[5]T. W. Donnelly, S. J. Freedman, R. S. Lytel, R. D. Peccei, and M. Schwartz, Phys. Rev. D 18, 1607 (1978); W. A. Bardeen, S.-H. H. Tye, and J. A. M. Vermaseren, Phys. Lett. 76B, 580 (1978); R. D. Peccei, Max-Planck-Institut für Physik, Munich, Report No. MPI-PAE/Pth 45/81 (unpublished); J. M. Frere, M. B. Gavela, and J. A. M. Vermaseren, Phys. Lett. 103B, 129 (1981).
[6]H. Faissner *et al.*, Phys. Lett. 103B, 234 (1981).
[7]D. J. Bechis *et al.*, Phys. Rev. Lett. 42, 1511 (1979).
[8]A. Zehnder, Phys. Lett. 104B, 494 (1981).
[9]J. L. Vuilleumier *et al.*, Phys. Lett. 101B, 341 (1981); H. Faissner *et al.*, in Proceedings of the Symposium on Lepton and Photon Interactions at High Energies, Bonn, 1981 (to be published).
[10]T. Goldman and C. M. Hoffman, Phys. Rev. Lett. 40, 220 (1978); Y. Nagashima *et al.*, in Proceedings of the International Conference on Neutrino Physics and Astrophysics: Neutrino 81, Hawaii, 1981 (to be published).
[11]J. C. Tompkins, in *Quantum Chromodynamics*, edited by A. Mosher (Stanford Univ. Press, Stanford, 1980), p. 556; E. D. Bloom, in *Proceedings of the Ninth International Symposium on Lepton and Photon Interactions at High Energies, Batavia, Illinois, 1979*, edited by T. B. W. Kirk and H. D. I. Abarbanel (Fermilab, Batavia, Ill., 1980), p. 92; M. Oreglia, Ph.D. thesis, Stanford University, Report No. SLAC-236, 1980 (unpublished).
[12]See, e.g., *Cosmic Rays at Ground Level,* edited by A. W. Wolfendale (The Institute of Physics, London, 1977), p. 42.
[13]R. L. Ford and W. R. Nelson, Stanford Linear Accelerator Center Report No. 210, 1978 (unpublished).
[14]F. C. Porter and K. C. Konigsmann, California Institute of Technology Report No. CALT-68-860 (unpublished), and Stanford University Report No. HEPL-897 (unpublished).
[15]M. Dine, W. Fischler, and M. Srednicki, Phys. Lett. 104B, 199 (1981); S. Dimopoulos, S. Raby, and F. Wilczek, Institute of Theoretical Physics, University of California, Santa Barbara Report No. NSF-ITP-81-31 (unpublished); H. P. Nilles and S. Raby, Stanford Linear Accelerator Center Report No. SLAC-PUB-2743 (unpublished); M. B. Wise, H. Georgi, and S. I. Glashow, Phys. Rev. Lett. 47, 402 (1981).
[16]P. Fayet and M. Mezard, Phys. Lett. 104B, 226 (1981).

Search for Structure in $\sigma(e^+e^- \rightarrow \text{hadrons})$ between $\sqrt{s} = 10.34$ and 11.6 GeV

E. Rice, T. Böhringer,[a] P. Franzini, K. Han, S. W. Herb,[b] G. Mageras, D. Peterson, and J. K. Yoh[c]
Columbia University, New York, New York 10027

and

J. Lee-Franzini, G. Giannini,[d] R. D. Schamberger, Jr., M. Sivertz, L. J. Spencer, and P. M. Tuts
The State University of New York at Stony Brook, Stony Brook, New York 11794

and

R. Imlay, G. Levman, W. Metcalf, and V. Sreedhar
Louisiana State University, Baton Rouge, Louisiana 70803

and

G. Blanar, H. Dietl, G. Eigen, E. Lorenz, F. Pauss, and H. Vogel
Max-Planck-Institut für Physik, D-8000 Munich 40, Federal Republic of Germany
(Received 4 January 1982)

The CUSB detector at the Cornell Electron Storage Ring has been used to measure $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ in the c.m. energy regions between the Υ'' and the Υ''', and above the Υ''' up to $\sqrt{s} = 11.6$ GeV, with integrated luminosities of 5000 and 2100 nb^{-1}, respectively. No narrow resonances are observed, and limits on the leptonic widths are presented. The average value of R increases by 0.31 ± 0.06 across the flavor threshold.

PACS numbers: 13.65.+i, 14.40.Gx

The measured properties[1] of the $\Upsilon(9.4)$, $\Upsilon'(10.0)$, and $\Upsilon''(10.3)$ are consistent with models which associate these resonances with the 1^3S, 2^3S, and 3^3S states of a bound $b\bar{b}$ quark pair which decay mostly by annihilation of the heavy quark pair.[2] The $\Upsilon'''(10.5)$ has been identified with the 4^3S level, and lies above the threshold for the decay to B mesons containing isolated b quarks,[3,4] which then decay weakly. This is proved by its mass and width ($\Gamma \sim 20$ MeV, compared to ~ 25 keV for the lower states[5]) and by the observation of the leptonic decay of the B meson.[6] As the c.m. energy is raised above the $\Upsilon'''(10.5)$ mass, one expects a new contribution to the nonresonant $e^+e^- \to$ hadrons cross section from $e^+e^- \to b\bar{b}$ which increases the cross section by approximately $\frac{1}{3}$ unit of $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ $[\equiv \sigma_{had}/\sigma_{\mu\mu}]$, according to the parton model,[7] for a quark of charge $\frac{1}{3}e$. A similar behavior has been observed and extensively studied around the charm threshold.[8] In this paper we present measurements of R at energies above the $\Upsilon''(10.3)$, which we analyze for changes in the average value of R and for resonant structure.[9]

The data discussed here were obtained using the CUSB detector at the Cornell Electron Storage Ring. This detector[3,10] is a segmented electromagnetic calorimeter covering approximately 60% of 4π. The NaI array is 9 radiation lengths thick, consisting of 324 NaI crystals divided into 64 azimuthal sectors (32 in each polar half), each of which is divided into five radial layers. It is surrounded by an additional layer of lead glass. Photons and electrons deposit all their energy, while ~ 300 MeV is measured for each minimum-ionizing track; an average of $\sim 42\%$ of the total c.m. energy is visible for hadronic events. Drift chambers provide precision charged-particle tracking (2 mm in z) over $\sim 70\%$ of 4π. We use a small-angle luminosity monitor, calibrated using large-angle Bhabha scatters.

Our trigger is the logical OR of two requirements: (1) at least 1-GeV energy deposition in the outer three radial layers of NaI, and (2) at least 700 MeV in the outer three planes of NaI together with a "distributed" energy requirement of at least one quadrant with more than 100 MeV in the outer four NaI planes in one polar half, and at least two such quadrants in the other half. The dead time was well below 1%. Using Monte Carlo (MC) simulation we have determined the triggering efficiency to range from 85% to 97% depending on the topology of the events. The triggering efficiency for large-angle Bhabha events in our solid angle is $\simeq 100\%$, due to their unique signature.

The hadronic-event selection criteria are: (1) at least one radial minimum-ionizing track in the NaI, and (2) at least 300 MeV deposited in each polar half of the detector at $\sqrt{s} = 10.5$ GeV, and (3) additional energy distributed in each polar half. The additional energy requirements are scaled linearly according to the c.m. energy and inversely with the number of minimum-ionizing tracks found. Five independent radial samplings of dE/dx in a single azimuthal NaI sector provide a unique signature for noninteracting minimum-ionizing tracks coming from the interaction vertex. In contrast, electromagnetic showers show a larger spread in transverse energy deposition (typically 2–3 sectors) and increasing radial energy deposition.

We have studied the hadronic event criteria efficiency by means of the University of Lund MC program with Field and Feynman fragmentation for both the continuum and Υ resonances.[11] We find the probability, ϵ, that an event enters our final data sample is 0.58 for continuum events and 0.73 for the $b\bar{b}$ type events, from $\sqrt{s} = 10.34$ to 11.5 GeV. As a result of the 60% solid angle coverage, $b\bar{b}$ events and resonance decays, with their higher multiplicity and more spherical topology, have higher trigger and event-selection efficiency than two-jet-like continuum events.

We apply first-order initial-state radiative corrections according to Bonneau and Martin and others.[12] The physical cross section, σ, is

$$\sigma = \sigma_0(1+\delta_c)\int[\sigma_1(k)/\sigma_0][\epsilon(k)/\epsilon(0)]dk,$$

where σ_0 is the zeroth-order cross section; δ_c is a constant, detector-independent correction; $\sigma_1(k)$ is the differential cross section for radiating a photon of energy k; and $\epsilon(k)$ is the corresponding detector efficiency. We assume a $1/s$ dependence for σ_0. The photon spectrum peaks at both ends, and so we divide the integral into two parts at $k = 0.5\,E_{beam}$. Also, we compute the integrals without and with efficiencies included, with the following results:

	$\int(\sigma_1/\sigma_0)$	$\int(\sigma_1/\sigma_0)[\epsilon(k)/\epsilon(0)]$
$0 < k/E_{beam} < 0.5$	0.99	0.95
$0.5 < k/E_{beam} < 0.95$	0.089	0.02

The whole integral contributes a factor of 0.97. Including $\delta_c = 11.1\%$ gives a radiative correction of 7.8%, i.e., $\sigma_0 = \sigma/1.078$. The choice of cutoff does not affect the result since $\epsilon(k)$ is small for large k. Changing the cutoff from 95% to 80% of E_{beam} changes our value for R by 0.5%.

Backgrounds to σ_{had} include $\tau\bar{\tau}$ events, two-photon mediated processes, and beam-wall and beam-gas interactions. The hadronic criteria effectively eliminate non-beam-beam events. We make a distribution of reconstructed event z vertices from our drift chambers for events passing our

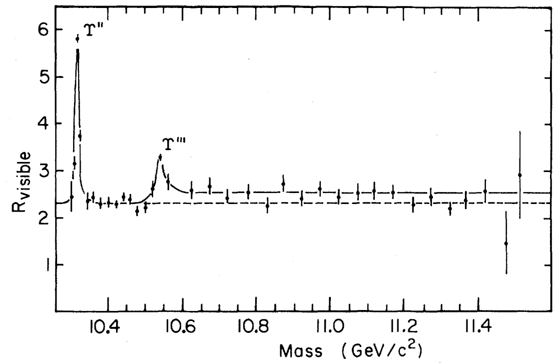

FIG. 1. R_{vis} in the Υ'' and Υ''' region. The solid line is a fit to the data, and the dashed line represents the R_{vis} level below the Υ'''.

hadronic criteria, and find it to be Gaussian over two decades with appropriate width. Thus we estimate the non-beam-beam background to be less than 2%, and we do not subtract it from our final R values. Since hadrons from two-photon events are strongly collimated at 0° and 182°, and carry only a small fraction of the total c.m. energy, this contamination is estimated to be less than 2%, and we do not correct for it. We have studied $\tau\bar{\tau}$ decays by MC methods and find an 8% efficiency for these low-multiplicity events.

The data, before corrections, are shown in Fig. 1 as $R_{\text{vis}} = \sigma_{\text{had visible}}/\sigma_{\mu\mu}$ vs c.m. energy, $\sqrt{s}$, with $\sigma_{\mu\mu}$ taken as $4\pi\alpha^2/3s$. The data are shown coarsely binned, together with Υ'' and the Υ''' for reference. The data are consistent with an abrupt change in R from below to above the Υ'''. Since there is no evidence of observable resonances above the Υ''' or between the Υ'' and the Υ''' (as discussed below), we add separately all data below and above the Υ''' and determine $R_{\text{vis below}} = 2.29 \pm 0.029$ (using a 3500-nb^{-1} sample of the data taken concurrently with the above Υ''' data) and $R_{\text{vis above}} = 2.54 \pm 0.040$, from which we obtain $\Delta R_{\text{vis}} = 0.24 \pm 0.049$. The χ^2 value per degree of freedom in the two regions is $\frac{170}{172}$ below and $\frac{154}{157}$ above the Υ'''.

If we assume that this increase is due to the production of B mesons and their excited states, our efficiency for observing the excess events should be that for $b\bar{b}$ events. Dividing by this efficiency and the radiative correction factor gives $\Delta R = 0.31 \pm 0.06$. Use of our efficiency for continuum events, including radiative corrections, gives for the continuum below the Υ''', after $\tau\bar{\tau}$ subtraction, $R = 3.54 \pm 0.05$, and for continuum above, $R = 3.85 \pm 0.05$. We estimate that the systematic errors are composed of 10% for the acceptance and 5% for the luminosity monitor calibration. We summarize the existing determinations[13] of R in the Υ energy range in Table I. The value above threshold is consistent with those obtained at PETRA.[14]

Our assumption that the excess events are due to the production of B mesons is supported by a change in the observed thrust distribution from below to above the Υ'''. Using the pseudothrust variable T' (Ref. 15), we find a decrease in the average thrust above the Υ'''. The observed 4σ decrease is consistent with our hypothesis, as is shown in Table II.

We have searched for resonances between the Υ'' and the Υ''', and above the Υ'''. There is a predicted 2^3D_1 state at ~10.55 GeV, but S-D mixing is expected to be small,[16] with a peak change in R of less than 0.25. Also, the "string" picture predicts "vibrational" states; the lowest ($\Upsilon_{v=1}$) lies between the Υ'' and the Υ''', with a possible relatively large leptonic width of 0.20 ± 0.15 keV and presumed narrow total width.[17] Thus we have searched for a single resonance of machine width between the Υ'' and the Υ'''. Above the Υ''' most models predict a series of broad n^3S_1 states with mass differences of $\Delta M \sim 200$ MeV and Γ_{ee} proportional to $1/n$.[18] There is another prediction for a 6S state which is comparable in total and leptonic width to the observed 4S state.[19] With the present level of statistics we are not able to resolve a series of broad overlapping resonances;

TABLE I. R values in the Υ region. The first error shown is statistical and the second systematic.

Source	R
CUSB (below Υ''')	$3.54 \pm 0.05 \pm 0.40$
DASP II	$3.73 \pm 0.16 \pm 0.28$
DESY-Heidelberg	$3.80 \pm 0.27 \pm 0.42$
PLUTO	$3.67 \pm 0.23 \pm 0.29$

TABLE II. Pseudothrust values for continuum above and below the Υ''', with the Υ''' value shown for reference.

Region	Pseudothrust
Υ''' (continuum subtracted)	0.7353 ± 0.0043
Continuum below (10.34–10.52 GeV)	0.8194 ± 0.0010
Continuum above (10.58–11.60 GeV)	0.8135 ± 0.0013
Continuum (above − below)	0.0059 ± 0.0016

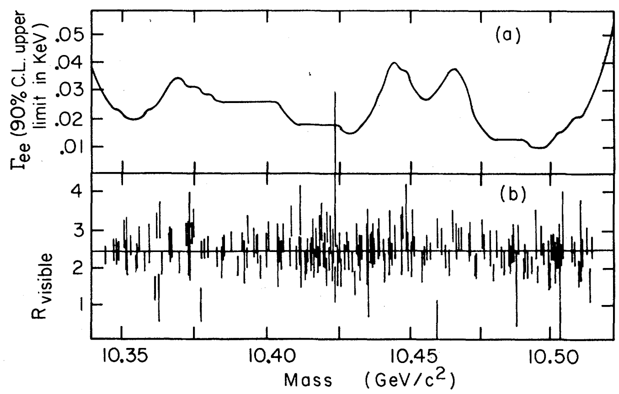

FIG. 2. (a) The curve is the maximum-likelihood 90% confidence-level upper limit for Γ_{ee}, if one assumes a single Gaussian resonance of machine width on top of a fixed continuum level of $R_{vis}=2.29$. (b) The actual scan data, in R_{vis}, used in the maximum-likelihood calculation from $\sqrt{s}=10.34$ to 10.52 GeV.

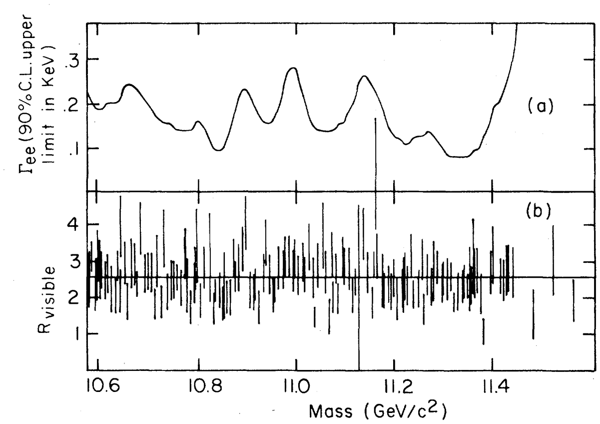

FIG. 3. (a) The curve is the maximum-likelihood 90% confidence-level upper limit for Γ_{ee}, if one assumes a single Gaussian resonance with $\Gamma_{tot}\sim 45$ MeV on top of a fixed continuum level of $R_{vis}=2.54$. (b) The actual scan data, in R_{vis}, used in the maximum-likelihood calculation from $\sqrt{s}=10.58$ to 11.6 GeV.

therefore we have limited our search to a single resonance with a reasonable total width twice that of the Υ'''. We calculate the maximum likelihoods for the two regions separately, assuming a fixed continuum level of $R_{\text{vis below}}=2.29$ and $R_{\text{vis above}}=2.54$, plus a single Gaussian of variable height at a given mass and machine width $\sigma\sim 3.7(M/M_\Upsilon)^2$ MeV for the region between the Υ'' and the Υ''', and of width $\Gamma_{tot}\sim 45$ MeV for the region above the Υ'''. The resulting 90% confidence-level limit for Γ_{ee} as a function of mass is shown in Figs. 2 and 3, along with the actual scan data points; recall that the measured leptonic widths for the Υ'' and the Υ''' are 0.39 and 0.27 keV, respectively.[5]

In conclusion, we find no evidence for a large ($\Gamma_{ee}>0.04$ keV) narrow resonance between the Υ'' and the Υ''' from $\sqrt{s}=10.34$ to 10.52 GeV, suggesting that the first vibrational state is not present in that region at the predicted levels.[17] We have also shown that S-D mixing is indeed small. We observe a step in R which coincides with the Υ''' resonance and which we associate with the threshold for the production of B mesons. The increase is consistent with QCD calculations of the locally averaged contribution to R from the production of a quark with $\frac{1}{3}$ integer charge. We do not observe further resonant states with natural width and leptonic width comparable to those of the Υ'''.

This work was supported in part by the National Science Foundation, the U. S. Department of Energy, and the Max Planck Gesellschaft. One of us (S.H.) acknowledges the support of the Sloan Foundation. We also wish to thank the Cornell Electron Storage Ring operating staff.

---

[a]Present address: EP Division, CERN, CH-1211 Geneva 23, Switzerland.

[b]Present address: Cornell University, Ithaca, N.Y. 14853.

[c]Present address: Fermilab, Batavia, Ill. 60510.

[d]Present address: University of Pisa, I-56100, Pisa, Italy.

[1]T. Böhringer *et al.*, Phys. Rev. Lett. 44, 1111 (1980); D. Andrews *et al.*, Phys. Rev. Lett. 44, 1108 (1980).

[2]C. Quigg and J. Rosner, Phys. Lett. 71B, 153 (1977); G. Bhanot and S. Rudaz, Phys. Lett. 78B, 119 (1978); E. Eichten *et al.*, Phys. Rev. D 17, 3090 (1978).

[3]G. Finocchiaro *et al.*, Phys. Rev. Lett. 45, 222 (1980).

[4]D. Andrews *et al.*, Phys. Rev. Lett. 45, 219 (1980).

[5]R. D. Schamberger, in *Proceedings of the 1981 International Symposium on Lepton and Photon Interactions at High Energies, Bonn, 1981*, edited by W. Pfeil (Physikalisches Institut Universität, Bonn, 1981), p. 217.

[6]L. Spencer *et al.*, Phys. Rev. Lett. 47, 771 (1981); C. Bebek *et al.*, Phys. Rev. Lett. 46, 84 (1981).

[7]R. P. Feynmann, *Photon-Hadron Interactions* (Benjamin, Reading, Mass., 1972).

[8]A review of charm is given by J. Kirkby, in *Proceedings of the Ninth International Symposium on Lepton and Photon Interactions at High Energies, Batavia, Illinois, 1979*, edited by T. Kirk and H. Abarbanel (Fermi National Accelerator Laboratory, Batavia, Ill., 1979), p. 107.

[9]E. Rice *et al.*, in *Proceedings of the International Symposium on Photon and Lepton Interactions at High Energies, Bonn, 1981*, edited by W. Pfeil (Physikal-

isches Institut Universität, Bonn, 1981), p. 1030; P. Tuts *et al.*, *ibid.*, p. 1039.

[10]G. Mageras *et al.*, Phys. Rev. Lett. 46, 1115 (1981).

[11]T. Sjöstrand, University of Lund Reports No. LU TP79-8, 1979 (unpublished), and No. LU TP80-30, 1980 (unpublished); R. D. Field and R. P. Feynman, Nucl. Phys. B136 (1978).

[12]G. Bonneau and F. Martin, Nucl. Phys. B27, 381 (1971); F. A. Berends and R. Kleiss, Deutsches Elektronen-Synchrotron Report No. DESY 80/73, 1980 (unpublished).

[13]Ch. Gerke, thesis, University of Hamburg, 1980 (unpublished); P. Bock *et al.*, Z. Phys. C 6, 125 (1980); S. Weseler, thesis, University of Heidelberg, 1981 (unpublished).

[14]PETRA results, in *Proceedings of the Ninth International Symposium on Lepton and Photon Interactions at High Energies, Batavia, Illinois, 1979,* edited by T. Kirk and H. Abarbanel (Fermi National Accelerator Laboratory, Batavia, Ill., 1979), p. 3.

[15]T. Böhringer *et al.*, to be published.

[16]E. Eichten, Phys. Rev. D 22, 1819 (1980).

[17]W. Buchmüller and S.-H. H. Tye, Phys. Rev. Lett. 44, 850 (1980).

[18]W. Buchmüller and S.-H. H. Tye, Phys. Rev. D 24, 132 (1981).

[19]S. Ono, Technische Hochschule Aachen Report No. PITHA 81/26, 1981 (unpublished).

Neutral-Current $\nu_\mu n$ and $\nu_\mu p$ Cross Sections from High-Energy Neutrino Interactions in Deuterium

T. Kafka, W. A. Mann,[(a)] S. Sommars,[(b)] and R. Englemann
State University of New York at Stony Brook, Stony Brook, New York 11974

and

R. A. Burnstein, J. Hanlon, and H. A. Rubin
Illinois Institute of Technology, Chicago, Illinois 60616

and

C. Y. Chang, G. A. Snow, D. Son, P. H. Steinberg, and D. Zieminska[(c)]
University of Maryland, College Park, Maryland 20742

and

T. Kitagaki, S. Tanaka, H. Yuta, K. Abe, K. Hasegawa, A. Yamaguchi, K. Tamai, T. Hayashino, S. Kunori, Y. Otani, and H. Hayano
Tohoku University, Sendai 980, Japan

and

C. C. Chang, A. Napier, and J. Schneps
Tufts University, Medford, Massachusetts 02155

(Received 28 December 1981)

In an exposure of the deuterium-filled 15 ft bubble chamber, $\sigma(\nu_\mu n \rightarrow \nu_\mu X)/\sigma(\nu_\mu p \rightarrow \nu_\mu X)$ is measured to be 1.01 ± 0.14. The ratios of neutral-current to charged-current cross sections are 0.30 ± 0.03, 0.22 ± 0.03, and 0.49 ± 0.06 for D_2, n, and p targets, respectively, which imply values $u_L^2 = 0.19 \pm 0.06$ and $d_L^2 = 0.13 \pm 0.04$ for the neutral-current chiral couplings. Evidence for both u- and d-quark jets in neutral-current reactions is observed in distributions of energy fraction of the fastest hadron of either charge from each event.

PACS number: 13.15.Ks

Since its initial vindication in the observation of neutrino-induced neutral-current interactions, the $SU(2)_L \otimes U(1)$ electroweak theory has adequately described extensive and varied experimental data.[1] Nevertheless, this "standard model" may, at some level, be only approximate, as it may represent the low-energy limit of a more fundamental theory; hence, continued experimental scrutiny is needed. We report the first determination of relative rates of deep-inelastic neutral-current (NC) reactions $\nu_\mu n \rightarrow \nu_\mu X$ and $\nu_\mu p \rightarrow \nu_\mu X$ which, together with charged-current (CC) reac-