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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(Received 15 February 1980)

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

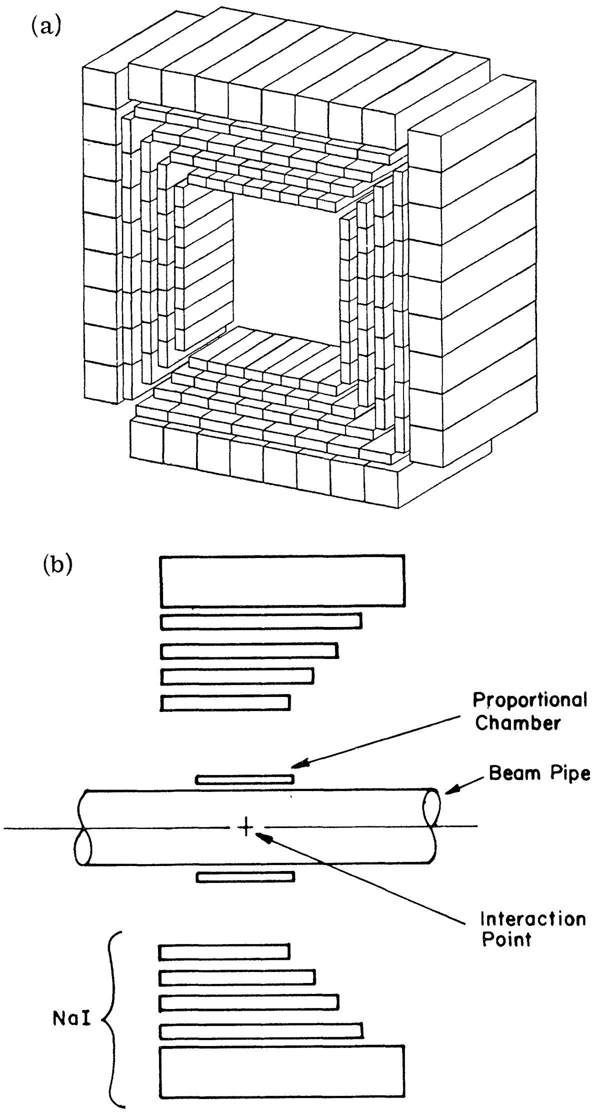

FIG. 1. (a) An isometric view of the NaI array as used in the present run and (b) a side view showing the positioning of the array relative to the interaction point and the positions of proportional chambers.

2^3S_1 bound states of a quark-antiquark pair, $b\bar{b}$, where the b quark has a mass of about 5 GeV and carries $\frac{1}{3}$-integer charge. The results from the Fermilab experiment[7] included evidence for a third state near 10.4 GeV. We report here a new observation of the Υ, Υ', and Υ'' states in e^+e^- collisions with improved energy resolution which confirms the existence of the Υ'' and gives, for the first time, a precise measurement of both level spacings. Preliminary values for the relative leptonic widths are also given.

These results were obtained during the first energy scan in the 10-GeV region performed at the Cornell Electron Storage Ring (CESR). This scan lasted ~ 5 weeks yielding an integrated luminosity of ~ 1000 nb^{-1} of which ~ 600 nb^{-1} were concentrated in three intervals around 9.5, 10.0, and 10.3 GeV. The additional 400 nb^{-1} were used for a scan around 10.6 GeV.

Our detector is located at one of the two interaction regions at CESR (the "North Area") and is designed primarily for the study of photons and electrons. The detector as designed consists of a segmented array of NaI, 8 radiation lengths (r.l.) thick, followed by 7 r.l. of lead glass. Drift chambers before the NaI, and cathode readout proportional chambers ("strip chambers") within the NaI array, provide tracking. The NaI is divided into 32 azimuthal sectors and 2 polar sectors. This provides complete azimuthal coverage in the region $45° < \theta < 135°$. In addition, it is subdivided radially into five layers. At normal incidence, the inner four layers are 1 r.l. each and the last layer is 4 r.l. For the scan reported here, only one NaI half array was used, centered optimally over the interaction point. Four strip chambers at the beam pipe gave the actual position of the interaction point. Complete azimuthal coverage was maintained [Fig. 1(a)]. The polar acceptance was $70° < \theta < 110°$ with some asymmetry [Fig. 1(b)].

Charged particles originating at the interaction point deposit energy in each layer, yielding five independent dE/dx measurements. This signature helped us to eliminate events resulting from beam-gas and beam-wall interactions, although such events were already suppressed since our region of acceptance was located at 90° to the beam.

An absolute energy scale for each NaI crystal was set with γ rays from Cs^{137} and Co^{60}. Full-scale settings ranged from 0.5 to 3.0 GeV. Photomultiplier tube (PM) stability was monitored with light from a spark in argon.

All signals from PM's and strips were integrated every beam crossing (every 2.56 μs) while a trigger decision was made. If no trigger was present, all integrators were reset to be ready for the next crossing. Only a total-energy trigger was used for the data presented. This was generated by adding all signals from the three outer layers of NaI and requiring this sum to exceed a threshold equivalent to 420 MeV and to be coincident with the beam. If the trigger was produced, all signals were digitized and recorded on tape. This trigger gave an event rate of 0.3 Hz for a luminosity of 1 $\mu b^{-1}\ s^{-1}$. A typical fill of CESR lasts 3 to 5 hours yielding an integrated luminosity of up to ~15 nb^{-1}. The integrated luminosity for each run was measured by detecting and counting small-angle (40 to 80 mrad) collinear Bhabha scatters with lead-scintillator sandwich shower detectors. The long-term stability of the luminosity monitor is confirmed by the yield of large-angle Bhabha scattering events in the NaI array.

Because of the limited solid angle of the NaI array as used, a major fraction of the hadronic e^+e^- annihilations gave very few particles in the detector. Rather than trying to identify all hadronic events, which would result in an unacceptable amount of background, our aim in the analysis was to obtain a clean sample through the use of strict event-selection criteria. Fundamental in all criteria used was the identification of minimum-ionizing hadrons. At normal incidence, minimum-ionizing particles deposit 15 MeV in the first four NaI layers and ~68 MeV in the last layer of a single sector. In all scans one unambiguous and isolated minimum-ionizing track plus at least two other tracks or showers were required. All data were scanned by physicists and with computer programs. The acceptance criteria for data presented were determined by maximizing detection efficiency while maintaining the background level well below 10% of the continuum cross section. The overall efficiencies for detecting continuum and Υ events are, respectively, 28% and 37%. These values are obtained by use of the cross sections measured at DORIS[2,3] ($\sigma_{\rm cont} = 3.8$ nb at 9.4 GeV, $\sigma_{\Upsilon\,{\rm peak}} = 18.5$ nb after correcting for the difference in beam energy spread at CESR and DORIS). Absolute normalization was obtained by use of large-angle Bhabha-scattering data. The difference in efficiencies is due to the fact that Υ decays have higher multiplicity and sphericity than continuum events.[2] The actual number of Υ, Υ', and Υ'' events detected above continuum were, respectively, 214, 53, and 133. From the continuum around the three Υ's we collected 272 events.

The major sources of background were (i) far single beam-wall and beam-gas interactions, (ii) close beam-wall interactions, (iii) close beam-gas interactions, and (iv) cosmic rays. Case (i) was trivially removed by the requirement of an isolated track. Cases (ii) and (iii) occur with very small probability of producing penetrating hadrons at $\theta = 90° \pm 30°$ with 5-GeV electrons. Case (ii), which is more frequent, is also recognizable by tracks crossing azimuthal sector boundaries. Case (iv) was rejected by the requirement of three tracks. We point out that the minimal residual background does not affect the results presented here.

The hadronic yield is presented in Fig. 2, plotted in arbitrary units proportional to the ratio of detected events to small-angle Bhabha yield. In this way, the energy dependence (~$1/E^2$) of the single-photon processes is removed. The hori-

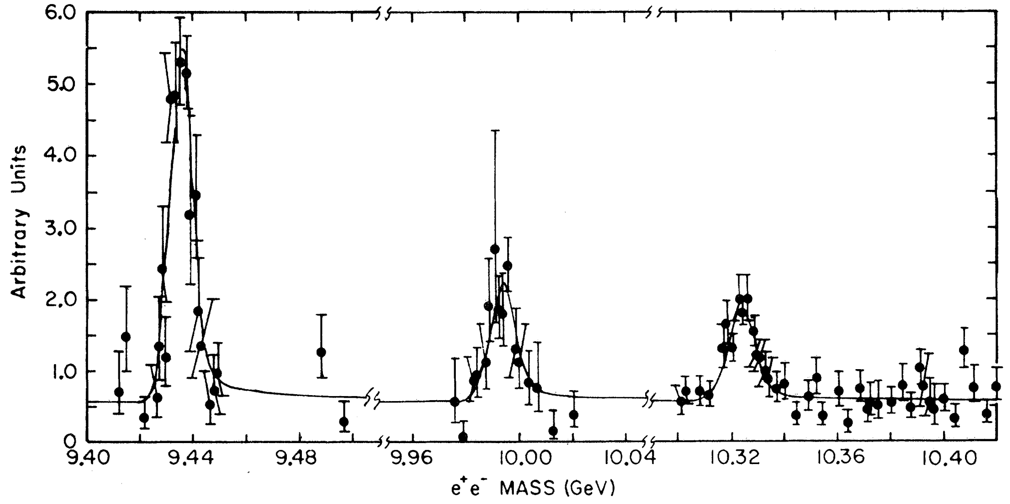

FIG. 2. The number of hadronic events, normalized to the small-angle Bhabha yield. The solid line indicates a fit described in the text.

zontal scale is $M(e^+e^-)$, twice the nominal machine energy. Mass values of the three resonances are determined by fitting the data with a constant continuum plus three radiatively corrected[8] Gaussians, with widths representing the machine energy spread. This fit is shown as a solid line in Fig. 2. A single free width parameter is used for all three resonances, allowing for scaling as E^2 as predicted for the stored-beam energy spread. Our fitted e^+e^- invariant-mass spread at 9.5 GeV is 4.0 ± 0.3 MeV rms, in agreement with the computed value for CESR. Our mass values for Υ and Υ' are ~0.3% lower than the DORIS results. This difference is consistent with the accuracy of the CESR energy calibration.

More relevant to model calculations of the $q\bar{q}$ bound states are the mass differences. Our result for $M(\Upsilon') - M(\Upsilon)$ is 559 ± 1 MeV. To this purely statistical error one should add an estimated systematic uncertainty of ± 3 MeV due to the machine energy calibration. This result is in good agreement with the DORIS results.[2,3] The mass differences $M(\Upsilon'') - M(\Upsilon)$ has been measured accurately for the first time in this experiment, and at the same time by the CLEO collaboration.[9] Our result is 889 ± 1 MeV, with an additional systematic uncertainty of ± 5 MeV. Table I contains a summary of all measured parameters obtained from the fit described.

Another quantity of interest for the phenomenology of the $q\bar{q}$ bound states is the ratio of the leptonic widths for the three resonances. Here the lack of information on decay details and our limited solid angle introduces severe uncertainties on such quantities. Our best estimates, computed without correcting for possible differences in decay multiplicities and angular distributions at the three resonances, are $\Gamma_{ee}(\Upsilon')/\Gamma_{ee}(\Upsilon) = 0.39 \pm 0.06$ and $\Gamma_{ee}(\Upsilon'')/\Gamma_{ee}(\Upsilon) = 0.32 \pm 0.04$. These errors represent only the statistical uncertainty. An estimate of the systematic errors for the partial-width ratios given above was obtained by relaxing the acceptance criteria which increased the number of accepted events for the three resonances by ~50%. In this way, we concluded that the systematic errors are smaller than the quoted statistical errors. The results represented here are in good agreement with many predictions,[4-6] reinforcing the validity of the interpretation of the Υ family as $b\bar{b}$ bound states.

TABLE I. Results from the fit[a].

σ_{machine}	4.0 ± 0.3 MeV
$\Gamma_{ee}(\Upsilon')/\Gamma_{ee}(\Upsilon)$	0.39 ± 0.06
$\Gamma_{ee}(\Upsilon'')/\Gamma_{ee}(\Upsilon)$	0.32 ± 0.04
$M(\Upsilon)$	9.4345 ± 0.0004 GeV
$M(\Upsilon')$	9.9930 ± 0.0010 GeV
$M(\Upsilon'')$	10.3232 ± 0.0007 GeV

[a] Only statistical errors are given.

We wish to acknowledge the tremendous effort of the whole CESR staff in bringing the storage ring successfully into operation. We thank B. McDaniel, M. Tigner, and members of the Cornell Laboratory of Nuclear Studies for help during many months of installation. Part of the electronics design and construction and most of the mechanical design and construction were done by the Nevis Laboratories and Stony Brook shops. We thank Paula Franzini for help in running, and Carl Brown, Tom Regan, and Bill Marterer for help during assembly and testing of the detector at CESR. This research was supported in part by the National Science Foundation.

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