Observation of Three Upsilon States

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(Received 15 February 1980)

Three narrow resonances have been observed in e^+e^- annihilation into hadrons at total energies between 9.4 and 10.4 GeV. Measurements of mass spacings and ratios of lepton pair widths support the interpretation of these "Υ" states as the lowest triplet-S levels of the $b\bar{b}$ quark-antiquark system.

PACS numbers: 13.65.+i

We report here on the first results from the CLEO detector at the Cornell Electron Storage Ring (CESR). CLEO is a magnetic detector built around a 1.05-m-radius, 3-m-long solenoid coil producing a magnetic field parallel to the beams (see Fig. 1). Charged particles are observed and their momenta measured over a solid angle of $0.90\times4\pi$ sr in a cylindrical drift chamber occupying most of the field volume. A smaller cylindrical proportional chamber immediately surrounding the beam pipe provides improved resolution along the beam axis. Outside the 0.9-radiation-length thick aluminum solenoid coil are scintillation counters 2.2 m from the beam line (covering

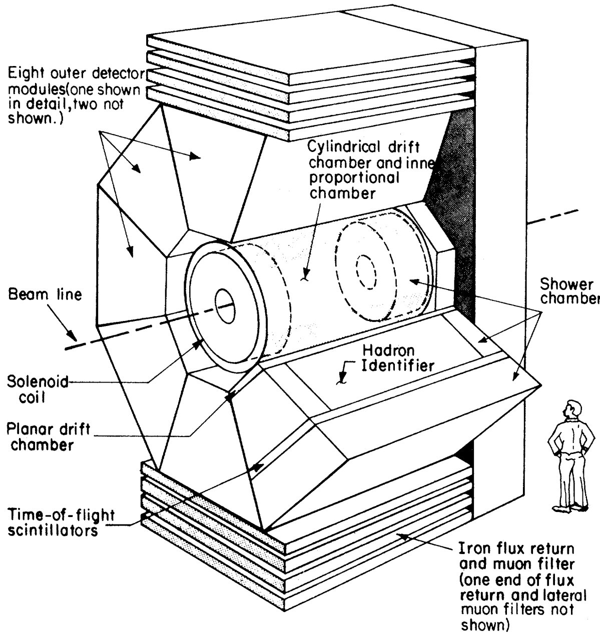

FIG. 1. A simplified view of the CLEO detector, not showing two of the octant modules, one end of the magnet iron, and the muon detection system. The hadron and muon identification components and two of the octants were not used in the present experiment.

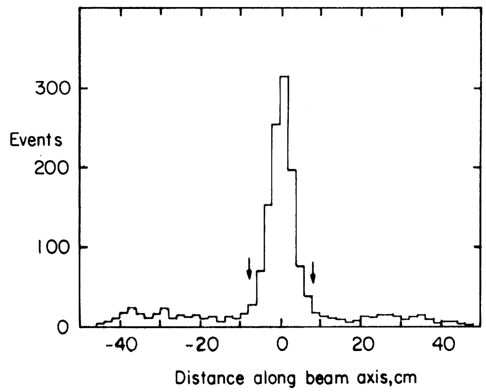

FIG. 2. Beam axis distribution of reconstructed vertices for events in the 10.3-GeV runs satisfying all analysis criteria except possibly the vertex position. The acceptance cuts on the vertex are shown by arrows.

$0.45\times 4\pi$ sr during the present experiment) for measuring the time of flight of charged particles, followed by shower detectors ($0.47\times 4\pi$ sr) made of alternating layers of lead and proportional tubes. Additional detector components for particle identification, covering a wider portion of solid angle, were not used in the present experiment.

The luminosity was measured by counting elastic e^+e^- scatters in lead-scintillator telescopes at angles between 39 and 70 mr to the beam, and checked against the number of large-angle scatters observed in the CLEO detector. The luminosity calibration error is estimated to be ± 15%. During the experiment, peak luminosities were typically 10^{30} cm^{-2} sec^{-1}, corresponding to currents of about 4 mA in each beam. The total integrated luminosity was 445 nb^{-1}, an average of 25 nb^{-1} per day of running.

A fast track-finding processor required at least three charged tracks in the cylindrical drift chamber and inner proportional chamber. If either this requirement was satisfied or at least 2 GeV was deposited in each of two shower detectors, and if pulses were detected in time-of-flight scintillators in at least two octants, the event was recorded for analysis. Electron-positron annihilations into hadrons were selected by requiring at least three charged tracks forming a vertex within ± 8 cm of the nominal intersection point along the beam line and within 2.5 cm transverse to the beam, as well as a total charged and neutral visible energy of at least 15% of the initial total energy, including at least 250 MeV deposited in the shower detectors. The accepted hadronic rate was between 0.2% and 0.8% of the raw trigger rate.

The efficiency of the trigger and analysis selection criteria was estimated by Monte Carlo simulation and by observing the effects of varying the trigger and analysis requirements. The efficiency for hadronic annihilation events was typically (77 ± 11)%, varying slightly with energy and running conditions. The hadronic event sample includes some contamination from background processes. A subtraction, typically less than 9%, was made for events not coming from beam-beam collisions, based on the observed rate of events with vertices outside the accepted collision region (see Fig. 2). The fraction subtracted is consistent with the number of cosmic rays and beam-gas and beam-wall collisions seen in a visual scan of a large sample of the data. Since none of the background processes has a significant dependence on beam energy, they contribute only to the nonresonant continuum.

The measured cross sections, corrected for efficiencies, for electron-positron annihilation into hadrons are plotted in Fig. 3. The total center-of-mass energy is calculated from the integral of magnetic field around the storage-ring

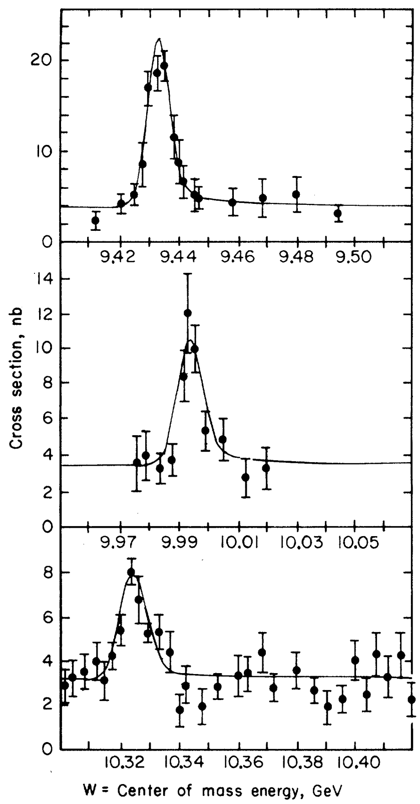

FIG. 3. Measured cross sections, including corrections for backgrounds and for acceptance, but not for radiative effects. Errors shown are statistical only. There is an additional systematic normalization error of ±20% arising from uncertainties in efficiencies and in the luminosity calibration. The energy scale has a calibration accuracy of 30 MeV. The curves show the best fit described in the text.

orbit. Although CESR energy settings were found by repeated resonance scans to be reproducible to better than 0.01% accuracy, there is at present an uncertainty in the overall calibration scale factor amounting to about 0.3%.

The resonances near 9.4 and 10.0 GeV match the Υ and Υ' observed first by Herb *et al.*[1] and confirmed at the DORIS e^+e^- ring.[2-4] Because of the superior energy resolution of the CESR machine, our resonance peaks appear about two times higher and narrower than those observed at DORIS. The resonance near 10.3 GeV is the first confirmation of the Υ'' claimed by Ueno *et al.*[5]

We fit the data by three very narrow resonances, each with a radiative tail convoluted with a Gaussian energy spread, added to a continuum.[6] A single fit to the three peaks with a common energy spread proportional to W^2 and a common continuum proportional to W^{-2} has a χ^2 equal to 0.94 per degree of freedom. The rms energy spread is 4.1 ± 0.3 MeV at $W=10$ GeV, as expected from synchrotron radiation and beam-orbit dynamics in CESR. Individual fits to the three peaks with independent continuum levels and peak widths give results for the rms energy spread and for Γ_{ee} which remain within the errors quoted. From the radiatively corrected area under each peak we extract the leptonic width Γ_{ee}, using the relation $\int\sigma\, dW = 6\pi^2\Gamma_{ee}/M^2$. The results are given in Table I. We list our results in terms of relative masses and leptonic widths, since systematic errors in these quantities tend to cancel. Our measurements agree with those reported by Böhringer *et al.*[7] On the Υ and Υ' our results agree with those from DORIS[2-4] for the mass difference but not for the Γ_{ee} ratio. Because of rather large uncertainties in the contribution of background processes such as τ production and two-photon collisions, we do not regard our present measurement of the continuum cross section as definitive.

Mass differences have been predicted by assuming that the Υ, Υ', and Υ'' are the triplet $1S$, $2S$, and $3S$ states of a $b\bar{b}$ quark pair bound in a phenomenological potential, essentially the same as that responsible for the psion spectrum. When the potential is adjusted to fit masses in the psion region and earlier measurements of the Υ'-Υ difference, the predictions for the Υ''-Υ mass difference[8-10] range from 881 to 898 MeV,

TABLE I. Measured masses and leptonic widths for the second and third Υ states, relative to values for the first state, $\Upsilon(9.4)$. The first error is statistical, the second systematic.

	$M-M(9.4)$ (MeV)	$\Gamma_{ee}/\Gamma_{ee}(9.4)$
$\Upsilon'(10.0)$, DORIS (Ref. 3)	555 ± 11	0.23 ± 0.08
$\Upsilon'(10.0)$, DORIS (Ref. 4)	560 ± 10	0.31 ± 0.09
$\Upsilon'(10.0)$, this experiment	$560.7\pm 0.8\pm 3.0$	$0.44\pm 0.06\pm 0.04$
$\Upsilon''(10.3)$, this experiment	$891.1\pm 0.7\pm 5.0$	$0.35\pm 0.04\pm 0.03$

in agreement with our measurement.

The leptonic widths are proportional to the square of the $b\bar{b}$ wave function at zero separation and to the square of the charge of the b quark. It has already been established that, although various potentials give a range of predictions for the leptonic width of the Υ, the comparison with data favors charge $\frac{1}{3}$.[11] Ratios of leptonic widths are more reliably predicted. Bhanot and Rudaz,[8] for example, give $\Gamma_{ee}(\Upsilon')/\Gamma_{ee}(\Upsilon)=0.44$ and $\Gamma_{ee}(\Upsilon'')/\Gamma_{ee}(\Upsilon)=0.32$, in agreement with our results.

In conclusion, our measurements strongly support current theoretical notions on the nature of the binding between heavy quarks.

We acknowledge with gratitude the heroic efforts of B. D. McDaniel, M. Tigner, and the CESR operating staff during the course of this experiment, and very useful conversations with K. Gottfried, T.-M. Yan, and S.-H. H. Tye. This work was supported in part by the National Science Foundation and in part by the U. S. Department of Energy.

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Observation of Υ, Υ', and Υ'' at the Cornell Electron Storage Ring

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The Υ, Υ', and Υ'' states have been observed at the Cornell Electron Storage Ring as narrow peaks in $\sigma(e^+e^- \to \text{hadrons})$ versus beam energy. Data were collected during a run with integrated luminosity of 1000 nb^{-1}, using the Columbia University–Stony Brook segmented NaI detector. The measured mass differences are $M(\Upsilon')-M(\Upsilon)=559\pm1(\pm3)$ MeV and $M(\Upsilon'')-M(\Upsilon)=889\pm1(\pm5)$ MeV, where the errors in parentheses represent systematic uncertainties. Preliminary values for the leptonic width ratios were also obtained.

PACS numbers: 13.65.+i

The discovery at Fermilab[1] of narrow enhancements in the dimuon spectrum near 10 GeV invariant mass was considered evidence for the existence of a new heavy quark. Two of these states, Υ and Υ', were later observed with much better resolution at the electron-positron storage ring DORIS[2,3] through the process $e^+e^- \to$ hadrons. The leptonic decay widths inferred from the DORIS measurements were consistent with models[4-6] describing the Υ and Υ' as the 1^3S_1 and