Observation of a Fourth Upsilon State in e^+e^- Annihilations

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A fourth state in the upsilon energy region has been seen in e^+e^- collisions at the Cornell Electron Storage Ring. A resonance is observed with a mass 1112 ± 5 MeV above the lowest upsilon state. The 9.6-MeV rms width is greater than the 4.6-MeV energy resolution of the e^+e^- beams. The observed characteristics of the new state make it a likely candidate for the 4^3S state of the $b\bar{b}$ system, lying above the threshold for the production of B mesons.

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The experimental study of the family of upsilon particles began with the discovery of two heavy narrow states (Υ and Υ') with masses near 10 GeV in the dimuon spectrum from proton-nucleus collisions at Fermilab.[1] From the dimuon data there was also evidence for the possible existence of a third (Υ'') state.[1] The first two states (Υ and Υ') were subsequently observed as narrow resonances in e^+e^- annihilations at DORIS.[2] In the first data run at the Cornell Electron Storage Ring (CESR) the Υ and Υ' were observed with improved energy resolution, and the the third state

(Υ'') was observed for the first time as a narrow resonance in e^+e^- annihilations.[3,4] We now report first results[5] from a scan of the center-of-mass energy region 10.46 GeV $< W <$ 10.64 GeV at CESR.

The data were gathered with the large magnetic detector CLEO.[3] A cylindrical proportional wire chamber and a drift chamber form the track detector inside an aluminum solenoid. Outside the coil are octants containing planar drift chambers, particle identifiers, time-of-flight counters, and proportional-tube shower detectors. Surrounding the entire assembly is an iron hadron filter with drift chambers for muon detection. The trigger for hadronic events required three charged tracks in the inner detector in coincidence with two time-of-flight counters in separate octants.

In the analysis, hadronic events were selected by requiring at least three charged tracks forming a common vertex within ± 8 cm of the interaction point along the beam axis and within ± 2.5 cm transverse to the beam, and a total charged energy of at least 3 GeV. A subtraction, typically less than 5%, was made for events not coming from beam-beam collisions, by use of the observed rate of events with vertices outside the accepted collision region. The trigger and event-selection efficiencies were calculated by Monte Carlo simulations using two-jet and phase-space event generators. The overall detection efficiency is 70%, with an estimated systematic uncertainty of ± 15%.

Figure 1(a) shows the cross section for $e^+e^- \to$ hadrons. No attempt has been made to subtract contributions from τ production and two-photon collisions. The error bars represent statistical errors only. The absolute calibration of the energy scale is uncertain to 0.3%.[6] The energy differences between Υ states quoted here have an estimated systematic uncertainty of ± 5 MeV. The data in Fig. 1(a) correspond to an integrated luminosity of 1090 nb^{-1} and 2398 observed hadronic events. There is a clear enhancement of the total hadronic cross section in the energy region around 10.55 GeV. At this energy, the CESR rms center-of-mass energy spread is expected to be 4.6 ± 0.3 MeV, as extrapolated from the measured values[3] at the Υ, Υ', and Υ''. The width of the observed enhancement at 10.55 GeV is considerably larger than this value. If it is assumed that this indicates the opening of new decay channels, the shape of the resonance is expected to depend crucially on how far above threshold the new state lies.[7] We present the parameters of the resonance obtained from a radiatively corrected Gaussian fit to the resonance above a continuum varying smoothly as W^{-2}. This fit to the data gives an rms width of 9.6 ± 2.3 MeV and a mass difference between this state and the $\Upsilon(1S)$ of 1112 ± 5 MeV. The integrated cross section for the resonance leads to a value of $\Gamma_{ee}/\Gamma_{ee}(\Upsilon) = 0.19 \pm 0.06$. Use of the measured width and unfolding of the beam-energy spread yields a value for the total decay width: $\Gamma_{\text{tot}} = 19.8 \pm 5.5 \pm 5$ MeV. The second error is an estimate of the systematic error due to the uncertainty in the actual shape of the resonance. Bhanot and Rudaz[8] predict for the $\Upsilon(4S)$ state $M_{4s} - M_{1s} = 1141$ MeV and $\Gamma_{ee}(4S)/\Gamma_{ee}(1S) = 0.27$.

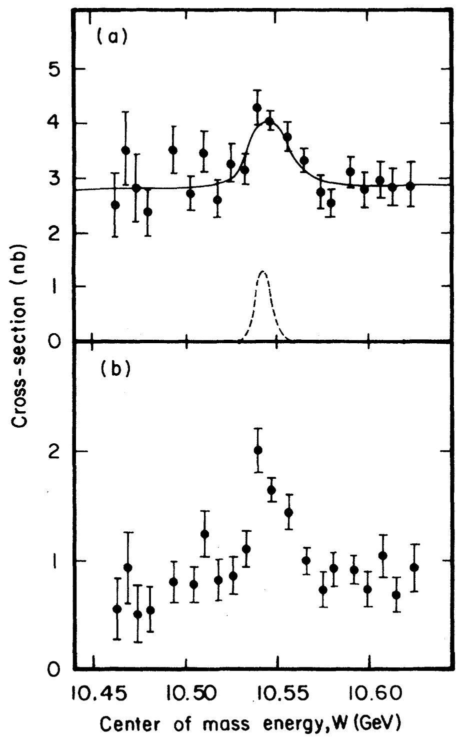

FIG. 1. Hadronic cross sections corrected for acceptance, as a function of center-of-mass energy, W There is an additional overall systematic error of ± 15%, arising mainly from the uncertainty in the detector acceptance. (a) Total hadronic cross section. The curve is a radiatively corrected Gaussian fit to the resonance above a smooth continuum varying as W^{-2}. The dashed curve indicates the beam energy resolution. (b) Partial cross section for events with $R_2 < 0.3$. (See text.)

We have analyzed the event shapes of the hadronic decays using a set of rotationally invariant observables suggested by Fox and Wolfram.[9] We define

$$H_l = \sum_{i,j}(|p_i||p_j|/W^2)P_l(\cos\varphi_{ij}),$$

where i and j are summed over all observed charged particles, p_i (p_j) is the momentum of particle i (j), P_l is the Legendre polynomial of degree l, and φ_{ij} is the angle between particles i and j. The zeroth moment, H_0, is a measure of the energy observed in charged particles, and serves as the normalization factor for higher moments. The ratio $R_2 = H_2/H_0$ is used to describe the event shape. Spherical events have R_2 near zero, while the other extreme, $e^+e^- \to q\bar{q}$, gives $R_2 = 1$. Figure 2 shows the differential cross sections in R_2 for the region of the resonance and for the continuum regions above and below the peak. The observed distribution for the continuum regions agrees with that expected for two-jet events.[9] In the energy region of the peak, the data show a clear excess of events with low values of R_2 when compared with the continuum. This is shown in Fig. 2(b) where we plot the differential cross section in the region of the peak with the continuum distribution subtracted. The difference in event shapes is qualitatively what is expected for production and decay of a heavy resonance, or for the production of a pair of heavy particles at rest which then decay into light hadrons. The event-shape variable R_2 can be used to discriminate against two-jet final states, and thereby enhance the signal-to-background ratio on the resonance.[10] Figure 1(b) shows the hadronic cross section for events with $R_2 < 0.3$. With this shape cut, the signal-to-background ratio is

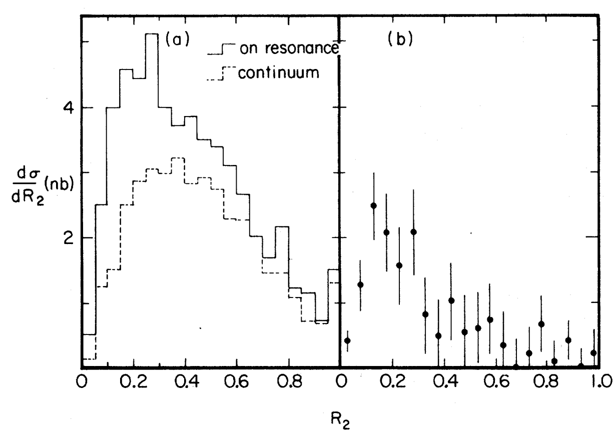

FIG. 2. Differential cross sections in R_2, not corrected for acceptance, for (a) resonance region (10.536 GeV< W < 10.564 GeV) and continuum regions above and below the resonance and (b) resonance region with continuum distribution subtracted.

increased to roughly unity. The mass and width of the enhancement are not significantly altered by this shape cut. A fit with an rms width of 9.6 MeV yields a χ^2 of 42 for 39 degrees of freedom while a narrow width of 4.6 MeV corresponding to the beam-energy resolution yields a χ^2 of 58.

In summary, we have presented evidence for the existence of a new heavy resonance in e^+e^- annihilations in the upsilon energy region at CESR. The observed mass and integrated cross section of the new Υ state make it a likely candidate for the 4^3S state of the $b\bar{b}$ quark system. The observed width suggests strong decay into b-flavored mesons. If we assume that the $B\bar{B}$ threshold lies between the 3S and 4S upsilon states we can fix the B-meson mass between 5.14 and 5.29 GeV. This range includes the energy calibration uncertainty of 0.015 GeV.

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[10]A cut on R_2 also increases the signal-to-background ratio of the narrow Υ resonances. Appropriate cuts on the sphericity or thrust variables also increase the signal-to-background ratio for the broad resonance, but not as much as in Fig. 1(b). We believe that the variable R_2 is more suited to describe the event shape of these nearly isotropic events because it does not require the defining of an axis.