Measurement of B-Meson Semileptonic Decay

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

and

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

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 Institute of Physics, Munich, Federal Republic of Germany
(Received 13 April 1981)

Using the Columbia University–Stony Brook detector we have measured the production of energetic electrons ($E > 1$ GeV) in e^+e^- annihilations in the center-of-mass energy range 10.4 to 11.4 GeV. We observe an enhanced electron signal at the $\Upsilon'''(4S)$ resonance, which we interpret as evidence for the β decay of a new flavor of quark, b, bound within a new flavor meson, B. We derive a branching ratio for $B \to Xe\nu$ of $(13.6 \pm 2.5 \pm 3)\%$. The observed energy spectrum of the electrons favors the decay $b \to ce\nu$ over $b \to ue\nu$.

PACS numbers: 13.20.Jf, 13.65.+i, 14.40.Pe

A series of three narrow resonances[1] ($\Upsilon, \Upsilon', \Upsilon''$) and a fourth broader one (Υ''' at 10.55 GeV) have been observed recently in e^+e^- annihilations at the Cornell Electron Storage Ring (CESR).[2,3] In the quarkonium model these resonances are interpreted as the 1^3S_1, 2^3S_1, 3^3S_1, and 4^3S_1 bound states of a $b\bar{b}$ quark system where b is a new flavored quark. The quarkonium models have been successful in predicting both the level positions and the ratios of leptonic widths for such bound systems.[4] The first three states have narrow widths, as expected in these models. Once the bare-flavor threshold is passed, however, quasibound $b\bar{b}$ states will decay predominantly into $B\bar{B}$ meson pairs which are stable bound states of the b quark and light quarks. The $\Upsilon'''(4S)$ has an observed width of 23 MeV compared with the machine resolution of approximately 11 MeV at this energy. This indicates that it lies above bare-flavor threshold and has strong decay channels.

The direct observation of B mesons through structures in the multiparticle mass spectra is difficult due to combinatorial background arising from the high particle multiplicity (approximately 20) in $B\bar{B}$ events. Thus, evidence for the existence of b quarks can most readily be obtained through the observation of the weak decay of a new heavy, otherwise stable meson. The β decay of the b quark ($M \simeq 5$ GeV) produces electrons lying mostly in the energy range 1–2.5 GeV where electrons from other sources are scarce. Both groups at CESR have reported enhanced production of energetic electrons ($E_e > 1$ GeV) at the $4S$.[5] The present paper details the analysis procedures and results from the Columbia University–Stony Brook (CUSB) nonmagnetic detector, and includes recent measurements in the center-of-mass energy range 10.56 to 11.4 GeV. The CUSB electromagnetic shower detector, a segmented NaI-Pb glass array surrounding drift chambers, has been described elsewhere.[2] Here we will focus on those features which enable us to distinguish between electromagnetic and hadronic final products in e^+e^- annihilations, and to discriminate against chance overlap of charged tracks with electromagnetic showers.

Charged-particle trajectories are measured by twelve planes of drift chambers which cover 70% of the total solid angle. The drift-chamber wires are parallel to the beam in six planes and at 7° for stereo reconstruction in the remaining six. The resulting accuracy in track direction is 3 mrad in azimuth and 25 mrad in polar angle. Segmentation of the NaI and lead-glass arrays allows measurements of both the longitudinal and transverse shower development. Radially there are four thin layers of NaI [each 1.12 r.l. (r.l. denotes radiation length)], a thicker NaI layer (4.1 r.l.), and finally a lead-glass layer (7 r.l.). Segmentation of each NaI layer into 32 azimuthal and 2 polar sectors allows us to make an accurate measurement of the azimuthal angle of a shower. The lead-glass layer has 4 times finer segmentation in polar angle and thus provides the best measurement of the polar angle of the shower.

An electron shower is identified by a characteristic pattern of energy deposition in the NaI and lead glass. Selection criteria for electrons between 1 and 3 GeV were developed using a clean electron sample from quantum electrodynamics (QED) processes in which only one electron hit the shower counters. The longitudinal requirements include a minimum energy deposition in each layer, an energy-dependent requirement on the maximum energy in the lead glass, and limits on the relative energy in adjacent layers. The transverse criteria require that most of the shower energy in a given layer be confined to one or two adjacent NaI sectors. Finally, for a shower to be designated as arising from an electron it is required that the direction of the track associated with the shower agree with the direction determined from the energy deposition in the shower counters within an elliptical cone whose half-opening angles are 4.5° in φ and 7° in θ.

Table I shows the observed results in the mass range 10.4 GeV (below 4S) to 11.44 GeV (above 4S). For each energy bin we show the integrated luminosity; number of electron candidates; $R_{\mathrm{vis}}(e)$, the visible electron cross section divided by $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$; and $R_{\mathrm{vis}}(\mathrm{had})$, the visible cross section for hadronic events divided by $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$. In the present analysis, we use only hadronic events which pass our standard multihadron-event criteria (see Ref. 2 for details) which results in 57% acceptance for continuum events and 74% acceptance for resonance events. In addition, we require five or more detected tracks and thrust[6] less than 0.95 in order to reject $\tau\bar{\tau}$ events. Approximately 81% of our continuum events and 92% of the resonance events satisfy these cuts. These efficiencies were obtained by generating events with a modified version of the University of Lund Monte Carlo program[7] and allowing these events to develop in our detector. The validity of the calculation is demonstrated by the good agreement between computed and observed multiplicity, energy deposited in the detector, and thrust distribution. Figure 1 shows the visible electron and hadron cross sections. In the 4S data sample we observe, after subtracting the continuum contribution, 155.5 $\pm$ 21.4 electrons in 4541 resonance events or 0.0342 $\pm$ 0.0047 electrons per event, compared with 0.0115 $\pm$ 0.0015 electrons per event in the continuum and 0.0042 $\pm$ 0.0013 electrons per resonance event at the Υ, Υ', and Υ''. These electron candidates include backgrounds from pion interactions in the first layer of NaI, overlap of charged

TABLE I. Observed results in the mass range from 10.4 to 11.4 GeV/c^2. The results for each energy bin include the integrated luminosity, the number of electron candidates, the visible electron cross section divided by $\sigma(e^+e^-\rightarrow\mu^+\mu^-)$, and the visible cross section for hadronic events divided by $\sigma(e^+e^-\rightarrow\mu^+\mu^-)$ as described in the text.

Beam energy	$\int\mathcal{L}$ (nb^{-1})	No. e	$10^2 R_{\mathrm{vis}}(e)$	R_{vis}(hadrons, $T < 0.95$ charge multiplicity ≥ 5)
		Continuum		
5.166 – 5.261	3482	52	1.88 ± 0.3	1.85 ± 0.06
		4S region		
5.261 – 5.270	1836	58	4.0 ± 0.6	2.73 ± 0.12
5.270 – 5.271	1471	51	4.4 ± 0.8	2.74 ± 0.13
5.271 – 5.272	1310	75	7.3 ± 1.1	2.94 ± 0.15
5.272 – 5.282	1717	53	4.0 ± 0.7	2.75 ± 0.12
		Above 4S		
5.282 – 5.720	2142	33	2.1 ± 0.4	2.11 ± 0.09

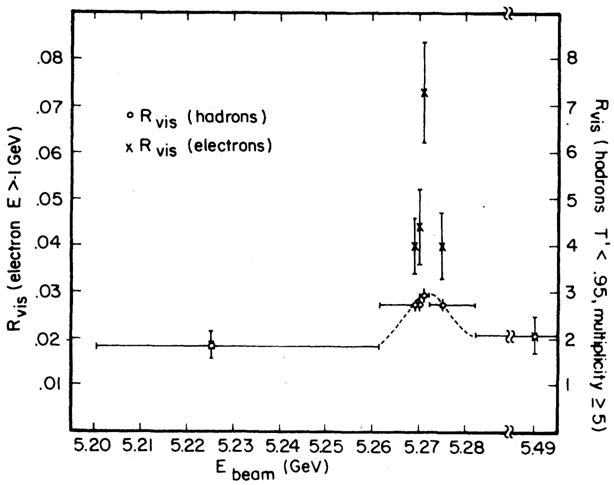

FIG. 1. R_{vis} for high-energy electrons and hadronic events including all cuts described in text. Dashed line through hadronic data points indicates the location of the 4S resonance.

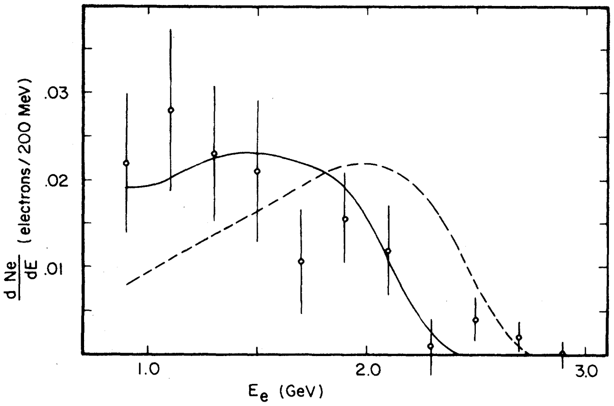

FIG. 2. Observed differential electron energy spectrum per B decay from 4S resonance data (continuum subtracted and corrected for efficiencies) compared with the expected spectra from $B \to e\nu(D, D^*)$ (solid curve) and $B \to e\nu X_u$ (dotted curve) with $M_{X_u} = 1$ GeV, normalized to same area. See text.

tracks with photons, and photon conversions in the beam pipe. We have studied these backgrounds using Monte Carlo simulations and find levels of the order of half the total expected electron yield from continuum events and Υ, Υ', and Υ'' events. We expect these backgrounds to contribute 5% of the 4S resonance yield.

In order to determine the semileptonic branching ratio for $B \to Xe\nu$ we use the following procedure:

(i) The continuum contribution under the 4S peak (10.522 GeV $< M <$ 10.564 GeV) is subtracted with use of our observed yield in the continuum below 4S, thus removing all background from τ decays, QED processes, and continuum $e^+e^- \to c\bar{c}$ events.

(ii) The remaining (5%) background is removed by subtracting the electron spectrum, properly normalized, observed in Υ, Υ', and Υ'' events.

(iii) The electron detection efficiency is the product of a geometric efficiency of 46%, a track reconstruction efficiency of 88%, an electron identification efficiency of 36% (averaged over the energy range), and 61% for the acceptance of hadronic events with a high-energy electron, multiplicity ≥ 5, and thrust ≤ 0.95. The major source of inefficiency in the selection criteria is the overlap of the electron with other particles. A measurement of this loss was obtained by the previously mentioned Monte Carlo simulation method. The total efficiency for hadronic events with an electron decay is $(10.2 \pm 0.8)\%$ and varies from 8.6% to 10.7% for $0.8 < E_{\mathrm{electron}} < 2.5$ GeV.

(iv) The β decay of the B meson is due to two couplings: $b \to ce\nu$ and $b \to ue\nu$. In the former case one expects charmed mesons (D's) to be produced in B decays. D-meson leptonic decays produce additional electrons, mostly below 1 GeV. In the latter case, D mesons and therefore low-energy electrons, are absent. As a result of the high energy available in the decay $B \to e\nu X$, X will, in general, be a more complex state than the lightest pseudoscalar and vector mesons which can be formed by a light $q\bar{q}$ pair, as could be naively expected. Using the observed electron spectrum for $E > 1.4$ GeV we obtain from a fit $M_X = 1.8 \pm 0.3$ GeV, a value in good agreement with the D and D^* meson masses and unreasonably high for the $b \to u$ case. Figure 2 shows the expected spectra from $b \to ce\nu$, assuming 50% $B \to De\nu$ decay, 50% $B \to D^*e\nu$ decay, and including electrons from the subsequent decay $D \to Ke\nu$, and for $B \to e\nu X_u$ from $b \to ue\nu$ assuming an average value of $M_{X_u} = 1$ GeV, folded with our energy-resolution function. Figure 2 also shows the spectrum of observed electrons (continuum subtracted and corrected for efficiencies). Our energy resolution at 2 GeV is σ_E/E about 3%, and we estimate the uncertainty in absolute calibration to be less than 3% (see Mageras *et al.*[8] for further details on energy resolution). For the $b \to c$ case resulting in $B \to (D, D^*)e\nu$, 81% of the electrons from direct B decay lie above 1 GeV, while 9% of the electrons from the cascade decay $B \to D \to Ke\nu$ are in this energy region. Assuming that all Υ''' resonances decay into a $B\bar{B}$ pair, we obtain a branching ratio for $B \to (D, D^*)e\nu$ of $(13.6 \pm 2.5)\%$. For the $b \to u$ case, 90% of the spectrum is above 1 GeV and no extra contribution is expected, giving the same branching ratio. We estimate that our Monte Carlo modeling of the electron acceptance introduces a systematic uncertainty on the value of the branching ratio of the order of 20% of its value.

We also use our results to obtain upper limits for the decay $B \to e\nu X_u$ induced by a $b \to u$ coupling. For this analysis we include electrons whose energy is greater than 800 MeV. The resultant upper limit depends on the assumed $\langle M_X \rangle$ value. We obtain for the ratio of branching fractions $B(B \to e\nu X_u)/B(B \to e\nu D, D^*) \leq 0.23$ for $X_u = 50\%$ (π, η) and $50\% (\rho, \omega)$, ≤ 0.32 for $M_{X_u} = 1$ GeV, and < 1.5 for $M_{X_u} = 1.8$ GeV, at 90% confidence level. In all cases the best fit is obtained for $B(B \to e\nu X_u) = 0$, with the fit for $B \to e\nu D, D^*$ having a value of $\chi^2/\mathrm{D.F.} = 0.96$.

In conclusion, we have detected a strong enhancement of electron yield in multihadron events at the $4S$ peak giving evidence for the weak decay of a new quark, b. The semileptonic branching ratio of $B \to Xe\nu$ has been determined and the observed energy spectrum of the electrons favors $b \to ce\nu$.

We wish to acknowledge the effort of the Cornell Electron Storage Ring machine group and thank S. Lusin, K. Freese, and J. Gavilano for work during various stages of the experiment. This work was supported in part by the National Science Foundation, the U. S. Department of Energy, and the Max Plank Gesellschaft. One of us (S.H.) acknowledges support of the Sloan Foundation.

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[a]Presently Visiting Professor at Cornell University, Ithaca, New York 14853.

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

[c]Present address: Fermi National Accelerator Laboratory, Batavia, Illinois 60510.

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[6]We define thrust (T) as the maximum over the 32 possible values of $\varphi_0 \Sigma E_i \cos(\varphi_i - \varphi_0)/\Sigma E_i$, where E_i is the measured energy in sector i with azimuth φ_i. This variable is close to 0.6 for spherical events. See also Ref. 2.

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Measurement of Deuteron-Deuteron Elastic Scattering at 5.75 GeV/*c*

Edgar T. Whipple, V. Perez-Mendez, A. L. Sagle, R. L. Talaga,[a] and F. Zarbakhsh
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

and

J. B. Carroll, G. J. Igo, J. B. McClelland,[a] M. Bleszynski, and K. Ganezer
Department of Physics, University of California, Los Angeles, California 90024

(Received 19 March 1981)

The elastic differential cross section of 5.75-GeV/c deuterons scattered from deuterium has been measured over a range of $0.125 < -t < 2.0$ (GeV/c)^2. The result shows a narrow interference minimum at $-t = 0.18$ (GeV/c)^2, but does not have a simple exponential behavior in the double-scattering region. The latter effect is attributed to constructive interference between the two double-scattering amplitudes, which have different t dependences. The results are compared to existing data and to a Glauber-model calculation.

PACS numbers: 21.30.+y, 13.75.Cs, 25.10.+s, 25.50.Dt

The multiple-diffraction model of Glauber[1] successfully explains many of the major features of elastic hadron-nucleus scattering. The model treats the scattering process as a sequence of individual collisions between the projectile and the nucleons of the target, and its predictions de-