B Semileptonic Decays at the $\Upsilon(4S)$ and the $\Upsilon(5S)$

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B-meson semileptonic decay spectra have been obtained at the $\Upsilon(4S)$ and at the $\Upsilon(5S)$ at the Cornell Electron Storage Ring with the Columbia University–Stony Brook (CUSB-II) detector. The branching ratio for $B \to e\nu X$ at the $\Upsilon(4S)$ is found to be $(10.0 \pm 0.5)\%$. The electron spectrum of $B \to e\nu X$ at the $\Upsilon(5S)$ is observed for the first time and the average branching ratio for $B, B_s \to e\nu X$ is consistent with that for B's from $\Upsilon(4S)$ decays. The shape of the electron spectrum at the $\Upsilon(5S)$ indicates production of B mesons which are heavier than nonstrange B's, presumably strange B's.

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B-meson semileptonic decays, $B \to l\nu X$, have branching ratios of $\sim(10\text{–}11)\%$,[1-4] for both $l=e$ and $l=\mu$. The $B \to e\nu X$ decays are characterized by high-energy electrons in events with relatively low multiplicity. These properties enable their study in precision electromagnetic (EM) calorimeters where the electrons produce distinctive EM showers. Early studies using the Columbia University–Stony Brook (CUSB) electromagnetic calorimeter at the Cornell Electron Storage Ring (CESR) had measured the $B \to e\nu X$ decays of B mesons produced at the $\Upsilon(4S)$ peak.[1,2] These and other studies gave the first determinations of the magnitudes of the Cabibbo-Kobayashi-Maskawa[5] (CKM) matrix element $|V_{cb}|$ and limits for $|V_{ub}/V_{cb}|$.[3]

In this paper we expand on those B-meson studies through an analysis of a more extensive recent data sample obtained at the $\Upsilon(4S)$ energy and the first data obtained at the $\Upsilon(5S)$ energy, using the CUSB-II detector at CESR. With these data we have been able to make a first determination of the branching ratio of $B \to e\nu X$ at the $\Upsilon(5S)$ and to improve our determination of the branching ratio of $B \to e\nu X$ at the $\Upsilon(4S)$. The data at the $\Upsilon(5S)$ were obtained from a run with an integrated luminosity of 139 pb^{-1}, corresponding to 45000 produced $\Upsilon(5S)$ mesons, and at the $\Upsilon(4S)$ they were obtained from a run with an integrated luminosity of 254 pb^{-1}, corresponding to 290000 $\Upsilon(4S)$ mesons. In addition to the data taken at the $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances, continuum data were taken at an average energy of 10.52 GeV with an integrated luminosity of 133 pb^{-1} corresponding to 490000 produced hadronic events. These continuum data are used for subtraction of the residual continuum contributions at the resonances.

Semileptonic B-meson decays at the $\Upsilon(5S)$ energy offer the opportunity to study the contribution from both nonstrange (B, B^*) and strange (B_s, B_s^*) mesons[6] to the decay. We expect that the semileptonic-B-decay electron spectrum at the $\Upsilon(5S)$ energy is a superposition of spectra with different amounts of Doppler smearing and different end points due to the mass differences of the B-meson species, or, equivalently, the production of B mesons of different velocities β. From the study of the shape of the electron spectrum we find that the measured spectrum is less Doppler broadened than would be expected from B mesons produced at the $\Upsilon(5S)$, thus indicating that an admixture of heavier B mesons, presumably *strange* B mesons, is produced. In the following analysis, we begin with the results obtained on the $\Upsilon(4S)$, where the larger statistics allow us to accurately determine the model parameters which can then be used in determining the shape of the semileptonic decay spectrum obtained on the $\Upsilon(5S)$.

This study was carried out using the CUSB-II detector,[7] which has five layers of bismuth germanate (BGO) crystals followed by five layers of NaI crystals, providing an excellent electron identification and energy resolution. The energy scale is known to 0.5%. Electron showers have a distinct longitudinal shower profile which we test by use of the correlations between the energy deposits in the five BGO layers and the total energy deposit in NaI, by using the covariance matrix method.[8] The observed shower must be associated with one and only one track in the inner drift chamber, where the ϕ coordinate of the tract agrees ($\pm 2°$) with the value obtained from the shower centroid.

The electron candidates contain background from four possible misidentification mechanisms: (1) a single interacting hadron, which is totally negligible for energy >1 GeV, (2) a π^0 with a photon converting before the chamber with a total probability of 5% (2.5% probability for each photon), (3) a π^0 Dalitz decay with a 1.2% probability, and (4) an overlap between a photon or two merged photons from π^0 decays with a charged hadron which in $\Upsilon(4S) \to B\bar{B}$ decays has a geometric probability of about 11%, verified by adding EGS photons to hadronic events. This last probability is mildly dependent on the photon energy since the multiplicity is lower for events with high-energy photons.

The shape of the background due to misidentification is mostly derived from the measured photon spectrum on the $\Upsilon(4S)$, with a small correction due to the mild energy dependence of contribution (4) as obtained from the ratio of the "electron" spectrum to the photon spectrum in $\Upsilon(1S)$ data, where there is no significant source of electrons with energies above 1 GeV. This energy dependence is then folded into the measured photon spectrum observed in $\Upsilon(4S)$ decays to obtain the shape and magnitude of contribution (4). The shape is fitted with a polynomial which is used in the subsequent analysis. From this method we find that the fraction of all electron candidates which are misidentified falls rapidly from (7%, 17%) at 1.1 GeV to (3.6%,6.4%) at 1.5 GeV and to (1.8%,3.2%) at 2.3 GeV, for contributions (2)+(3) and (4), respectively. The total fractional correction a (the ratio of the above-background to the electron signal before continuum subtraction) from 1.1 to 3.0 GeV is $a=(11\pm0.2\pm1.1)\%$. a is left free in the final fit to the B decay spectrum.

The energy resolution is estimated by adding electron showers generated with the EGS Monte Carlo program to real hadronic events and then analyzing them. The detection efficiency, including geometrical acceptance, for electrons with energy greater than 1 GeV is obtained by analyzing LUND Monte Carlo events in which one B meson decays semileptonically. They are $0.126\pm0.001\pm0.003$, $0.126\pm0.002\pm0.008$, and $0.120\pm0.002\pm0.008$ for B decays at the $\Upsilon(4S)$, at the $\Upsilon(5S)$, and for B_s decays at the $\Upsilon(5S)$, respectively.

There are six real sources of high-energy electrons in $\Upsilon(4S)$ and $\Upsilon(5S)$ decays: (1) electrons from $B\rightarrow e\nu X_c$ and $B\rightarrow e\nu X_u$, corresponding to the quark-level processes $b\rightarrow e\nu c$ and $b\rightarrow e\nu u$, (2) semileptonic decays of D mesons from B-meson decays, (3) semileptonic decays of D mesons from continuum $c\bar{c}$ production, (4) $B\rightarrow(\psi,\psi')X\rightarrow e^+e^-X$, (5) $B\rightarrow\tau X\rightarrow eX$, and (6) $B\rightarrow\Lambda_c X\rightarrow eX$. We neglect in the following the $b\rightarrow u$ contribution, which occurs at the 1% level of the semileptonic rate.[4] In order to extract the branching ratios we need to model the spectra due to (1) and (2), and subtract the contribution from (3), which is reduced, but not eliminated, by requiring that the thrust of the event be smaller than 0.83, not including the contribution of the electron. The subtraction of the continuum contribution is done by fitting the electron spectrum taken at continuum energies with a polynomial curve and normalizing by the ratio of integrated luminosities, including the $1/s$ dependence of the cross section. The contribution from (4) is estimated to be $(1.4\pm0.5)\%$ of the observed electrons and is subtracted. The contribution from (5) is estimated to be 1% and is included in the systematic error, and that from (6) is negligible. In order to model the $B\rightarrow e\nu X$ decay spectrum shape, we have used the free-quark model of Altarelli *et al.*[9] (ACCMM) and the form-factor model of Isgur *et al.*[10] (ISGW). The ACCMM model has three parameters: the spectator quark mass m_{sp} ($=m_{u,d}$ for $B_{u,d}$ decays and m_s for B_s decays), the decay quark mass m_c, and p_F, a parameter which describes the Fermi motion of the b quark in the B meson. The spectator quark mass m_{sp} is used, together with p_F, to obtain the off-shell mass of the decaying b quark, $\tilde{m}_b$, satisfying energy and momentum conservation, in terms of the well-known B-meson mass.[11] Since changes in m_{sp} affect $\tilde{m}_b$ and the spectrum in the same way as changes in p_F, we fix the value for $m_{sp}=m_{u,d}$ at 0.15 GeV/c^2 for decays $b\rightarrow e\nu c$, as proposed in Ref. 9. For $m_{sp}=m_s$ we fix the value at 0.30 GeV/c^2. The ISGW model sums the contributions from each exclusive final state. There are no adjustable parameters in this model, except for the overall normalization. The semileptonic decays of D mesons from B decay are modeled using the measured momentum spectrum of secondary D mesons by CLEO at the $\Upsilon(4S)$.[12] The D-meson semileptonic decay is modeled according to the ISGW model.

After subtracting the continuum background, a fit is made to the electron spectrum in the range $1.1<p_e<3.0$ GeV/c using the model predictions for the decay $B\rightarrow e\nu X$ and for the secondary D-meson semileptonic decay. In both of the models considered, two of the parameters in the fit are the branching ratio $B(B\rightarrow e\nu X)$ and the product branching ratio $B(B\rightarrow DX)B(D\rightarrow e\nu X)$. The value of the product branching ratio in the fit is allowed to vary, within errors, around the experimental value of $(9.8\pm1.3)\%$ which was obtained from the measured values for $B(B\rightarrow D^{\pm},D^0,\bar{D}^0,D_s^{\pm}X)$ and $B(D^{\pm},D^0,\bar{D}^0\rightarrow e\nu X)$,[13] and by assuming that the branching ratio $B(D_s^{\pm}\rightarrow e\nu X)=B(D^0\rightarrow e\nu X)$, since the lifetimes of $D_s^{\pm}$ and D^0 are almost the same.[11] Therefore, for the analysis of the $\Upsilon(4S)$ data with the ACCMM model there are five parameters in the fit, m_c, p_F, a, $B(B\rightarrow e\nu X_c)$, and $B(B\rightarrow DX)B(D\rightarrow e\nu X)$, while for the analysis with the ISGW model there are three parameters, a, $B(B\rightarrow e\nu X_c)$, and $B(B\rightarrow DX)\times B(D\rightarrow e\nu X)$. After minimizing χ^2 we find $p_F=0.33\pm0.11$ GeV/c, $m_c=1.50\pm0.11$ GeV/c^2, $a=(11.4\pm1.7)\%$ (in good agreement with the calculated value), and the branching ratios listed in Table I. The systematic error is due to the effects of detection efficiency (2.7%), electroweak radiative corrections[14] (1.5%), energy scale (1%), τ contribution (1%), and the ψ,ψ' contribution (0.5%). Thus, using the fitted value for $B(B\rightarrow e\nu X)$ and $\tau_B=1.18\pm0.11$ ps,[11] we can determine the CKM matrix element from $B(B\rightarrow e\nu X)/\tau_B=|V_{cb}|^2 f(m_b,m_c)$, where $f(m_b,m_c)$ is a weakly model-dependent factor for B-meson semileptonic decay (see Table I). We note that the semileptonic branching ratio is essentially model independent and in agreement with other recent experimental values.[3,4] The measured spectrum and the fit for the ACCMM model is shown in Fig. 1.

Having established our ability to accurately measure

TABLE I. Fitted parameter values for the semileptonic electron spectrum on the $\Upsilon(4S)$ for the ACCMM and ISGW models.

Model	χ^2/N_{DF}	$B(B\to DX)B(D\to e\nu X)$ (%)	$B(B\to e\nu X)$ (%) [a]	V_{cb}
ACCMM	14.7/15	9.8 ± 0.7	$10.0\pm0.4\pm0.3$	0.044 ± 0.004
ISGW	19.8/17	9.5 ± 1.1	$10.0\pm0.4\pm0.3$	0.046 ± 0.007

[a]The first and second errors are statistical and systematic, respectively.

the B-meson semileptonic decay spectrum on the $\Upsilon(4S)$, we can use some of the parameter values obtained from that analysis in the determination of the semileptonic decay spectrum on the $\Upsilon(5S)$. The $\Upsilon(5S)$ data analysis follows the $\Upsilon(4S)$ analysis closely, except for fixing the m_c, p_F, and appropriately scaled down a parameters to the values obtained for the above $\Upsilon(4S)$ analysis, and assuming that the spectator quark mass is $m_{\mathrm{sp}}=m_s=0.3$ GeV/c^2. We have verified that the sensitivity to changes in these parameters is small; a change in m_c, p_F, or a by 1 standard deviation corresponds to changing the semileptonic branching ratio by 1% of its value, and a 30% change in the strange-quark mass only changes the semileptonic branching ratio by 3% of its value. Finally, we must specify the values of the masses of the various B-meson species since unlike the semileptonic branching ratio measured at the $\Upsilon(4S)$ energy, the semileptonic branching ratio for B decays at the $\Upsilon(5S)$ energy must take into account the possibility that B^*, B_s, and B_s^* mesons are produced at that energy. Early CUSB measurements with data taken at center-of-mass energies (W) above the $\Upsilon(4S)$ showed that B^*'s were produced and that $\Delta M(B^*-B)$ could be determined from the $\sim$50-MeV photons from the decays of $B^*\to B\gamma$ (with branching ratio$=1.0$).[15] Furthermore, a detailed study of the resonance structure above the b-flavor threshold using a coupled-channel calculation,[16] which successfully explained the shape of the hadronic cross section as a function of W,[17] predicted that at the $\Upsilon(5S)$ six two-body decay channels, $B\bar{B}$, $B\bar{B}^*+\bar{B}B^*$, $B^*\bar{B}^*$, $B_s\bar{B}_s$, $B_s\bar{B}_s^*+\bar{B}_sB_s^*$, and $B_s^*\bar{B}_s^*$, would be open and suggested that $\Upsilon(5S)$'s decay into strange B pairs $\sim$30% of the time. This prediction is consistent with the results of a recent analysis of data taken at the $\Upsilon(5S)$ energy in an earlier run using CUSB-II, where we found that the favored value for $M(B_s)-M(B)$ was 82.5 or 121 MeV and that $\Delta M(B_s^*-B_s)\approx\Delta M(B^*-B)\approx46$ MeV.[6] Thus we expect there to be contributions from all nonstrange and strange B-meson species at the $\Upsilon(5S)$ energy, and so we must choose values for all six species. The semileptonic branching ratio is not very sensitive to the choice of $M(B_s)-M(B)$ within the range between 50 and 130 MeV; the change is less than 1% of its value. The electron spectrum shape and end point is, however, sensitive to the B-meson masses. To illustrate this, we have chosen values for the $B_{u,d}$, $B_{u,d}^*$, B_s, and B_s^* of 5.279, 5.325, 5.362, and 5.409 GeV, respectively. These values are obtained from our recent measurements of the B-meson hyperfine splitting and B_s-to-B mass splitting.[6] Table II gives results of fitting the electron spectrum under the assumption that only one particular channel contributes (entries 1–6). The semileptonic branching ratios obtained use the ACCMM model only, since the ISGW model does not include other B-meson species [recall that both models give identical results for the $\Upsilon(4S)$ analysis]. The results are consistent with that for B mesons as given in Table I. Notice that for pure $B\bar{B}$ production one expects the end point of the electron spectrum to move to higher energy and to exhibit considerable Doppler smearing because $B_{u,d}$ are the lightest B

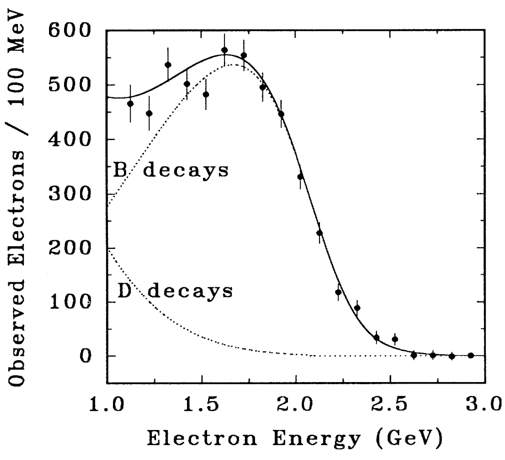

FIG. 1. Electron spectrum observed at the $\Upsilon(4S)$ fit with the ACCMM model. Dotted curves are the B and D decay contributions.

TABLE II. Fits to the electron spectrum at the $\Upsilon(5S)$ for the ACCMM model, assuming $M(B_s)-M(B)=82.5$ MeV.

Final state	p (GeV/c)	β	$B(B\to e\nu X)$ (%) [a]	χ^2/N_{DF}
$B\bar{B}$	1.281	0.236	$9.6\pm0.5\pm0.7$	26.3/14
$B\bar{B}^*+\bar{B}B^*$	1.184	0.218	$9.7\pm0.5\pm0.7$	22.0/14
$B^*\bar{B}^*$	1.076	0.198	$9.7\pm0.5\pm0.7$	18.5/14
$B_s\bar{B}_s$	0.874	0.161	$10.5\pm0.6\pm0.7$	14.7/14
$B_s\bar{B}_s^*+\bar{B}_sB_s^*$	0.714	0.132	$10.4\pm0.5\pm0.7$	15.0/14
$B_s^*\bar{B}_s^*$	0.507	0.093	$10.3\pm0.6\pm0.7$	17.4/14

[a]The first and second errors are statistical and systematic, respectively.

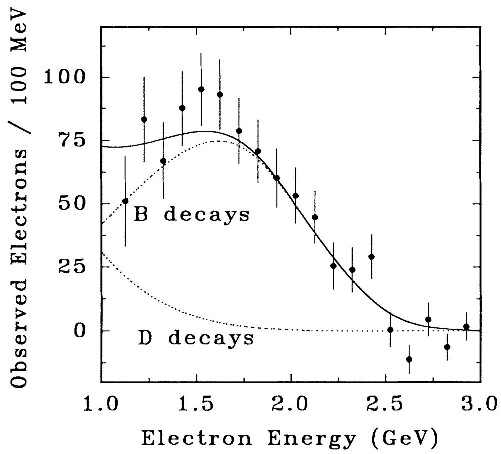

FIG. 2. Electron spectrum observed at the $\Upsilon(5S)$ fit with the ACCMM model for the $B_s\bar{B}_s$ decays. Dotted curves are the B and D decay contributions.

mesons and receive the largest boost. The momentum p and velocity β for each channel are shown in the second and third columns of Table II. As illustration, the result of the fit for the fourth case (pure $B_s\bar{B}_s$ production) is shown in Fig. 2. We note that the values of χ^2, shown in the last column of Table II, computed from the spectrum for electron energy greater than 1.6 GeV, suggest that a relatively small Doppler smearing is favored, corresponding to production of slow B mesons, as would be expected for B_s and/or B_s^* production. Although Table II assumes $M(B_s)-M(B)=82.5$ MeV, the conclusion has been checked to be valid for any choice of $50<M(B_s)-M(B)<130$ MeV.

In conclusion, we have measured the semileptonic branching ratio $B(B\to e\nu X)$, for B-meson decays at the $\Upsilon(4S)$ and the $\Upsilon(5S)$ energies. For the semileptonic decays at the $\Upsilon(4S)$ energy we find a model-independent value for the branching ratio of $(10.0\pm0.4\pm0.3)\%$, leading to a slightly model-dependent value of $|V_{cb}|=0.44\pm0.004$ (ACCMM) or 0.046 ± 0.007 (ISGW). The semileptonic branching ratio at the $\Upsilon(5S)$ energy has been measured under differing assumptions for the B-meson species produced. The branching ratio ranges from 9.6% to 10.5%, and the fits to the spectrum suggest that larger-mass B mesons are produced, providing a further indication of B_s and B_s^* production at the $\Upsilon(5S)$ energy.

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