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Observation of the $\Upsilon(1^3D_J)$ bottomonium state through decays to $\pi^+\pi^-\Upsilon(1S)$

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Based on 122×10^6 $\Upsilon(3S)$ events collected with the *BABAR* detector, we have observed the $\Upsilon(1^3D_J)$ bottomonium state through the $\Upsilon(3S) \to \gamma\gamma\Upsilon(1^3D_J) \to \gamma\gamma\pi^+\pi^-\Upsilon(1S)$ decay chain. The significance is 6.2 standard deviations including systematic uncertainties. The mass of the $J = 2$ member of the $\Upsilon(1^3D_J)$ triplet is determined to be $10164.5 \pm 0.8\,(\mathrm{stat.}) \pm 0.5\,(\mathrm{syst.})$ MeV/c^2. We use the $\pi^+\pi^-$ invariant mass and decay angular distributions to confirm the consistency of the observed state with the orbital angular momentum and parity assignments of the $\Upsilon(1^3D_J)$.

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Heavy quark bound states below open flavor thresholds provide a key probe of the interactions between quarks. The mass spectrum and branching fractions of these states can be described by potential models and quantum chromodynamics [1–3]. S-wave and P-wave bottomonium ($b\bar{b}$) states were first observed in the 1970s and 1980s. Only recently [4] has a D-wave bottomonium state, the triplet $\Upsilon(1^3D_J)$ [5], been observed, where $J = 1, 2, 3$. The separation between the members of the triplet (intrinsic widths about 30 keV/c^2) is predicted to be on the order of 10 MeV/c^2 [2]. A single state, interpreted to be the $J = 2$ member of the $\Upsilon(1^3D_J)$ triplet, was observed [4] by the CLEO Collaboration in the radiative $\Upsilon(1^3D_2) \to \gamma\gamma\Upsilon(1S)$ decay channel, but the quantum numbers L, J [5] and parity P were not verified.

In this Letter, we report the observation of the $\Upsilon(1^3D_J)$ in the hadronic $\pi^+\pi^-\Upsilon(1S)$ decay channel. The $\Upsilon(1S)$ is reconstructed through its decays to $\ell^+\ell^-$ ($\ell = e$, μ). The hadronic decay provides better $\Upsilon(1^3D_J)$ mass resolution than the radiative decay and allows L, J, and P to be tested through measurement of the angular distributions of the $\pi^\pm$ and $\ell^\pm$. The only previous result for the $\Upsilon(1^3D_J) \to \pi^+\pi^-\Upsilon(1S)$ channel is the 90% confidence level (CL) branching fraction upper limit $\mathcal{B}_{\Upsilon(3S)\to\gamma\gamma\Upsilon(1^3D_J)} \times \mathcal{B}_{\Upsilon(1^3D_J)\to\pi^+\pi^-\Upsilon(1S)} \times \mathcal{B}_{\Upsilon(1S)\to\ell^+\ell^-} < 6.6 \times 10^{-6}$ [4].

The analysis is based on a sample of $(121.8 \pm 1.2) \times 10^6$ $\Upsilon(3S)$ decays collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage rings at the SLAC National Accelerator Laboratory, corresponding to an integrated luminosity of 28.6 fb^{-1}. The *BABAR* detector is described elsewhere [6]. Monte Carlo (MC) event samples that include simulation of the detector response are used to determine the signal and background characteristics, optimize selection criteria, and evaluate efficiencies. Pure electric-dipole transitions [7] are assumed when generating radiative decays.

The $\Upsilon(1^3D_J)$ in our study are produced through $\Upsilon(3S) \to \gamma\chi_{bJ'}(2P) \to \gamma\gamma\Upsilon(1^3D_J)$ transitions, with $J' = 0, 1, 2$. To reconstruct the $\Upsilon(3S) \to \gamma\gamma\pi^+\pi^-\ell^+\ell^-$ final states, we require exactly four charged tracks in an event, two of which are identified as pions with opposite charge and the other two as either an e^+e^- or $\mu^+\mu^-$ pair. Pion candidates must not be identified as electrons. To reject Bhabha events with bremsstrahlung followed by γ conversions, we require the cosine of the polar angle of the electron with respect to the e^- beam direction to satisfy $\cos\theta_{e^-} < 0.8$ in the laboratory frame. To improve the $e^\pm$ energy measurements, up to three photons are combined with $e^\pm$ candidates to partially recover bremsstrahlung [8]. The $\Upsilon(1S)$ candidate is selected by requiring $-0.35 < m_{e^+e^-} - m_{\Upsilon(1S)} < 0.2$ GeV/c^2 or $|m_{\mu^+\mu^-} - m_{\Upsilon(1S)}| < 0.2$ GeV/c^2, where the invariant mass of the lepton pair $m_{\ell^+\ell^-}$ is then constrained to the nominal $\Upsilon(1S)$ mass value [9]. The pion pair is combined with the $\Upsilon(1S)$ candidate to form a $\Upsilon(1^3D_J)$ candidate (mass resolution 3 MeV/c^2). To eliminate background from $\gamma \to e^+e^-$ conversions in which both the e^+ and e^- are misidentified as pions, we reject events with a laboratory $\pi^+\pi^-$ opening angle $\cos\theta_{\pi^+,\pi^-}$ greater than 0.95 if the converted e^+e^- mass is less than 50 MeV/c^2, and events with a laboratory angle between the $\pi^+\pi^-$ pair and $\ell^\pm$ that satisfies $\cos\theta_{\pi^+\pi^-,\ell^\pm} > 0.98$.

Photons from $\Upsilon(3S) \to \gamma\chi_{bJ'}(2P)$ ($\chi_{bJ'}(2P) \to \gamma\Upsilon(1^3D_J)$) have energies between 86 and 122 MeV [9] (80 and 117 MeV [2]) in the $\Upsilon(3S)$ center-of-mass (CM) frame, depending on the member of the $\chi_{bJ'}(2P)$ (and $\Upsilon(1^3D_J)$) triplet. Our resolution for 80 MeV photons is about 6.6 MeV. We require at least two photons in an event: one (the other) with CM energy larger than 70 MeV (60 MeV). Photons from final-state radiation (FSR) are rejected by requiring the cosines of the laboratory angles between the cascade photons and leptons to satisfy $\cos\theta_{\ell,\gamma} < 0.98$. In case of multiple cascade photon combinations, we choose the combination that minimizes $\chi^2 = \sum_i \left(E^i_\gamma - E^i_{\mathrm{exp}}\right)^2 / \sigma^2_{E^i_\gamma}$ ($i = 1, 2$), where E^i_{exp} are the nominal [9] (for $\Upsilon(3S) \to \gamma\chi_{bJ'}(2P)$) or expected [2] (for $\chi_{bJ'}(2P) \to \gamma\Upsilon(1^3D_J)$) photon energies that correspond to one of the six possible $\Upsilon(3S) \to \gamma\chi_{bJ'}(2P) \to \gamma\gamma\Upsilon(1^3D_J)$ transition paths allowed by angular momentum conservation, with E^i_γ and $\sigma_{E^i_\gamma}$ the measured energies and resolutions. The requirements placed on the $\Upsilon(3S)$ candidate are very loose, so that the final results are not sensitive to the choice of $E^i_{\rm exp}$ within a wide range.

The $\Upsilon(1^3D_J)$ candidate is combined with the two photons to form a $\Upsilon(3S)$ candidate, whose CM momentum is required to be less than 0.3 GeV/c. The $\Upsilon(3S)$ mass is then constrained to its nominal value [9]. The $\Upsilon(3S)$ laboratory energy (resolution 25 MeV) is required to equal the summed e^+ and e^- beam energies to within 0.1 GeV.

We identify four background categories within our fit interval $10.11 < m_{\pi^+\pi^-\ell^+\ell^-} < 10.28$ GeV/c^2: $\Upsilon(3S)$ decays to (I) $\gamma\chi_{bJ'}(2P)$ with $\chi_{bJ'}(2P) \to \omega\Upsilon(1S)$ and $\omega \to \pi^+\pi^-(\pi^0)$, (II) $\pi^+\pi^-\Upsilon(1S)$ with FSR, (III) $\eta\Upsilon(1S)$ with $\eta \to \pi^+\pi^-\pi^0(\gamma)$, and (IV) $\gamma\gamma\Upsilon(2S)$ or $\pi^0\pi^0\Upsilon(2S)$ with $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$. Categories I and II are the main backgrounds.

An extended unbinned maximum likelihood (ML) fit is applied to the sample of 263 selected events that fall within the fit interval. The ML fit has a component for each of the three $\Upsilon(1^3D_J)$ signal states and four background categories. The likelihood function has the form $\mathcal{L} = \exp\left(-\sum_j n_j\right) \prod_{i=1}^{N} \left[\sum_j n_j \mathcal{P}_j\left(m_i\right)\right]$, with N the number of events, n_j the yield of component j, $\mathcal{P}_j$ the probability density function (PDF) for component j, and m the $\pi^+\pi^-\ell^+\ell^-$ invariant mass.

The PDFs are derived from MC simulations. Each signal PDF is parameterized by the sum of two Gaussians and a Crystal Ball (CB) function [10]. For background category I, we use the sum of a CB function, which describes the $\omega \to \pi^+\pi^-\pi^0$ events, and two Gaussians, which model the two peaks from $\chi_{b1,2}(2P)$ decays to $\omega\Upsilon(1S)$ with $\omega \to \pi^+\pi^-$. A bifurcated Gaussian, a high statistics histogram, and a Gaussian, model the PDFs for background categories II, III, and IV, respectively. A data control sample of $\Upsilon(3S) \to \gamma\chi_{bJ'}(2P) \to \gamma\gamma\Upsilon(2S)$ events with $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(1S) \to \ell^+\ell^-$ is used to verify the simulation of the reconstructed $\Upsilon(2S)$ mass and its resolution and the $\Upsilon(3S)$ energy. We find the reconstructed $\Upsilon(2S)$ mass to be shifted downwards by 0.70 ± 0.15 (stat.) MeV/c^2 compared to its nominal value [9]. We apply this shift as a correction to the fitted $\Upsilon(1^3D_J)$ mass results presented below.

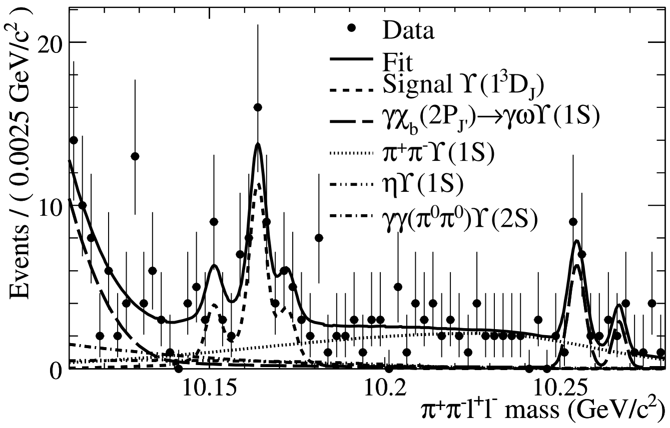

FIG. 1: The $\pi^+\pi^-\ell^+\ell^-$ mass spectrum and fit results. The two peaks near 10.25 GeV/c^2 arise from $\chi_{bJ'}(2P) \to \omega\Upsilon(1S)$ background events with $\omega \to \pi^+\pi^-$.

Eleven parameters are determined in the fit: the three signal yields and three masses, the yields of background categories I and II, and – within background category I – the $\chi_{b1}(2P)$ mass and the relative yields of the $\chi_{b1}(2P)$ and $\chi_{b2}(2P)$ peaks from $\omega \to \pi^+\pi^-$ decays. The mass difference between the $\chi_{b1}(2P)$ and $\chi_{b2}(2P)$ peaks is fixed to its measured value [9]. The yields of background categories III and IV are fixed to their expected values based on the measured branching fractions [9, 11].

Figure 1 shows the $\pi^+\pi^-\ell^+\ell^-$ mass distribution and fit results. We find $10.6^{+5.7}_{-4.9}$ $\Upsilon(1^3D_1)$, $33.9^{+8.2}_{-7.5}$ $\Upsilon(1^3D_2)$, and $9.4^{+6.2}_{-5.2}$ $\Upsilon(1^3D_3)$ events, corresponding to $53.8^{+10.2}_{-9.5}$ summed $\Upsilon(1^3D_J)$ events. The two fitted background yields agree with MC expectations. The fitted $\chi_{b1}(2P)$ mass of 10255.0 ± 0.7 (stat.) MeV/c^2 agrees with its nominal value [9]. The statistical significance of each $\Upsilon(1^3D_J)$ state is given by the square root of the difference between the value of $-2\ln\mathcal{L}$ for zero signal events and the value at its minimum, with the masses of the other two states held at their fit values. These results are validated with frequentist techniques. Systematics (see below) are included by convoluting $\mathcal{L}$ with a Gaussian whose standard deviation (σ) equals the total systematic uncertainty. The significances of the $\Upsilon(1^3D_1)$, $\Upsilon(1^3D_2)$, $\Upsilon(1^3D_3)$, and summed $\Upsilon(1^3D_J)$ observations are 2.0 (1.8), 6.5 (5.8), 1.7 (1.6), and 7.6 (6.2) σ without (with) systematics included, respectively. The significance for the sum of the $J = 1$ and 3 states is 2.6 (2.4) σ.

Potential fit biases are evaluated by applying the ML fit to an ensemble of 2000 simulated experiments constructed by randomly extracting events from MC samples, where the numbers of signal and background events and the $\Upsilon(1^3D_J)$ masses correspond to those of the fit.

The biases are found to be 1.6 ± 0.1, -1.8 ± 0.2, 1.0 ± 0.1, and 0.7 ± 0.2 events for the $\Upsilon(1^3D_1)$, $\Upsilon(1^3D_2)$, $\Upsilon(1^3D_3)$, and summed $\Upsilon(1^3D_J)$ yields, respectively. The fit biases on the masses are negligible. We correct the signal yields by subtracting these biases.

The branching fractions are derived by dividing the bias-corrected signal yields by the selection efficiencies and number $N_{\Upsilon(3S)}$ of $\Upsilon(3S)$ events in the initial sample. The efficiencies for the six allowed $\Upsilon(3S) \to \gamma\chi_{bJ'}(2P) \to \gamma\gamma\Upsilon(1^3D_J)$ paths differ by up to 7.5% and therefore do not factorize, leaving six unknown branching fractions but only three measured signal yields. However, 91.4% of the $\Upsilon(3S) \to \gamma\gamma\Upsilon(1^3D_1)$ and 88.7% of the $\Upsilon(3S) \to \gamma\gamma\Upsilon(1^3D_2)$ transitions are predicted [2] to proceed through the $\chi_{b1}(2P)$ state, while $\Upsilon(3S) \to \gamma\gamma\Upsilon(1^3D_3)$ transitions can only proceed through the $\chi_{b2}(2P)$. Therefore, we evaluate the branching fractions for the dominant modes only, using the predicted ratios of the branching fractions to account for the non-dominant transitions. The efficiencies of the dominant modes, averaged over the $\Upsilon(1S) \to e^+e^-$ and $\mu^+\mu^-$ final states, are $26.7 \pm 0.1\%$, $26.7 \pm 0.1\%$, and $25.7 \pm 0.2\%$ for the $\Upsilon(1^3D_1)$, $\Upsilon(1^3D_2)$, and $\Upsilon(1^3D_3)$, respectively.

Multiplicative systematic uncertainties arise from the uncertainty in $N_{\Upsilon(3S)}$ (1.0%) and in the reconstruction efficiencies for tracks (1.4%), photons (3.0%), and particle identification (2.0%). Additive systematic uncertainties originate from the signal PDFs, evaluated by varying the PDF parameters within their uncertainties, background yields, evaluated by varying the background category IV (III) yield by its uncertainties (by ±100%), the fit bias, and the mass calibration based on $\Upsilon(2S)$ events. The fit bias uncertainties are defined as the quadratic sum of half the biases and their statistical uncertainties. The mass calibration uncertainty is taken to be half the $\Upsilon(2S)$ mass shift added in quadrature with the $\Upsilon(2S)$ mass uncertainty [9]. The overall additive uncertainties for the signal yields (masses) are $1.5 - 2.0$ events (0.48 MeV/c^2) and are dominated by the contribution from the background yields ($\Upsilon(2S)$ mass calibration).

The branching fraction products for the dominant modes $\mathcal{B}_{J'J} \equiv \mathcal{B}_{\Upsilon(3S)\to\gamma\chi_{bJ'}(2P)} \times \mathcal{B}_{\chi_{bJ'}(2P)\to\gamma\Upsilon(1^3D_J)} \times \mathcal{B}_{\Upsilon(1^3D_J)\to\pi\pi\Upsilon(1S)} \times \mathcal{B}_{\Upsilon(1S)\to\ell\ell}$ (or the upper limits at 90% CL with systematics included) are, in units of 10^{-7}, $\mathcal{B}_{11} = 1.27^{+0.81}_{-0.69} \pm 0.28\,(< 2.50)$, $\mathcal{B}_{12} = 4.9^{+1.1}_{-1.0} \pm 0.3$, and $\mathcal{B}_{23} = 1.34^{+0.99}_{-0.83} \pm 0.24\,(< 2.80)$.

We determine the $\Upsilon(1^3D_2)$ mass to be $10164.5 \pm 0.8 \pm 0.5$ MeV/c^2, which is consistent with, and more precise than, the result $10\,161.1 \pm 0.6\,(\text{stat.}) \pm 1.6\,(\text{syst.})$ MeV/c^2 from CLEO [4]. For completeness, we also report the corresponding mass values for the $\Upsilon(1^3D_1)$ and $\Upsilon(1^3D_3)$ peaks in our fit, which are $10151.6\,^{+1.3}_{-1.4} \pm 0.5$ and $10172.9 \pm 1.7 \pm 0.5$ MeV/c^2, respectively.

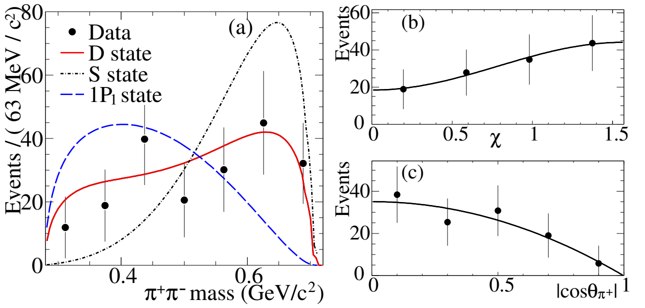

FIG. 2: (a) The $\pi^+\pi^-$ mass spectrum in the $\Upsilon(1^3D_J)$ signal region. The area under each curve equals the number of events. (b,c) Distributions in the $\Upsilon(1^3D_2)$ signal region of (b) the angle χ between the $\pi^+\pi^-$ and $\ell^+\ell^-$ planes, and (c) the π^+ helicity angle. The uncertainties include both statistical and systematic terms.

From the $\Upsilon(3S) \to \gamma\chi_{bJ'}(2P)$ branching fractions and uncertainties [9] and $\chi_{bJ'}(2P) \to \gamma\Upsilon(1^3D_J)$ branching fraction predictions [2] we determine $\mathcal{B}[\Upsilon(1^3D_J) \to \pi^+\pi^-\Upsilon(1S)]$ (or 90% CL upper limits including systematics) to be $0.42\,^{+0.27}_{-0.23} \pm 0.10\%$ ($< 0.82\%$) for the $\Upsilon(1^3D_1)$, $0.66\,^{+0.15}_{-0.14} \pm 0.06\%$ for the $\Upsilon(1^3D_2)$, and $0.29\,^{+0.22}_{-0.18} \pm 0.06\%$ ($< 0.62\%$) for the $\Upsilon(1^3D_3)$.

Figure 2(a) shows the $\pi^+\pi^-$ mass distribution for events in the $\Upsilon(1^3D_J)$ signal region $10.140 < m_{\pi^+\pi^-\ell^+\ell^-} < 10.178$ GeV/c^2 after subtraction of the backgrounds using the estimates from the ML fit. The data are corrected for mass-dependent efficiency variations. Shown in comparison are the expectations for the decay of a D [12], S [12], or $^1P_1$ [13] bottomonium state to $\pi^+\pi^-\Upsilon(1S)$. The resulting χ^2 probabilities of 84.6%, 3.1%, and 0.3%, respectively, strongly favor the D state.

The distribution of the angle χ between the $\ell^+\ell^-$ and $\pi^+\pi^-$ planes in the $\Upsilon(1^3D_J)$ rest frame, for events in the $\Upsilon(1^3D_2)$ signal region $10.155 < m_{\pi^+\pi^-\ell^+\ell^-} < 10.168$ GeV/c^2, is shown in Fig. 2(b). The data are corrected for background and efficiency. The χ distribution is expected to have the form $1 + \beta\cos 2\chi$ with $sign(\beta) = (-1)^J P$ [14], where P is the parity. A fit to the data yields $\beta = -0.41 \pm 0.29\,(\text{stat.}) \pm 0.10\,(\text{syst.})$, consistent with the expected assignments $J = 2$ and $P = -1$.

The background-subtracted, efficiency-corrected distribution of the helicity angle θ_π, for events in the $\Upsilon(1^3D_2)$ signal region, is shown in Fig. 2(c), where θ_π

is the angle of the π^+ in the $\pi^+\pi^-$ rest frame with respect to the boost from the $\Upsilon(1^3D_2)$ frame. For D-state decays to $\pi^+\pi^-\Upsilon(1S)$, θ_π follows a $1+\frac{\xi}{2}(3\cos^2\theta_\pi-1)$ distribution, where ξ is a dynamical parameter to be determined experimentally. For S-state decays, the θ_π distribution is flat ($\xi=0$). A fit to data yields $\xi = -1.0 \pm 0.4\,(\text{stat.}) \pm 0.1\,(\text{syst.})$, disfavoring the S state.

In summary, we have observed the $\Upsilon(1^3D_J)$ bottomonium states through decays to $\pi^+\pi^-\Upsilon(1S)$. The significance is 6.2σ. We improve the measurement of the $\Upsilon(1^3D_2)$ mass and determine the $\Upsilon(1^3D_J) \to \pi^+\pi^-\Upsilon(1S)$ branching fractions or set upper limits. We use the $\pi^+\pi^-$ invariant mass, the angle between the $\pi^+\pi^-$ and $\ell^+\ell^-$ planes, and the π^+ helicity angle, to confirm the consistency of the observed state with $L=2$ for the $\Upsilon(1^3D_J)$, and $J=2$ and parity $P=-1$ for the dominant member of the triplet $\Upsilon(1^3D_2)$.

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