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STUDIES OF EXCLUSIVE SEMILEPTONIC B DECAYS AT CLEO

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Exclusive semileptonic decays of the B meson provide information about fundamental parameters of the Standard Model and about the nature of meson structure. This paper presents studies of the decays $B \to D\ell\bar{\nu}$, $B \to \pi\ell\bar{\nu}$, and $B \to \rho(\omega)\ell\bar{\nu}$ using data taken with the CLEO detector. The results include measurements of the branching fractions for these processes, of the heavy quark effective theory (HQET) form factor, and of the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$.

Exclusive semileptonic decays of the B meson provide an excellent laboratory for the study of weak and hadronic interactions. They are quite possibly our best source of information about $|V_{cb}|$ and $|V_{ub}|$, CKM matrix elements that are fundamental parameters of the Standard Model, and which govern all of B physics. By measuring the form factors of the exclusive decays, we gain information about QCD, and how mesons are held together. As a consistency check, it is important to measure the branching fractions for all the exclusive modes and to see if they saturate the measured inclusive semileptonic decay rate.

The challenge of the analysis of these decays is not so much finding semileptonic B decays, but distinguishing the various exclusive modes. It is easy enough to find a B decay to a D and a lepton, for instance, but harder to know that the D came directly from the B, and not from a D^* or D^{**} decay. This paper describes two techniques that the CLEO experiment uses to distinguish different modes, and applies them to the decays $B \to D\ell\bar{\nu}$, $B \to \pi\ell\bar{\nu}$, and $B \to \rho(\omega)\ell\bar{\nu}$. These analyses have been described in more detail elsewhere [1,2]; only a summary is given here.

1 Full Reconstruction of $B \to D\ell\bar{\nu}$

One way to distinguish the different exclusive semileptonic decay modes of the B meson is to reconstruct all of the B decay products, including the neutrino. This is done by using information from the entire event, and conservation of momentum and energy, to determine the missing momentum and energy, which is attributed to the neutrino. There is a neutrino consistency requirement of

$E_{\bar{\nu}}^2 - |\vec{p}_{\bar{\nu}}|^2 \approx 0$. Events must be measured nearly perfectly to perform such a full reconstruction, so algorithms are used to remove fake tracks and showers. Events must have only one lepton and a net charge near zero, to reduce the number of missing particles. In clean events, $\sigma_{\vec{p}_{\bar{\nu}}} \approx 100$ MeV/c. Then, since $E_B = E_{beam}$ in $\Upsilon(4S)$ events, a $B \to X\ell\bar{\nu}$ event is reconstructed by requiring the beam constrained mass $M_B = \sqrt{E_{beam}^2 - (\vec{p}_X + \vec{p}_\ell + \vec{p}_{\bar{\nu}})^2}$ to be close to the known B mass, and the energy difference $\Delta E = E_{beam} - E_X - E_\ell - E_{\bar{\nu}}$ to be near zero.

This technique is applied to the decay $B \to D\ell\bar{\nu}$, using 2.63×10^6 $B\bar{B}$ events recorded by the CLEO detector. Both charged and neutral B decays are studied, by reconstructing $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$. Leptons with momenta $0.8 < |p_\ell| < 2.4$ GeV/c are accepted, giving an efficiency of 2.94% for $B^- \to D^0\ell^-\bar{\nu}$ events and 2.63% for $\bar{B}^0 \to D^+\ell^-\bar{\nu}$ events. 252 and 582 events satisfy the full reconstruction cuts for the two decay modes, respectively. The largest background to the $B^- \to D^0\ell^-\bar{\nu}$ events is from feed-down from $B \to D^*\ell\bar{\nu}$ decays; this background is modeled by a Monte Carlo simulation, and is normalized to measured branching fractions. An explicit veto of events containing D^* decays reduces the size of the background. The largest background to $\bar{B}^0 \to D^+\ell^-\bar{\nu}$ events is from fake D^+ formed by random track combinations; this background is modeled in the data by events in the sidebands about the D^+ mass peak. All other backgrounds, including feed-down from $B \to D^{**}\ell\bar{\nu}$ decays, are small. 121.4 ± 17.5 events remain in the $B^- \to D^0\ell^-\bar{\nu}$ sample, and 237.8 ± 27.2 events remain in the $\bar{B}^0 \to D^+\ell^-\bar{\nu}$ sample, where the errors are statistical only. The resulting beam constrained mass distribution is shown in Figure 1, with a Monte Carlo simulation of the signal mode.

Systematic uncertainties are dominated by the neutrino reconstruction process, because the entire detector must be well-modeled for this analysis. The measured branching ratios are

$$\mathcal{B}(B^- \to D^0\ell^-\bar{\nu}) = (2.00 \pm 0.29 \pm 0.47)\% \tag{1}$$

$$\mathcal{B}(\bar{B}^0 \to D^+\ell^-\bar{\nu}) = (1.89 \pm 0.22 \pm 0.35)\%, \tag{2}$$

where the first error is statistical and the second is systematic. Various kinematic distributions for selected events show that they are consistent with the decay $B \to D\ell\bar{\nu}$. The q^2 distribution is used to obtain the decay form factor. The form factor is expressed in terms of the HQET variable $w = \frac{M^2+m^2-q^2}{2Mm}$. Using the parameterization $\mathcal{F}(w) = \mathcal{F}(1)(1-\rho^2(w-1))$, a fit to the data gives

$$|\mathcal{F}(1)V_{cb}| = (3.60 \pm 0.57 \pm 0.42) \times 10^{-2} \tag{3}$$

$$\rho^2 = 0.73 \pm 0.24 \pm 0.10. \tag{4}$$

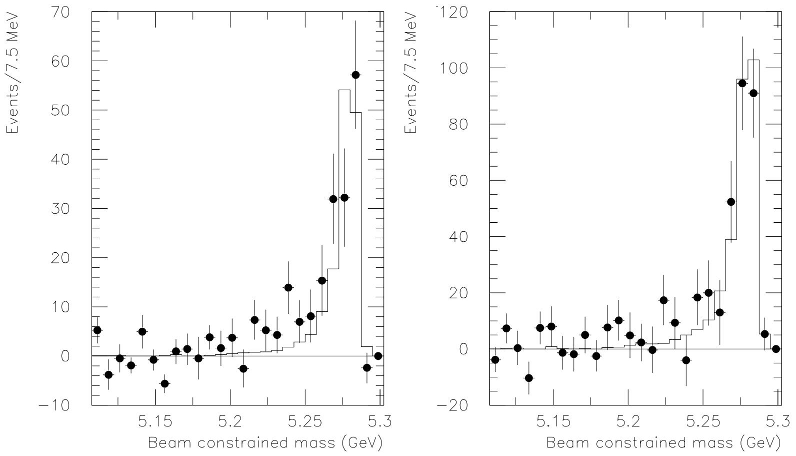

Figure 1: M_B distributions for $B^- \to D^0\ell^-\bar{\nu}$ (left) and $\bar{B^0} \to D^+\ell^-\bar{\nu}$ (right) decays. The points are the data after all background subtractions, and the histogram is the prediction of a Monte Carlo simulation of these decays, normalized to equal area in the signal region.

2 $\bar{B^0} \to D^+\ell^-\bar{\nu}$ via $D - \ell$ Correlations

$B \to D\ell\bar{\nu}$ decays can also be studied by examining only the D and the lepton. This allows for larger selection efficiency and less dependence on detector simulation, since cleanliness cuts for full reconstruction are not necessary. However, because less information is used, the backgrounds are substantially larger. As a result, this technique is only useful for $\bar{B^0} \to D^+\ell^-\bar{\nu}$ with $|p_\ell| > 1.4$ GeV. In this analysis the B momentum, which is about 320 MeV/c, is assumed to be zero. $\bar{B^0} \to D^+\ell^-\bar{\nu}$ events are distinguished from other semileptonic decays through the the missing mass squared,

$$\begin{aligned} MM^2 &= E_{\bar{\nu}}^2 - \vec{p_{\bar{\nu}}}^2 & (5) \\ &\approx (E_{beam} - (E_{D^+} + E_{\ell^-}))^2 - |\vec{p}_{D^+} + \vec{p}_{\ell^-}|^2, & (6) \end{aligned}$$

which peaks at zero for real $\bar{B^0} \to D^+\ell^-\bar{\nu}$ events. The approximation comes from the assumption that the B is at rest. For form factor studies, w is also estimated, using the constraint $MM^2 = 0$.

The largest background by far in this analysis is combinatoric. This is handled by fitting the $M_{K\pi\pi}$ distribution in 360 small regions of MM^2 and w. 3101 ± 143 events are found in the resulting D mass peaks. Other backgrounds are represented in Figure 2. The largest of these is feeddown from $B \to D^{*+}X\ell^-\bar{\nu}$, which is modeled with events in the data. The rate for $B \to D^{**}\ell\bar{\nu}$

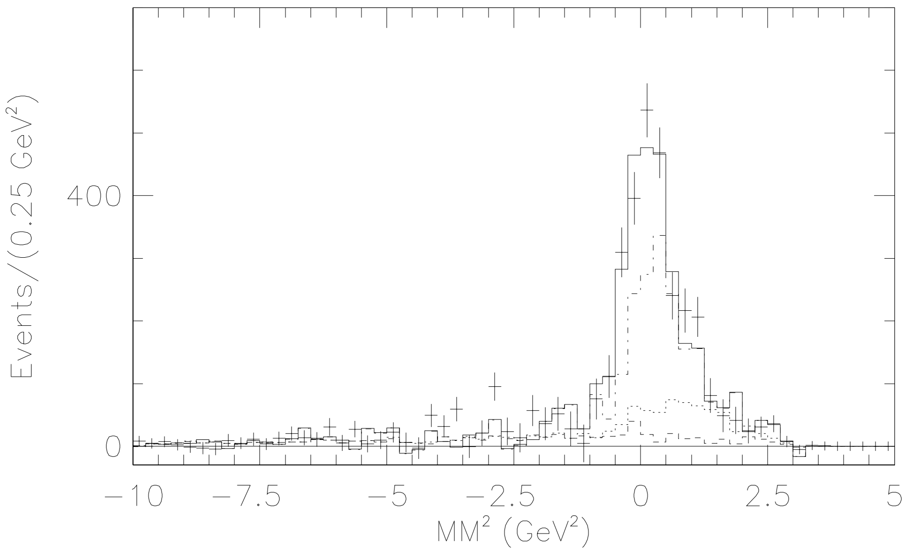

Figure 2: The MM^2 distribution summed over q^2 for all $\ell^- D^+$ events in data. The dashed line is the sum of the contributions from uncorrelated background and fake leptons, the dotted line includes the $D^+ X \ell^- \bar{\nu}$ background, the dot-dash line includes the $D^{*+} X \ell^- \bar{\nu}$ background, and the solid line includes the result of the fit for the signal yield. The contribution from the continuum has been subtracted.

background that feeds down to $B \to D^+ X \ell \bar{\nu}$ is unknown; its shape is modeled by a Monte Carlo simulation, and the normalization is determined by a fit of the MM^2 distribution in each w bin. The final yield of $\bar{B}^0 \to D^+ \ell^- \bar{\nu}$ is 867 ± 194 events. As a result,

$$\mathcal{B}(\bar{B}^0 \to D^+ \ell^- \bar{\nu}) = (1.75 \pm 0.25 \pm 0.20)\% \tag{7}$$

$$|\mathcal{F}(1) V_{cb}| = (3.25 \pm 0.60 \pm 0.53) \times 10^{-2} \tag{8}$$

$$\rho^2 = 0.52 \pm 0.29 \pm 0.10. \tag{9}$$

The results of the two $\bar{B}^0 \to D^+ \ell^- \bar{\nu}$ analyses are entirely consistent. They can be averaged, assuming that all statistical errors are uncorrelated, and all systematic errors are correlated, yielding

$$\mathcal{B}(\bar{B}^0 \to D^+ \ell^- \bar{\nu}) = (1.78 \pm 0.20 \pm 0.24)\% \tag{10}$$

$$|\mathcal{F}(1) V_{cb}| = (3.46 \pm 0.42 \pm 0.46) \times 10^{-2} \tag{11}$$

$$\rho^2 = 0.64 \pm 0.18 \pm 0.10. \tag{12}$$

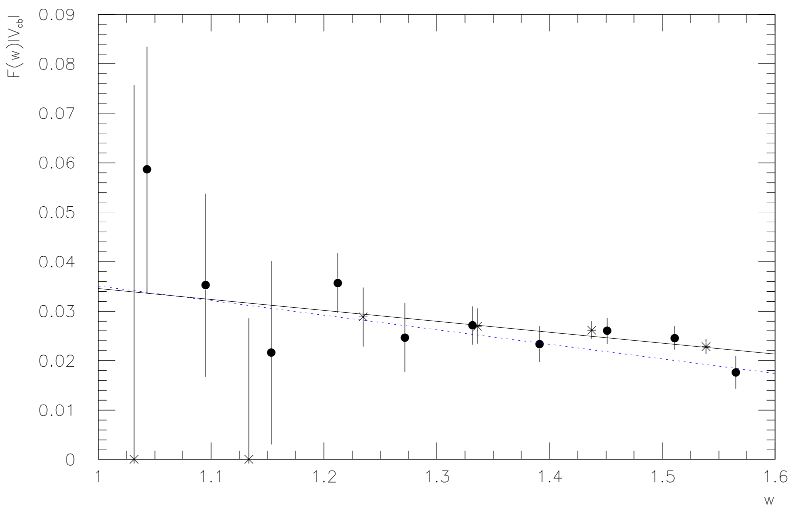

Figure 3: Measured values of $|\mathcal{F}(w)V_{cb}|$ with the results from the full reconstruction analysis (solid dots) and the missing mass analysis (asterisks) with the combined results shown as the solid line. The dashed line denotes $\mathcal{F}(w)$ as measured in $B \to D^*\ell\nu$ decays.

Figure 3 shows the measured values of $|\mathcal{F}(w)V_{cb}|$ from the two analyses, the form factor extracted, and the results of the CLEO analysis of $B \to D^*\ell\bar{\nu}$ decays. The similarity of the two form factor shapes is in agreement with the predictions of HQET.

This measurement provides a largely model-independent measurement of $|V_{cb}|$, because $\mathcal{F}(1)$ is expected to be very close to one. Using a value of $\mathcal{F}(1) = 0.98 \pm 0.07$ [3],

$$|V_{cb}| = (3.53 \pm 0.46 \pm 0.44 \pm 0.25) \times 10^{-2} \tag{13}$$

where the errors are statistical, systematic, and theoretical, respectively.

3 $B \to \pi/\rho/\omega\ell\bar{\nu}$ and $|V_{ub}|$

The full reconstruction technique is also used to study $b \to u$ semileptonic decays. The procedure is analogous to that for $B \to D\ell\bar{\nu}$ decays, with somewhat tighter lepton momentum cuts and smaller efficiencies. The background is dominated by $b \to c$ decays, but there is also background from crossfeed among the various $b \to u$ modes that are being measured. To extract the yields, the $\Delta E - M_B$ distribution is fit to a sum of Monte Carlo-derived shapes

Table 1: $|V_{ub}|$ for each model considered. Third errors, where given, arise from the model's estimated form-factor uncertainties. See Reference 2 for a description of the models.

Model	ISGW II	WSB	KS
$\lvert V_{ub}\rvert$	$3.4 \pm 0.2^{+0.3}_{-0.4}$	$2.9 \pm 0.2^{+0.3}_{-0.3}$	$2.2 \pm 0.1^{+0.2}_{-0.3}$
Model	Melikhov	Hybrid	
$\lvert V_{ub}\rvert$	$4.0 \pm 0.2^{+0.35}_{-0.5} \pm 0.5$	$3.1 \pm 0.2^{+0.3}_{-0.4} \pm 0.5$	

for the signal modes, $b \to c$ background, crossfeed amongst the modes, and feeddown from higher mass $B \to X_u \ell \bar{\nu}$ modes. The rates for five modes are simultaneously extracted in a single fit, giving a consistent treatment of signal and crossfeed rates. Isospin constraints are used to reduce the number of free parameters in the fit. For the $B \to \rho \ell \bar{\nu}$ and $B \to \omega \ell \bar{\nu}$ modes, information from the $\pi\pi$ and 3π mass spectra is introduced into the fit.

A projection of the fit on the M_B axis for the $\Delta E \approx 0$ region is shown in Figure 4. While $b \to c$ background dominates, there are clear peaks at the B mass, and the data are well-represented by the fit components. The resulting branching fractions are

$$\begin{aligned} \mathcal{B}(\bar{B}^0 \to \pi^+ \ell^- \bar{\nu}) &= (1.8 \pm 0.4 \pm 0.3 \pm 0.2) \times 10^{-4} \qquad (14) \\ \mathcal{B}(\bar{B}^0 \to \rho^+ \ell^- \bar{\nu}) &= (2.5 \pm 0.4^{+0.5}_{-0.7} \pm 0.5) \times 10^{-4}, \qquad (15) \end{aligned}$$

where the errors are statistical, systematic, and model dependence, respectively. A significant number of leptons are observed with momenta beyond the $b \to c$ endpoint, ensuring that these are $b \to u$ decays. Studies indicate that the contribution to $B \to \rho \ell \bar{\nu}$ from non-resonant $\pi\pi\ell\bar{\nu}$ final states is less than 20%; this is reflected in the systetmatic error, which is dominated by uncertainties in the neutrino detection process.

There is an error due to model dependence because different models result in different efficiencies. A wide range of models is used to estimate the spread in the results. This is particularly important for the measurement of $|V_{ub}|$. Here, fits are done within each model, fixing the ρ/π ratio to that predicted by the model. Table 1 gives values of $|V_{ub}|$ extracted from the various models. The average result is

$$|V_{ub}| = (3.3 \pm 0.2^{+0.3}_{-0.4} \pm 0.7) \times 10^{-3}, \qquad (16)$$

where the model dependence uncertainty is again found by varying the models used. This uncertainty dominates the errors on V_{ub}.

CLEO has used these exclusive semileptonic decays to extract fundamental parameters of the Standard Model and to study the structure of B mesons.

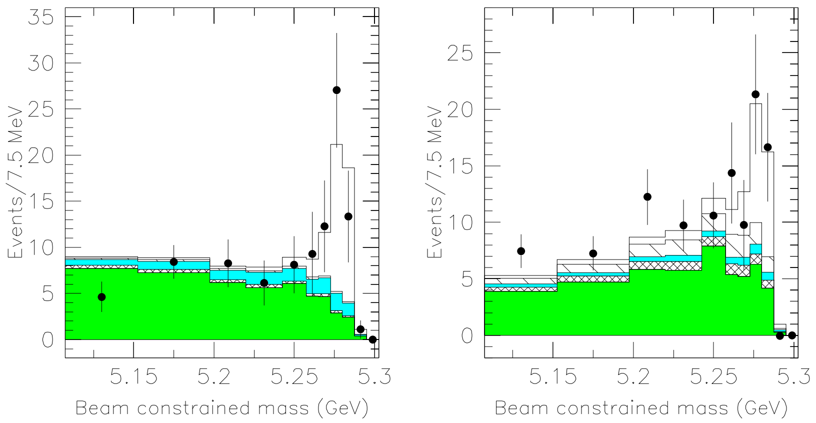

Figure 4: The M_B mass distributions in the ΔE signal band for the combined π modes (left) and the combined vector modes (right). The points are the data after continuum and fake background subtractions; the dark shaded, cross-hatched and unshaded histograms are $b \to cX$, $b \to u\ell\nu$ feeddown, and signal respectively. For the π (vector) modes, the light-shaded and hatched histograms are $\pi \to \pi$ (vector $\to$ vector) and vector $\to \pi$ ($\pi \to$ vector) crossfeed, respectively. The histogram normalizations are from the nominal fit.

Another two million $B\bar{B}$ events wait to be analyzed, and should provide even more insights on these topics.

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References

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