilon(1S)) < 0.7$, and $\mathcal{B}(\Upsilon(3S) \to \pi^0\Upsilon(2S)) < 5.1$.

In order to produce a pseudoscalar meson η or π^0 in $\Upsilon(nS) \to (\eta/\pi^0)\Upsilon(mS)$ transitions, the $b\bar{b}$ pair must emit either two M1 (chromomagnetic dipole) gluons or an E1 (chromoelectric dipole) and an M2 (chromomagnetic quadrupole) gluon [1–3], involving the flip of a heavy quark's spin. In this Letter we present the first observation

of $\Upsilon(2S) \to \eta\Upsilon(1S)$, and a search for similar π^0 or η transitions from the $\Upsilon(2S)$ and $\Upsilon(3S)$. A spin flip of a b-quark can shed light on its chromomagnetic moment, expected to scale as $1/m_b$. Electromagnetic transitions involving a b-quark spin flip should also have amplitudes scaling as $1/m_b$. They have not previously been observed.

The decay $\psi(2S) \to \eta J/\psi$ was observed in the early days of charmonium spectroscopy [4]. Its branching fraction is $\mathcal{B}(\psi(2S) \to \eta J/\psi) = (3.13 \pm 0.08)\%$ [5], while only an upper limit $\mathcal{B} < 2 \times 10^{-3}$ is known for the corresponding $\Upsilon(2S) \to \eta \Upsilon(1S)$ process [6]. The upper limit for $\Upsilon(3S) \to \eta \Upsilon(1S)$ is $\mathcal{B} < 2.2 \times 10^{-3}$ [7]. The quark spin-flip involved in $\Upsilon(nS) \to (\eta/\pi^0)\Upsilon(mS)$ transitions (we consider $3 \geq n > m \geq 1$) and the P-wave nature of the final state imply that rates should scale from charmonium as $\Gamma \propto (p^*)^3/m_Q^4$ [1,2], where p^* is the three-momentum of the η or π^0 in the $\Upsilon(nS)$ center-of-mass system and $Q = c, b$ is the heavy quark. Hence one expects

$$\frac{\Gamma(\Upsilon(2S, 3S) \to \eta \Upsilon(1S))}{\Gamma(\psi(2S) \to \eta J/\psi)} = (0.0025, 0.0013), \quad (1)$$

leading to $\mathcal{B}(\Upsilon(2S, 3S) \to \eta \Upsilon(1S)) \simeq (8.0, 6.5) \times 10^{-4}$. Direct calculation in a potential model [2] yields $(6.9, 5.4) \times 10^{-4}$ for these branching fractions. All predictions involve a perturbative calculation of gluon-pair emission followed by a nonperturbative estimate of materialization of the gluon pair into an η. Uncertainties associated with this estimate are difficult to quantify.

Similar predictions can be made for π^0 transitions under the assumption that they are due to an isospin-zero admixture in the π^0. The isospin-forbidden decay $\psi(2S) \to \pi^0 J/\psi$ has been seen [5] with a branching fraction of $(1.26 \pm 0.13) \times 10^{-3}$ which is $(4.03 \pm 0.43)\%$ of that for $\psi(2S) \to \eta J/\psi$. Using values of p^* appropriate to each process and assuming the same isospin-zero admixture in π^0 governs the transitions $\Upsilon(nS) \to \pi^0 \Upsilon(mS)$, one obtains the scaling predictions

$$\frac{\mathcal{B}(\Upsilon(2S, 3S) \to \pi^0 \Upsilon(1S))}{\mathcal{B}(\Upsilon(2S, 3S) \to \eta \Upsilon(1S))} = (16 \pm 2, 0.42 \pm 0.04)\%. \quad (2)$$

There is no prediction at present for the kinematically-allowed decay $\Upsilon(3S) \to \pi^0 \Upsilon(2S)$.

The data in the present analysis were collected in e^+e^- collisions at the Cornell Electron Storage Ring (CESR), at center-of-mass energies at and about 30 MeV below the $\Upsilon(2S, 3S)$ resonances. Integrated luminosities at these resonances were $(1.3, 1.4)$ fb^{-1}, amounting to $(9.32 \pm 0.14, 5.88 \pm 0.10)$ million decays of $\Upsilon(2S, 3S)$, as in the analysis of Ref. [8]. Events were recorded in the CLEO III detector, equipped with an electromagnetic calorimeter consisting of 7784 CsI(Tl) crystals and covering 93% of solid angle, initially installed in the CLEO II [9] detector configuration. The energy resolution of the crystal calorimeter is 5% (2.2%) for 0.1 (1) GeV photons. The CLEO III tracking system [10] consists of a silicon strip detector and a large drift chamber, achieving a charged particle momentum resolution of 0.35% (1%) at 1(5) GeV/c in a 1.5 T axial magnetic field.

We look for candidate events of the form $e^+e^- \to \Upsilon(nS) \to (\eta/\pi^0)\Upsilon(mS)$ with $\Upsilon(mS) \to \ell^+\ell^-$, where $\ell = e, \mu$. Candidates for $\ell^\pm$ are identified by picking the two

highest-momentum tracks in an event and demanding them to be of opposite sign. We explore separate e^+e^- and $\mu^+\mu^-$ samples in $\Upsilon(mS)$ decays by defining electron candidates to have a high ratio of energy E observed in the calorimeter to momentum p measured in the tracking system, i.e., $E/p > 0.75$, and muon candidates to have $E/p < 0.20$. We choose lepton candidates from tracks satisfying $|\cos\theta| < 0.83$, where θ is the angle with respect to the positron beam direction, to avoid a region of less uniform acceptance at larger $|\cos\theta|$. With these criteria we achieve a very clean separation of electron and muon candidates. In order to suppress contributions from Bhabha scattering, we demand for events with $(\eta, \pi^0) \to \gamma\gamma$ that e^+ candidates satisfy $\cos\theta_{e^+} < 0.5$. This greatly suppresses Bhabha scattering background while keeping 93% of the signal. Once leptons are identified, the entire event is kinematically fitted. We reconstruct the η candidates from their decays to $\gamma\gamma$, $\pi^+\pi^-\pi^0$, and $3\pi^0$. We did not employ the decay mode $\eta \to \pi^+\pi^-\gamma$ because of its small branching fraction ($\mathcal{B} = [4.69 \pm 0.10]\%$ [5]) and large backgrounds, primarily from $\Upsilon(nS) \to \pi^+\pi^-\Upsilon(mS)$.

Photon candidates must be detected in the central region of the calorimeter ($|\cos\theta| < 0.81$), must not be aligned with the initial momentum of a track, and should have a lateral shower profile consistent with that of a photon. Neutral pion candidates (except in the decay $\eta \to 3\pi^0$, where we only look for six photon candidates) are reconstructed from a pair of γ candidates required to have $\gamma\gamma$ invariant mass between 120 and 150 MeV.

Monte Carlo (MC) samples were generated for generic $\Upsilon(2S, 3S)$ decays using the routine QQ [11], and for $\Upsilon(nS) \to (\eta/\pi^0)\Upsilon(mS)$ and dipion transitions between Υ states using the package EVTGEN [12]. The final $\Upsilon(mS)$ state was taken to decay to e^+e^- or $\mu^+\mu^-$. A GEANT-based [13] detector simulation was used. These samples, as well as off-resonance $\Upsilon(2S)$ data, are useful both for validating background suppression methods and as possible background sources. In calculating branching fractions from data, we take $\mathcal{B}(\Upsilon(1S) \to e^+e^-) = \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) = 0.0248 \pm 0.0005$ [5] and $\mathcal{B}(\Upsilon(2S) \to e^+e^-) = \mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-) = 0.0203 \pm 0.0009$ [14] based on the more accurately measured $\mu^+\mu^-$ branching fractions and assuming lepton universality.

The $\Upsilon(nS) \to (\eta/\pi^0)\Upsilon(mS)$ MC samples were generated with η and π^0 decaying through all known decay modes. These decays proceed via a P wave, and hence are described by a matrix element $(\boldsymbol{\epsilon}_i \times \boldsymbol{\epsilon}_f^*) \cdot \mathbf{p}_{(\eta/\pi^0)}$ in the nonrelativistic limit (here * denotes complex conjugation), with $\boldsymbol{\epsilon}_{f,i}$ the polarization vectors of the final and initial Υ. The θ distribution for the final-state leptons in $\Upsilon(mS) \to \ell^+\ell^-$ then is $1 - (1/3)\cos^2\theta$, and was used in all signal MC samples for $\Upsilon(nS) \to (\eta/\pi^0)\Upsilon(mS)$. For $\Upsilon(nS) \to \pi\pi\Upsilon(mS)$ it was assumed that the $\Upsilon(mS)$ retains the polarization of the initial $\Upsilon(nS)$, so the lepton angular distribution for $\Upsilon(mS) \to \ell^+\ell^-$ is $1 + \cos^2\theta$.

As a cross-check, data were analyzed for the known transitions $\Upsilon(nS) \to \pi\pi\Upsilon(1S)$, and branching fractions were found in sufficiently good agreement with world averages [5]. We looked for systematic differences between detection of $\Upsilon(1S) \to e^+e^-$ and $\Upsilon(1S) \to \mu^+\mu^-$. Efficiencies for the two modes can differ as a result of the requirement on $\cos\theta_{e^+}$ mentioned above. The branching fractions calculated from $\Upsilon(1S) \to e^+e^-$ and $\Upsilon(1S) \to \mu^+\mu^-$ were found to be equal within statistical uncertainty, and consistent with those obtained from recoil mass spectra without requiring final leptons.

Kinematic fitting was used to study the decays $\Upsilon(nS) \to (\eta/\pi^0)\Upsilon(mS)$. The two tracks selected as leptons, including photon bremsstrahlung candidates within 100 mrad of the initial lepton direction, were constrained to have the known masses of $\Upsilon(mS)$ with a resultant reduced χ^2 ($\chi^2/\text{d.o.f.}$), $\chi^2_R \equiv \chi^2_{\ell^+\ell^-,m}$ required to be less than 10. (For off-resonance data the dilepton masses were reduced by an amount equal to the initial $M[\Upsilon(nS)]$ minus the off-resonance center-of-mass energy.) The sum of the four-momenta of these two fitted tracks, including photon bremsstrahlung candidates as well as the decay products of the η/π^0, were further constrained to the initial $\Upsilon(nS)$ four-momentum, with a reduced $\chi^2_R \equiv \chi^2_{\text{EVT},m}$ required to be less than 10, or 3 for $(\eta/\pi^0) \to \gamma\gamma$ to help suppress doubly radiative Bhabha events. Some of these Bhabha events can give small fitted $\chi^2_{\text{EVT},m}$, but have photon momenta shifted by relatively large amounts compared to signal events. To further suppress such events, two-photon "pull" masses, defined as $(\text{fitted} - \text{measured})/\sigma$, where σ is the two-photon mass resolution, were chosen on the basis of signal MC and off-resonance data (containing the doubly radiative Bhabha contribution) to lie between -2 and 3. Over 99% of the signal MC events for all transitions satisfy this criterion. All particles were also required to have common vertices in the above two constrained fits, with reduced $\chi^2_{\ell^+\ell^-,v} < 30$ required for the dilepton vertex, and reduced $\chi^2_{\text{EVT},v} < 30$ required for the full event vertex.

For $\Upsilon(2S) \to \eta\Upsilon(1S)$, the photons from $\eta \to \gamma\gamma$ have energies $E_\gamma = (281 - 64\cos\theta^*)$ MeV, where θ^* is the angle between the photon in the η center-of-mass and the η boost, so $217 \le E_\gamma \le 345$ MeV. Choosing $200 \le E_\gamma \le 360$ MeV then eliminates background from $\Upsilon(2S) \to \gamma\chi_{bJ} \to \gamma\gamma\Upsilon(1S)$ with little effect on the $\eta \to \gamma\gamma$ signal. Using the $\Upsilon(2S) \to \eta\Upsilon(1S)$ MC sample, the η candidate mass distribution was fitted to the sum of a double Gaussian and a linear background. Constant background gave a worse fit because of the kinematic limit at $M[\Upsilon(2S)] - M[\Upsilon(1S)] = 563$ MeV. The fitting range was chosen to be 533 to 563 MeV: roughly symmetric about the η peak ($M(\eta) = 547.51 \pm 0.18$ MeV [5]) with upper boundary at $M[\Upsilon(2S)] - M[\Upsilon(1S)]$ above which few events are expected or observed. The difference between fits with linear and flat backgrounds was found to be

insignificant compared with the systematic error associated with fitting range. The double-Gaussian parameters included a narrow width $\sigma_1 = 0.9$ MeV, a wide width $\sigma_2 = 2.1$ MeV, area of second peak 20% of total, and mean of second peak 0.14 MeV below the first.

The mass distribution for the sum of the η modes $\gamma\gamma$, $\pi^+\pi^-\pi^0$, and $3\pi^0$ in data (upper plot, Fig. 1) shows a clear peak near $M(\eta)$. We fit data points to the sum of the double Gaussian with floating area but fixed shape obtained from signal MC and a linear background. The $\pi^+\pi^-\pi^0$ and $3\pi^0$ decay modes each contribute two events near the peak and none elsewhere. The combined fitted peak corresponds to a branching fraction $\mathcal{B}(\Upsilon(2S) \to \eta\Upsilon(1S)) = (2.1^{+0.7}_{-0.6}) \times 10^{-4}$. Defining the significance N_σ as $\sqrt{-2\Delta\log\mathcal{L}}$, where $\mathcal{L}$ is the likelihood, the difference between fits with and without signal yields a statistical significance of 5.3 standard deviations.

In searching for $\Upsilon(3S) \to \eta(\to \gamma\gamma)\Upsilon(1S)$ transitions, we suppress backgrounds from cascades involving intermediate $\chi_b(1P,2P)$ states by requiring one photon to have $500 \le E_1 \le 725$ MeV and the other to have $140 \le E_2 \le 380$ MeV. Signal photons satisfy $E_\gamma = (435 - 350\cos\theta^*)$ MeV, so about 2/3 of them are retained by these choices. Small differences with respect to $\Upsilon(2S) \to \eta\Upsilon(1S)$ include (a) an η fit range 523–573 MeV and
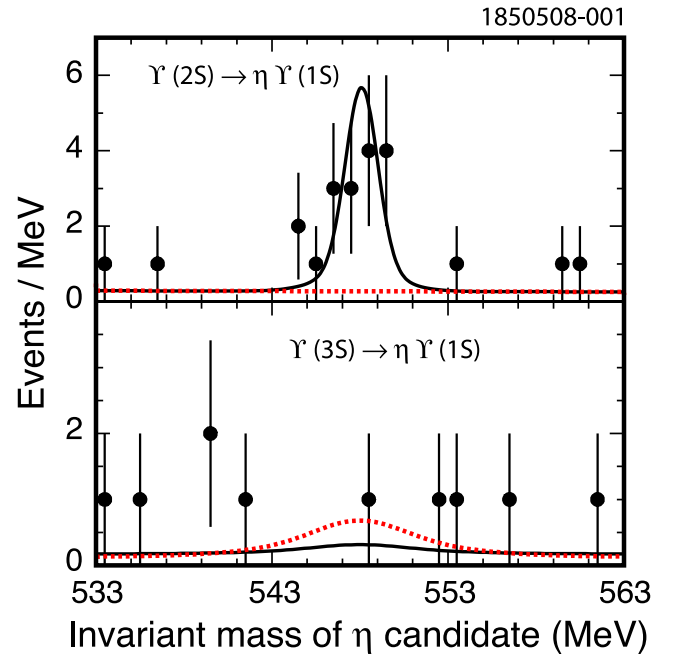

FIG. 1 (color online). Events per MeV vs invariant mass of candidates for $\Upsilon(2S) \to \eta\Upsilon(1S)$ (top) and $\Upsilon(3S) \to \eta\Upsilon(1S)$ (bottom). The sum of the modes $\eta \to \gamma\gamma$, $\eta \to \pi^+\pi^-\pi^0$, and $\eta \to 3\pi^0$ is shown. In the top figure the solid curve corresponds to the total fit, involving a signal of $13.9^{+4.5}_{-3.8}$ events above background (dashed line). In the bottom figure the solid curve corresponds to a best fit with signal MC shape, while the dotted curve corresponds to a 90% confidence level (C.L.) upper limit.
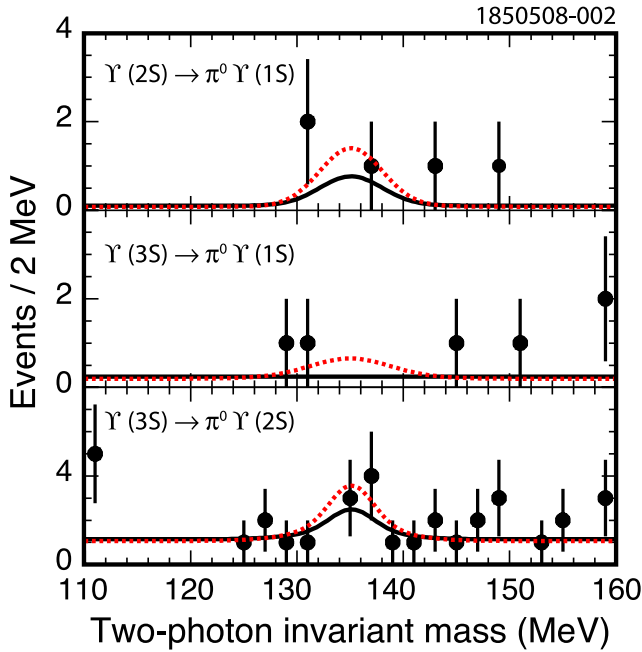
FIG. 2 (color online). Best fits to two-photon invariant mass distributions with signal MC shapes (solid curves are the results of total fits) and 90% C.L. upper limits (dotted curves) for $\Upsilon(2S) \to \pi^0 \Upsilon(1S)$ (top), $\Upsilon(3S) \to \pi^0 \Upsilon(1S)$ (middle), and $\Upsilon(3S) \to \pi^0 \Upsilon(2S)$ (bottom).

(b) a flat background, found here to be sufficient to describe MC calculations and data. The best fit to signal MC shape and the 90% confidence level (C.L.) upper limit are shown in the lower plot of Fig. 1. (No events were observed in the regions included in the fit but not shown in Fig. 1.)

For $\Upsilon(2S) \to \pi^0 \Upsilon(1S)$, the photons from $\pi^0 \to \gamma\gamma$ have energies $E_\gamma = (274 - 266\cos\theta^*)$ MeV, so $8 \leq E_\gamma \leq 540$ MeV. The choice $200 \leq E_\gamma \leq 360$ MeV for both photons, made to eliminate background from $\Upsilon(2S) \to \gamma\chi_{bJ} \to \gamma\gamma\Upsilon(1S)$, then retains about 30% of the $\pi^0 \to \gamma\gamma$ signal. A fit of the $M(\gamma\gamma)$ distribution in the data (using the signal MC double-Gaussian shape and uniform background) is shown in the top plot of Fig. 2. Details of this and other limits, as well as of the $\Upsilon(2S) \to \eta\Upsilon(1S)$ signal, are shown in Table I. For all π^0 transitions, MC simulations indicate a constant function is adequate to describe the background. Efficiency differences between decay modes are typically due to details of photon acceptance.

For $\Upsilon(3S) \to \pi^0 \Upsilon(1S)$, where signal photons from $\pi^0 \to \gamma\gamma$ satisfy $E_\gamma = (429 - 385\cos\theta^*)$ MeV, the same ranges of (E_1, E_2) are chosen as for $\Upsilon(3S) \to \eta\Upsilon(1S)$. For $\Upsilon(3S) \to \pi^0 \Upsilon(2S)$, we suppress backgrounds from cascades involving intermediate $\chi_b(2P)$ states by *excluding* photons with $60 \leq E_2 \leq 130$ MeV and $190 \leq E_1 \leq 260$ MeV. Here, the signal photons satisfy $E_\gamma = (164 - 149\cos\theta^*)$MeV, so about 40% are retained. No signal is seen in any of these π^0 transitions (Fig. 2).

TABLE I. Efficiencies, events in data, and product branching fractions $\mathcal{B} \times \mathcal{B}_\ell$, where $\mathcal{B} \equiv \Upsilon(nS) \to (\eta/\pi^0)\Upsilon(mS)$, and $\mathcal{B}_\ell \equiv \mathcal{B}(\Upsilon(1S) \to \ell^+\ell^-) = 4.96\%$ or $\mathcal{B}(\Upsilon(2S) \to \ell^+\ell^-) = 4.06\%$ ($\ell^+\ell^- \equiv e^+e^- + \mu^+\mu^-$). Efficiencies are based on MC samples generated with standard η and π^0 branching fractions and with $\mathcal{B}(\Upsilon(mS) \to e^+e^-) = \mathcal{B}(\Upsilon(mS) \to \mu^+\mu^-) = 50\%$. Decays involving η are based on combined $\gamma\gamma$, $\pi^+\pi^-\pi^0$, and $3\pi^0$ modes.

Decay	MC % detected	Events in data	$\mathcal{B} \times \mathcal{B}_\ell$ (10^{-5})
$\Upsilon(2S) \to \eta\Upsilon(1S)$	14.0	$13.9^{+4.5}_{-3.8}$	$1.06^{+0.35}_{-0.30}$
$\Upsilon(2S) \to \pi^0\Upsilon(1S)$	6.8	<5.0	<0.79
$\Upsilon(3S) \to \eta\Upsilon(1S)$	10.4	<4.8	<0.79
$\Upsilon(3S) \to \pi^0\Upsilon(1S)$	13.2	<2.3	<0.30
$\Upsilon(3S) \to \pi^0\Upsilon(2S)$	7.8	<8.3	<1.80

Systematic errors are shown in Table II. Other contributions investigated and found to be negligible were (i) cross feeds among η modes, (ii) signal shape, (iii) background shape, (iv) triggering details, and (v) differences in e/μ reconstruction. The dominant sources of systematic uncertainties are described below. (i) *Bhabha event suppression:* Uncertainties for all processes will arise from our Bhabha event suppression requirement. Although it is applied only to $\gamma\gamma$ modes, it will affect not only π^0 transitions but also those with η, whose $\gamma\gamma$ decays dominate our analyses statistically. To probe this uncertainty, we consider the separate sample of those events with $\cos\theta_{e^+} \geq 0.5$ which were removed by the Bhabha suppression requirement. The resultant $\mathcal{B}(\Upsilon(2S) \to \eta(\to \gamma\gamma)\Upsilon(1S))$ is consistent with our nominal result. Averaging the two gives a deviation of 9% which we take as a possible systematic uncertainty due to this requirement. We then propagate this estimated uncertainty to the rest of the decay modes with suitable weight for the fraction of the decay due to $\gamma\gamma$. (ii)

TABLE II. Systematic errors, in percent, on branching fractions for $\Upsilon(nS) \to$ (a) $\eta\Upsilon(1S)$; (b) $\pi^0\Upsilon(1S)$; (c) $\pi^0\Upsilon(2S)$. All errors are assigned symmetrically. Decays involving η are based on combined $\gamma\gamma$, $\pi^+\pi^-\pi^0$, and $3\pi^0$ modes. The last line (d) includes systematic errors.

Decay Final state	$\Upsilon(2S) \to$ (a)	(b)	$\Upsilon(3S) \to$ (a)	(b)	(c)
Tracks	2	2	2	2	2
Number of $\Upsilon(nS)$	1.5	1.5	1.7	1.7	1.7
η/π^0 recon.	6	5	8	5	5
$\mathcal{B}_{\ell\ell}[\Upsilon(mS)]$	2	2	2	2	4
$\gamma\gamma$ pull mass	4	0	4	0	0
Bhabha event sup.	7	9	6	9	9
Fit range	1	1	8	6	4
χ^2 cuts	7	7	7	7	7
MC stat.	1.1	1.6	1.3	1.1	1.5
Quad. sum	13	13	16	14	14
$\mathcal{B}(10^{-4})$ (d)	$2.1^{+0.7}_{-0.6} \pm 0.3$	<1.8	<1.8	<0.7	<5.1

Kinematic fitting: To probe any systematic bias introduced by our kinematic fitting procedure, we look at events with very similar topology to our signals: $\Upsilon(2S) \to \gamma\chi_b(1P_J)$, $\chi_b(1P_J) \to \gamma\Upsilon(1S)$, $\Upsilon(1S) \to \ell^+\ell^-$ where $J = 1$ or 2. We use the same analysis requirements as for $\eta \to \gamma\gamma$ but relax the requirements on E_γ in order to accept two-photon cascades through χ_b states. Varying the requirement on $\chi^2_{\mathrm{EVT},m}$ from *none* to $\chi^2_{\mathrm{EVT},m} < 3$, we observe a maximum deviation of 7% in this product of branching fractions which we assign as a possible source of systematic uncertainty. (iii) η/π^0 *reconstruction:* We assign 5% per π^0 or η decaying into two photons based on CLEO studies [15]. (iv) *Fit ranges:* Uncertainties due to fit ranges differ for different final states. To estimate them, we prepare many MC samples in which points are randomly scattered around best-fit values from data (signal plus background), bin-by-bin according to a Poisson distribution. We then fit them with the fit range boundaries symmetrically changed by ± 5 MeV for $\Upsilon(2S) \to \eta\Upsilon(1S)$. In $\Upsilon(3S) \to \eta\Upsilon(1S)$ as well as in $\Upsilon(nS) \to \pi^0\Upsilon(mS)$, where wider kinematic ranges are available, the fit range boundaries are symmetrically changed by ± 10 MeV. We assign variations of averages of these fitted yields as possible systematic shifts. Combining the effects from the systematic errors linearly with the results already listed, we find the results shown in the last line of Table II.

To summarize, we have observed for the first time a process involving *b*-quark spin-flip, with $\mathcal{B}(\Upsilon(2S) \to \eta\Upsilon(1S)) = (2.1^{+0.7}_{-0.6} \pm 0.3) \times 10^{-4}$. The statistical significance of the signal is 5.3σ. The result is about $1/4$ of the value one would predict on the basis of Eq. (1), indicating either a shortcoming in the description of two-gluon hadronization into an η or a fundamental suppression of the chromomagnetic moment of the *b* quark. In addition, we have set 90% C.L. upper limits on other pseudoscalar transitions summarized on the bottom line of Table II. The limit on $\mathcal{B}(\Upsilon(3S) \to \eta\Upsilon(1S))$ is about a factor of 2 below that predicted from Eq. (1), while the limits on the

transitions $\Upsilon(2S, 3S) \to \pi^0\Upsilon(1S)$ are consistent with the estimates of Eq. (2).

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