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Observation of the bottomonium ground state in the decay $\Upsilon(3S) \to \gamma\,\eta_b$

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We report the results of a search for the bottomonium ground state $\eta_b(1S)$ in the photon energy spectrum with a sample of (109 ± 1) million of $\Upsilon(3S)$ recorded at the $\Upsilon(3S)$ energy with the *BABAR* detector at the PEP-II B factory at SLAC. We observe a peak in the photon energy spectrum at $E_\gamma = 921.2^{+2.1}_{-2.8}(\mathrm{stat}) \pm 2.4(\mathrm{syst})$ MeV with a significance of 10 standard deviations. We interpret the observed peak as being due to monochromatic photons from the radiative transition $\Upsilon(3S) \to \gamma\,\eta_b(1S)$. This photon energy corresponds to an $\eta_b(1S)$ mass of $9388.9^{+3.1}_{-2.3}(\mathrm{stat}) \pm 2.7(\mathrm{syst})$ MeV$/c^2$. The hyperfine $\Upsilon(1S)$-$\eta_b(1S)$ mass splitting is $71.4^{+2.3}_{-3.1}(\mathrm{stat}) \pm 2.7(\mathrm{syst})$ MeV$/c^2$. The branching fraction for this radiative $\Upsilon(3S)$ decay is estimated to be $(4.8 \pm 0.5(\mathrm{stat}) \pm 1.2(\mathrm{syst})) \times 10^{-4}$.

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Thirty years after the discovery of the narrow $\Upsilon(nS)$ resonances [1], no evidence has been reported for the spin-singlet pseudoscalar partners $\eta_b(nS)$ of these states. Measurement of the hyperfine mass splittings between the triplet and singlet states in quarkonium systems is of key importance in understanding the role of spin-spin interactions in quarkonium models and in testing QCD calculations [2]. Theoretical estimates of the mass splitting between the $1S$ singlet and triplet states vary from 36 MeV$/c^2$ to 100 MeV$/c^2$ [3].

In this letter, we report the observation of the radiative transition $\Upsilon(3S) \to \gamma\,\eta_b(1S)$, where the $\eta_b(1S)$, hereafter referred to as the η_b, is the pseudoscalar partner of the triplet state $\Upsilon(1S)$, and corresponds to the ground state of the bottomonium system. Theoretical predictions of the decay branching fraction range from 1 to 20 $\times 10^{-4}$[3], where the unknown η_b mass is a major source of the uncertainties. The current limit from the CLEO III experiment, $\mathcal{B}[\Upsilon(3S) \to \gamma\,\eta_b] < 4.3 \times 10^{-4}$ at 90% confidence level, is based on 1.39 fb^{-1} of $\Upsilon(3S)$ data [4].

The data sample used in this study was collected with the *BABAR* detector [5] at the PEP-II asymmetric-energy e^+e^- storage rings. It consists of 28.0 fb^{-1} of integrated luminosity collected at a e^+e^- center-of-mass (CM) energy of 10.355 GeV, corresponding to the mass of the $\Upsilon(3S)$ resonance. Additional samples of 2.4 fb^{-1} and 43.9 fb^{-1} were collected 30 MeV below the $\Upsilon(3S)$ [below-$\Upsilon(3S)$] and 40 MeV below the $\Upsilon(4S)$ [below-$\Upsilon(4S)$] resonances, respectively and are used for background and calibration studies. The trajectories of charged particles are reconstructed using a combination of five layers of double-sided silicon strip detectors and a 40-layer drift chamber, all operated inside the 1.5-T magnetic field of a superconducting solenoid. Photons are detected using a CsI(Tl) electromagnetic calorimeter (EMC), which is also inside the coil. The energy resolution for photons varies from 2.9% (at 600 MeV) to 2.5% (at 1400 MeV).

The signal for $\Upsilon(3S) \to \gamma\,\eta_b$ is extracted from a fit to the inclusive photon energy spectrum in the CM frame. Any reference to photon energy hereafter will be in the CM frame, unless otherwise noted.

The monochromatic photon from the decay appears as a peak on top of a smooth non-peaking background from continuum ($e^+e^- \to q\bar{q}$ with $q = u, d, s, c$) events and bottomonium decays. Two other processes produce peaks in the photon energy spectrum close to the signal region. Double radiative decays $\Upsilon(3S) \to \gamma\chi_{bJ}(2P); \chi_{bJ}(2P) \to \gamma\Upsilon(1S)$, $J = 0, 1, 2$, produce a broad peak centered at 760 MeV due to photons from decays of the $\chi_{bJ}(2P)$ states. The peaks from the three $\chi_{bJ}(2P)$ transitions appear merged due to photon energy resolution and the Doppler broadening that arises from the motion of the $\chi_{bJ}(2P)$ in the CM frame. This $\chi_{bJ}(2P)$ photon peak is well separated from the signal region of interest (around $E_\gamma = 900$ MeV). We use the peak as a tool to verify the optimization of the selection criteria and to determine signal reconstruction efficiencies and the absolute photon energy scale. The other process leading to a peak near 860 MeV in the photon energy spectrum is the radiative production of the $\Upsilon(1S)$ via initial state radiation (ISR) $e^+e^- \to \gamma_{ISR}\Upsilon(1S)$. Knowledge of the magnitude and photon energy line shape of this background is crucial in extracting the η_b signal.

We employ a simple set of selection criteria to suppress the backgrounds while retaining a high signal efficiency. Decays of the η_b via two gluons, expected to be a large component of its decay modes, have high track multiplicity. Hadronic events are selected by requiring four or more charged tracks in the event and that the ratio of the second to zeroth Fox-Wolfram moments [6] be less than 0.98.

Photon candidates are required to be isolated from all charged tracks. To ensure that their shapes are consistent with an electromagnetic shower, the lateral moments [7] are required to be less than 0.55. The signal photon candidate is required to lie in the central angular region of the EMC, $-0.762 < \cos(\theta_{\gamma,LAB}) < 0.890$, where $\theta_{\gamma,LAB}$ is the angle between the photon and the beam axis in the laboratory frame. This requirement ensures high reconstruction efficiency and good energy resolution, and reduces the contributions of ISR photons from $e^+e^- \to \gamma_{ISR}\Upsilon(1S)$ events.

Due to the fact that there is no preferred direction in the decay of the spin-zero η_b, the correlation of the direction of the photon momentum in the CM frame with the thrust axis [8] of the η_b is small. In contrast, there is a strong correlation between the photon direction and thrust axis in continuum events. The thrust axis is computed with all charged tracks and neutral calorimeter clusters in the event, with the exception of the signal photon candidate. We require $|\cos\theta_T| < 0.7$ to reduce continuum background, where θ_T is the angle between the thrust axis and the signal photon candidate in the CM frame.

Photons from π^0 decays are one of the main sources of background. A signal photon candidate is rejected if it combines with another photon in the event to form a π^0 candidate within 15 MeV/c^2 of the nominal π^0 mass. To maintain high signal efficiency, we require the second photon of the π^0 candidate to have an energy in the laboratory frame greater than 50 MeV.

The above mentioned selection criteria were chosen by optimizing the $S/\sqrt{(B)}$ ratio between the expected signal yield (S) and the background (B). The signal sample in the optimization is provided by a detailed Monte Carlo (MC) simulation [9]. Since no reliable event generators exist to simulate the background photon distribution, especially from bottomonium decays, a small fraction (9%) of the $\Upsilon(3S)$ data is used in the optimization to model the background in the region $0.85 < E_\gamma < 0.95$ GeV. To avoid potential bias, these data are not used in the final fit of the photon energy spectrum. This optimization procedure, when applied to the $\chi_{bJ}(2P)$ yield in data in place of the simulated signal, yields the same optimal selection criteria. The final reconstruction efficiency evaluated from the simulated signal MC events is 37%.

The remaining $\Upsilon(3S)$ data used for the analysis has an integrated luminosity of 25.6 fb^{-1}, which corresponds to (109 ± 1) million $\Upsilon(3S)$ events.

To extract the η_b signal, we perform a binned maximum likelihood (ML) fit of the E_γ spectrum with $0.5 < E_\gamma < 1.1$ GeV with four components: non-peaking background, $\chi_{bJ}(2P) \to \gamma\Upsilon(1S)$, $\gamma_{ISR}\Upsilon(1S)$, and the η_b signal.

The non-peaking background is parametrized by the following probability density function (PDF), $f(E_\gamma) = A\left(C + \exp[-\alpha E_\gamma - \beta E_\gamma^2]\right)$.

The form of the $\chi_{bJ}(2P)$ PDF is complicated by the presence of Doppler broadening. Crystal Ball (CB) functions [10] are used as phenomenological PDFs for the three $\chi_{bJ}(2P) \to \gamma\Upsilon(1S)$ shapes. The CB function is a Gaussian modified to have an extended, power-law tail on the low (left) side. The relative rates and peak positions of the $\chi_{bJ}(2P)$ components are fixed to their world-averaged (PDG) values [11]. The parameters describing the low-side tail of the CB function are common to all three of the $\chi_{bJ}(2P)$ peaks. The $\chi_{bJ}(2P)$ PDF parameters are determined by fitting the photon energy spectrum, with the signal region (840 to 960 MeV) excluded, after subtraction of the non-peaking background. All of the $\chi_{bJ}(2P)$ PDF parameters from this fit, with the exception of the overall normalization, are fixed in the ultimate fit to the full photon energy spectrum.

The PDF of the peaking background from ISR $\Upsilon(1S)$ production is parametrized as a CB function form whose parameters are determined from simulated events. To

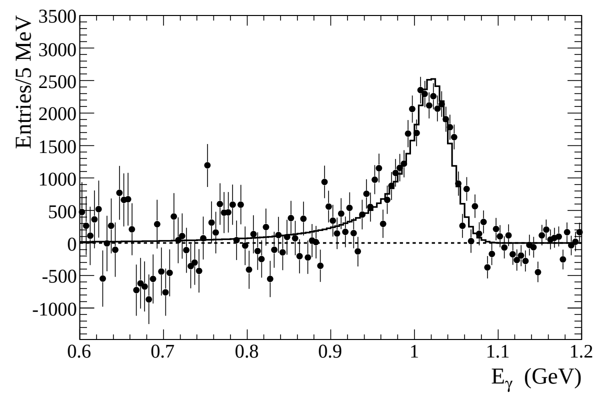

FIG. 1: Inclusive photon energy spectrum in the below-$\Upsilon(4S)$ data, with the non-peaking background subtracted.The peak at 1.03 GeV is from the ISR process $e^+e^- \to \gamma_{ISR}\Upsilon(1S)$. The superimposed histogram corresponds to a fit with a CB function.

estimate the rate of this continuum component in $\Upsilon(3S)$ data, we use the below-$\Upsilon(3S)$ and below-$\Upsilon(4S)$ data. Figure 1 shows the E_γ distribution in the below-$\Upsilon(4S)$ data, after applying the selection criteria and subtracting the non-peaking background. The fit with a CB function yields 35800 ± 1600 events. Extrapolating the cross section to the $\Upsilon(3S)$ energy and correcting for the luminosity ratio and the small difference in detection efficiency, the ISR photon background contribution in the final analysis is estimated to be 25200 ± 1700 events. The error includes systematic uncertainties. This is consistent with and more precise than the rate estimated using the below-$\Upsilon(3S)$ data.

In the final fit of the whole E_γ distribution to extract the η_b signal, all parameters of the $\chi_{bJ}(2P)$ peak and the ISR $\Upsilon(1S)$ PDFs are fixed to the values from the fits described above.

The η_b signal PDF is a non-relativistic Breit-Wigner convolved with a CB function to account for the experimental E_γ resolution. The CB parameters are determined from signal MC with the η_b width set to zero. Since the width of the η_b is not known, we have chosen a nominal value of 10 MeV/c^2 for the width. Theoretical predictions based on the expected ratio of the two-photon and two-gluon widths range from 4 to 20 MeV [12]. The free parameters in the fit are the η_b peak position and signal yield, the $\chi_{bJ}(2P)$ yield, and all of the non-peaking background PDF parameters.

Figure 2(a) shows the photon energy spectrum and the fit result. The non-peaking background is dominant with only the prominent $\chi_{bJ}(2P)$ peak visible. In Figure 2(b) we show the detail of the signal region, after subtracting the non-peaking background. The line shapes of the three peaking components, $\chi_{bJ}(2P)$, ISR $\Upsilon(1S)$, and the η_b signal are clearly visible. The χ^2 per degree of freedom

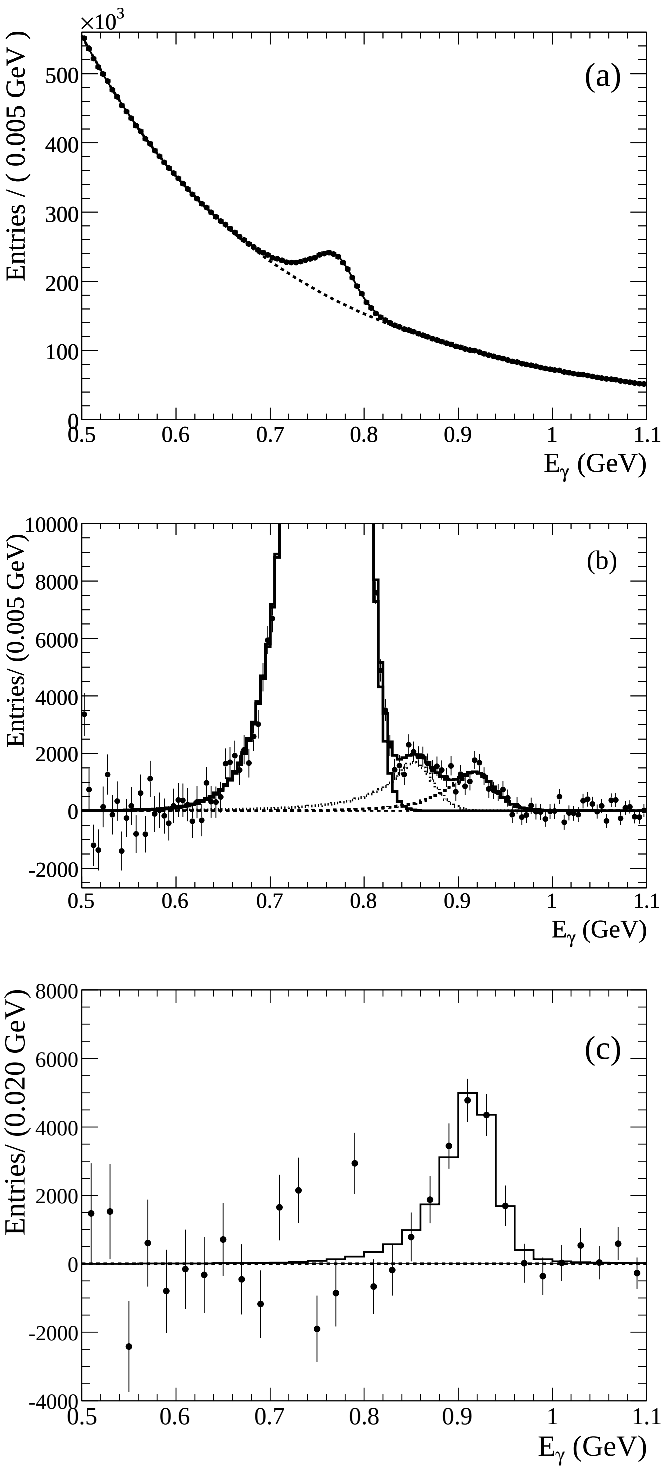

FIG. 2: (a) Inclusive photon spectrum in the region $0.50 < E_\gamma < 1.1\,\mathrm{GeV}$. The component PDFs determined from the fit are overlaid on the data points. A prominent $\chi_{bJ}(2P)$ peak is clearly seen. The dashed line corresponds to the non-peaking background component. (b) Inclusive photon spectrum after subtracting the non-peaking background, with PDFs for $\chi_{bJ}(2P)$ peak (solid), ISR $\Upsilon(1S)$ (dot), η_b signal (dash) and the sum of all three (solid). (c) Inclusive photon spectrum after subtracting all components except the η_b signal. The CB function shape describes the data points well.

from the fit is $147/113 = 1.3$. Finally Figure 2(c) shows the data points with all components except the η_b signal subtracted, overlaid with the η_b signal PDF. The fitted η_b signal yield is $19200 \pm 2000 \pm 2100$ events, where the first error is statistical and the second systematic. A total systematic uncertainty of 11% is estimated by varying the Breit-Wigner width in the η_b PDF to 5, 15, and 20 MeV, setting the ISR $\Upsilon(1S)$ component to $\pm 1\ \sigma$ of the nominal rate, and varying the PDF parameters fixed in the fit by $\pm 1\ \sigma$. The largest contribution (10%) is from the η_b width variation.

The η_b signal significance is estimated using the ratio $\log(L_{\max}/L_0)$, where $L_{\max}$ and L_0 are the likelihood values obtained from the nominal fit and from a fit with the η_b PDF removed, respectively. Fits have been performed where the parameters entering the systematic uncertainties have been varied within their errors. Data have then been fitted with all parameters simultaneously moved by one standard deviation in the direction of lower significance. This conservative approach yields a signal significance greater than 10 standard deviations.

As a cross check, we also perform a fit where the yield of the ISR $\Upsilon(1S)$ component is left free, and we obtain 24800 ± 2300 events for this component. This is consistent with the estimate using the below-$\Upsilon(4S)$ data and provides an important validation of the $\chi_{bJ}(2P)$ line shape parameterization. The yield and peak position of the η_b signal from this fit are unchanged.

The E_γ signal peak value from the fit is $917.4^{+2.1}_{-2.8}$ MeV. We apply a photon energy calibration shift of 3.8 ± 2.0 MeV, obtained by comparing the fitted position of the $\chi_{bJ}(2P)$ peak to the known PDG value. After including an additional systematic uncertainty of 1.3 MeV from the fit variations described above, we obtain a value of $E_\gamma = 921.2^{+2.1}_{-2.8} \pm 2.4$ MeV for the η_b signal.

The η_b mass derived from the E_γ signal is $M(\eta_b) = 9388.9^{+3.1}_{-2.3} \pm 2.7\ \mathrm{MeV}/c^2$. Using the PDG value of $9460.3 \pm 0.3\ \mathrm{MeV}/c^2$ for the $\Upsilon(1S)$ mass, we determine the $\Upsilon(1S)$-η_b mass splitting to be $71.4^{+2.3}_{-3.1} \pm 2.7\ \mathrm{MeV}/c^2$.

The value we measure for the splitting is larger than most predictions based on potential models [2], but reasonably in agreement with predictions from lattice calculations [13]. The mass splitting between the $\Upsilon(1S)$ and the $\eta_b(1S)$ is a key ingredient in many theoretical calculations. The precision of our measurement will allow, among others, a more precise determination of the lattice spacing [13] and new precision determinations of α_s [14].

We estimate the branching fraction by correcting the signal yield with the reconstruction efficiency (ϵ) from simulated signal MC events, and then dividing it by the number of $\Upsilon(3S)$ events in the data sample. The branching fraction of the decay $\Upsilon(3S) \to \gamma\,\eta_b$ is found to be $(4.8 \pm 0.5 \pm 1.2) \times 10^{-4}$, where the first uncertainty is statistical and the second systematic. The systematic uncertainty of 25% comes from uncertainties in the signal yield (11%) and ϵ (22%). The latter is obtained by comparing the yield of $\chi_{bJ}(2P)$ in data to the number of expected events, which is calculated from the known branching fractions [11], the number of $\Upsilon(3S)$ events, and MC reconstruction efficiency of $\chi_{bJ}(2P)$. They show a 13% discrepancy, but are consistent within the errors. We assign the full difference to the systematic uncertainty. A total uncertainty in ϵ is obtained, after adding the uncertainties in the $\chi_{bJ}(2P)$ branching fractions (18%).

In conclusion, we have observed, with a significance of 10 standard deviations, the radiative decay of the $\Upsilon(3S)$ to a narrow state lying slightly below the $\Upsilon(1S)$. The most likely interpretation of the signal peak is the $\Upsilon(3S)$ transition to the bottomonium ground state, although other hypotheses, such as a radiative transition to a light Higgs boson, are not excluded. Under the bottomonium interpretation, this is the first evidence for the η_b bottomonium state, the pseudoscalar partner of the $\Upsilon(1S)$. The mass of the η_b is $9388.9^{+3.1}_{-2.3} \pm 2.7$ MeV/c^2, which corresponds to a mass splitting between the $\Upsilon(1S)$ and the η_b of $71.4^{+2.3}_{-3.1} \pm 2.7$ MeV/c^2. The estimated branching fraction of the decay $\Upsilon(3S) \to \gamma\,\eta_b$ is found to be $(4.8 \pm 0.5 \pm 1.2) \times 10^{-4}$.

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