B MESON DECAYS: RECENT RESULTS FROM CLEO

S.P. PAPPAS
California Institute of Technology, 1200 East California Boulevard,
Pasadena CA, USA

The CLEO Collaboration has extracted improved values of $|V_{cb}|$ and $|V_{ub}|$ from measurements of exclusive and inclusive decays of $B$ mesons. The measurement of $B \rightarrow D^{*}\ell\nu$ at zero recoil combined with the predicted form factor $F_{D^{*}}(w_{\text{min}})$ yields $|V_{cb}|$. The photon energy spectrum in $b \rightarrow s\gamma$ and the hadronic recoil mass spectrum in $B \rightarrow X_{c}\ell\nu$ determine non-perturbative HQET parameters used with inclusive $b \rightarrow c$ and $b \rightarrow u$ rates to obtain $|V_{cb}|$ and $|V_{ub}|$.

1 Introduction

Decays of $B$ mesons provide a window into flavor physics, measuring CKM matrix unitarity and $CP$ violation. The CKM matrix elements $V_{cb}$ and $V_{ub}$ can be measured directly via $B$ meson decays (event yield is proportional to $V_{cb}$ or $V_{ub}$), and the elements $V_{ts}$ and $V_{td}$ indirectly via $B$ mixing. At CLEO, $B$ mesons are produced almost at rest, so mixing is not accessible (hence neither is $V_{ts}$ nor $V_{td}$). However, CLEO can measure $V_{ub}$ and $V_{cb}$ well via semi-leptonic decays of $B$ mesons. We present results from exclusive and inclusive semi-leptonic branching fractions.

In exclusive decays we reconstruct final states and use form factors from Heavy Quark Effective Theory (HQET)\(^{1,2}\) to extract the underlying CKM element. In inclusive decays we assume quark hadron duality, summing over the final states. Again, HQET provides the decay dynamics but requires inputs accounting for non-perturbative effects.

2 The CLEO Experiment

The CLEO experiment (described extensively elsewhere\(^{3-5}\)) is located at Cornell University in Ithaca, New York, USA. It is built around the CESR $e^{+}e^{-}$ storage ring operating at a center of mass energy of 10.58 GeV. Data is taken 2/3 at the $\Upsilon(4S)$ resonance and 1/3 continuum just below the resonance. The CLEO II (initial) and CLEO II.V (upgraded) detectors yielded respectively 1/3 and 2/3 of the total 13.5 fb\(^{-1}\) luminosity used in these analyses.

3 Exclusive $B \rightarrow D^{*}\ell\nu$

The $B \rightarrow D^{*}\ell\nu$ analysis measures the decay rate in the zero recoil limit where HQET makes precise predictions for the $B \rightarrow D^{*}$ form factor $F_{D^{*}}(w)$ ($w = v_{B}\mu v_{D^{*}\ell\nu}$, equivalent to $q^{2}$). Accounting for phase space and spin physics ($\Phi(w)$), the transition rate is:

$$\frac{dT}{dw} = \frac{G_{F}^{2}}{48\pi^{2}}|V_{cb}|^{2}|F_{D^{*}}(w)|^{2}\Phi(w)$$

(1)
Zero recoil is at \( w_{\text{min}} = 1 \) where the \( D^* \) is stationary relative to the \( B \). For infinite heavy quark masses, the \( b \to c \) transition does not disturb the light quarks, so \( F_{D^*}(w) \equiv 1 \). For finite quark masses, HQET provides corrections: \( F_{D^*}(w_{\text{min}}) = 0.913 \pm 0.042 \).

The \( D^* \) is reconstructed and combined with the lepton and the beam energy to yield the decay missing mass in terms of the angle between the \( B \) and \( D^* \ell \) momenta. Assuming a missing neutrino, the decay angle \( \cos \theta_{BD^*\ell} \propto \vec{p}_B \cdot (\vec{p}_{D^*} + \vec{p}_\ell) \) can be calculated. For non-signal decays this will fall outside \([-1,1]\), distinguishing them from signal.

We reconstruct charged and neutral modes, bin the yield in \( w \) and \( \cos \theta_{BD^*\ell} \), and correct by \( \Phi(w) \). This is fit to a polynomial form with slope and curvature related to dispersion relations fit to a polynomial form with slope and curvature related to dispersion relations. For finite \( B \) contributions, the fraction of the total branching fraction: \( \Delta B \) for charged and neutral modes of \( B \to D^* \ell \nu \). The curve is the fit yielding \( |V_{ub}|^2 F_{D^*}(1)^2 \).

\[
|V_{ub}| = (46.4 \pm 1.4 \pm 2.0 \pm 2.1) \times 10^{-3}
\]

Work is also underway to reconstruct exclusive \( b \to u \) transitions, relating \( |V_{ub}| \) to branching fractions for \( B \to \pi \ell \nu \) and \( B \to (\rho/\omega) \ell \nu \). Improved \( |V_{ub}| \) results are expected by summer.

\section*{4 \( |V_{ub}| \) from Lepton End Point}

The simplest measurement of \( |V_{ub}| \) counts events near the lepton momentum end point, which can only be populated by \( b \to u \) decays. Predicting the rate in the end point region is complicated by the kinematics of the bound state \( b \) quark, but these effects can be related to \( b \to s \gamma \) decays via a shape function \( |V_{ub}| \). Extrapolating from the end point to the total spectrum yields \( |V_{ub}| \).

We suppress continuum and other backgrounds by neural net and subtract them, then measure the end point branching fraction: \( \Delta B_{2.2-2.6 \text{GeV}} = (2.30 \pm 0.15 \pm 0.35) \times 10^{-4} \). The fraction of the total branching fraction in this region is \( f_{u}(p)_{2.2-2.6 \text{GeV}} = 0.130 \pm 0.024 \pm 0.015 \), yielding a total rate \( B_{ub} = (1.77 \pm 0.29 \pm 0.38) \times 10^{-3} \). We obtain \( |V_{ub}| \) (Fig. 3):

\[
|V_{ub}| = (3.06 \pm 0.08 \pm 0.08) \times 10^{-3} \times \sqrt{(B_{ub}/0.001) \cdot (1.6 \text{ ps/}\tau_B)}
\]

with uncertainties from \( \Delta B, f_{u}(p), V_{ub} \) from \( B_{ub} \) (theory), and the shape function.

\section*{5 Extracting non-perturbative HQET Parameters}

The inclusive semi-leptonic decay rate of \( B \) mesons to charmed states in HQET is

\[
\Gamma(B \to X_c \ell \nu) \propto \frac{G_F^2 m_B^5}{192 \pi^3 |V_{cb}|^2} \left[ 1 + \left( \frac{\bar{\Lambda}}{m_B} \right) + \left( \frac{\lambda_1, \lambda_2}{m_B^2} \right) + O \left( \frac{1}{m_B^3} \right) \right] + \text{rad. corr.}
\]

The parentheses represent functional forms depending on non-perturbative quantities \( \bar{\Lambda} \) (kinetic energy of the bound \( b \) quark), and \( \lambda_2 \) (hyperfine splitting, \( m_{B^*} - m_B \)), and inverse powers of \( m_B \). They cannot be calculated ab initio, but are universal. \( \bar{\Lambda} \) and \( \lambda_1 \) can be measured in \( b \to s \gamma \) and \( b \to c \ell \nu \) decays and applied via Eq. 3 to extract \( |V_{cb}| \).
5.1 $b \to s \gamma$ Photon Energy Moments

Initially, $b \to s \gamma$ decays were studied to seek non Standard Model physics. Current branching fractions agree with S.M. predictions \cite{1,2,3} and no CP asymmetry is observed, so the decay is now used to measure $\bar{\Lambda}$. The moments $\langle E_\gamma \rangle$ and $\langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2$ of the inclusive $b \to s \gamma$ photon spectrum are naively $m_b/2$ and $E_{\text{h,kin}}$, determining $\bar{\Lambda}$ and $\lambda_1$. However, only the expansion of $\langle E_\gamma \rangle$ converges.

We isolate the $b \to s \gamma$ signature \cite{4} by suppressing and subtracting three orders of magnitude larger backgrounds (continuum and $B \bar{B}$ decays). A neural net combines event shape, lepton identification, and pseudo reconstruction into a signal probability yielding the $\gamma$ spectrum (Fig. 3) with moments: $\langle E_\gamma \rangle = 2.364 \pm 0.032 \pm 0.011 \text{GeV}$ and $\langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2 = 0.226 \pm 0.066 \pm 0.0020 \text{GeV}^2$. HQET relates these \cite{5,6} to $\bar{\Lambda}$ ($M_H$ is $M_D$ or $M_B$):

$$\langle E_\gamma \rangle = \frac{M_B}{2} \left[ 1 - 0.385 \frac{\alpha_s}{\pi} - 0.620 \beta_0 \left( \frac{\alpha_s}{\pi} \right)^2 - \frac{\bar{\Lambda}}{M_B} \right] - 1.175 \beta_0 \left( \frac{\alpha_s}{\pi} \right)^2 + \mathcal{O}(1/M_H^3) \quad (5)$$

5.2 $b \to c\ell\nu$ Hadronic Mass Moments

An HQET expansion \cite{7,8} relates the moment $\langle M^2_{X_{c}} \rangle$ of the hadronic recoil mass in $b \to c\ell\nu$ decays to $\bar{\Lambda}$ and $\lambda_1$. (The second moment, $\langle (M^2_{X_{c}} - M^2_{D})^2 \rangle$, again does not converge). Measuring these decays \cite{9} and $\bar{\Lambda}$ uses neutrino reconstruction techniques pioneered by CLEO \cite{10}.

Neutrino reconstruction relies on detector hermiticity and careful modelling of energy flow. We sum the kinematics of all particles in the event, and use event charge, lepton count, and the invariant mass of the inferred neutrino to ensure the measurement precisely reflects the kinematics of the semi-leptonic decay. The hadronic recoil system is calculated from the $B$, $\ell$, and $\nu$ kinematics, neglecting the (small) term $p_B \cdot \vec{p}_\ell$.

The recoil mass spectrum is fit to three components (Fig. 4): $B \to D \ell \nu$, $B \to D^* \ell \nu$, and $B \to X_H \ell \nu(D^{**}$, etc.) and non-resonant). From this we measure \cite{11} $\langle M^2_{D} - M^2_{D} \rangle = 0.251 \pm 0.023 \pm 0.062 \text{GeV}^2$ and $\langle (M^2_{X_{c}} - M^2_{D})^2 \rangle = 0.639 \pm 0.056 \pm 0.178 \text{GeV}^4$

Combining the results of $b \to s \gamma$ and $b \to c\ell\nu$ measurements we obtain simultaneous constraints on $\bar{\Lambda}$ and $\lambda_1$. We perform a fit (Fig. 5), yielding \cite{12}:

$$\bar{\Lambda} = 0.35 \pm 0.07 \pm 0.10 \text{GeV}$$

$$\lambda_1 = -0.238 \pm 0.071 \pm 0.078 \text{GeV}^2 \quad (6)$$

6 $|V_{cb}|$ from Inclusive Semi-Leptonic $B$ Decays

Recalling Eq. 4, we can relate the rate of $b \to c$ semi-leptonic decays to $|V_{cb}|$. The rate has been measured via a two lepton tag technique \cite{13} and is corrected for $b \to u$ to extract $\mathcal{B}(B \to
$X_{c\ell \nu} = (10.39 \pm 0.46)\%$. Using the measured admixture fraction $f_{+} / f_{00} = 1.04 \pm 0.08$ and the lifetimes ($\tau_{B^+} = (1.548 \pm 0.032) \text{ps}$ and $\tau_{B^0} = (1.653 \pm 0.028) \text{ps}$) we determine $\Gamma_{sl} = (0.427 \pm 0.020) \times 10^{-10} \text{MeV}$, finally yielding $|V_{cb}|$ via measured $\bar{\Lambda}$, $\lambda_1$, and $\lambda_2$:

$$V_{cb} = (40.4 \pm 0.9 \pm 0.5 \pm 0.8) \times 10^{-3} = (40.4 \pm 1.3) \times 10^{-3}$$

(7)

This result has an error of only 3.2%, making it the most precise determination of $|V_{cb}|$ to date.

Acknowledgments

The author would like to thank the researchers at CLEO and CESR for providing such remarkable data and analyses as well as the agencies DOE and NSF for funding this research. Thanks also to the organizers of the XXXVII Rencontres de Moriond for a wonderful conference and environment to study and discuss physics.

References

1. N. Isgur, M.B. Wise, Phys. Lett. B 232, 113 (1989); Phys. Lett. B 237, 527 (1990).
2. M. Neubert, Phys. Rept. 245, 259 (1994).
3. Y. Kubota et al. (CLEO), NIM A320, 66 (1992).
4. T. S. Hill et al. (CLEO), NIM A418, 32 (1998).
5. R. A. Briere in Proc. of the 7th Intl. Symp. on Heavy Flavor Phys., ed. C. Campagnari, World Scientific, 1999, 442.
6. C.G. Boyd, B. Grinstein, and R. Lebed, Phys. Rev. D 56, 6895 (1997).
7. I. Caprini, L. Lellouch, and M. Neubert, Nucl. Phys. B 530, 153 (1998).
8. R.A. Briere et al. (CLEO), CLNS 01/1773, submitted to Phys. Rev. Lett. (2002).
9. I.I. Bigi, M.A. Schifman, N.G. Uraltsev, A.I. Vainshtein, Phys. Rev. Lett. 71, 496 (1993).
10. M.E. Luke, M.J. Savage, M.B. Wise, Phys. Lett. B 345, 301 (1995).
11. A. Ali, C. Greub, Phys. Lett. B 361, 146 (1995).
12. A.L. Kagan, M. Neubert, Eur. Phys. J. C 7, 5 (1999).
13. K. Chetyrkin, M. Misiak, M. M"unz, Phys. Lett. B 400, 206 (1997).
14. S. Chen, et al., Phys. Rev. Lett. 87, 251807 (2001).
15. C. Bauer, Phys. Rev. D 57, 5611 (1998).
16. Z. Ligeti, M.E. Luke, A.V. Manohar, and M.B. Wise, Phys. Rev. D 60, 034019 (1999).
17. A.F. Falk, M.E. Luke, and M.J. Savage, Phys. Rev. D 53, 2491 (1996); Phys. Rev. D 53, 6316 (1996).
18. A.F. Falk and M.E. Luke, Phys. Rev. D 57, 424 (1998).
19. D. Cronin-Hennessy et al. (CLEO), Phys. Rev. Lett. 87, 251808 (2001).
20. J.P. Alexander et al. (CLEO), Phys. Rev. Lett. 77, 5000 (1996).
21. M. Neubert, Phys. Rev. D 49, 4623 (1994); Phys. Lett. B 513, 88 (2001).
22. A.K. Leibovich, I. Low, and I.Z. Rothstein, Phys. Lett. B 486, 86 (2000); Phys. Lett. B 513, 83 (2001).
23. A.H. Hoang, Z. Ligeti, and A.V. Manohar, Phys. Rev. Lett. 82, 277 (1999); Phys. Rev. D 59, 074017 (1999).
24. A. Bornheim et al. (CLEO), CLNS 01/1767, submitted to Phys. Rev. Lett. (2002).
25. B. Barish et al., Phys. Rev. Lett. 76, 1570 (1996).
26. J.P. Alexander et al. (CLEO), Phys. Rev. Lett. 86, 2737 (2001).