Measurement of the Branching Ratio for $B \to D^* l\nu$ and V_{cb}

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On behalf of the CLEO Collaboration

Abstract

Using data collected by the CLEO II experiment at the Cornell Electron Storage Ring (CESR), the branching ratio for the reaction $B \to D^* l\nu$ is determined. We find $\mathcal{B}(\bar{B}^0 \to D^{*+} l\nu) = 4.49 \pm 0.32 \pm 0.39\%$ and $\mathcal{B}(B^- \to D^{*0} l\nu) = 5.13 \pm 0.54 \pm 0.64\%$ assuming equal production of B^+B^- and $B^0\bar{B}^0$ meson pairs at the $\Upsilon(4S)$ resonance. This assumption concerning production is also tested and found to be valid. The branching ratio measurements can be used to determine model dependent values of $|V_{cb}|$. Using measurements of the differential spectrum for this decay, and a method inspired by heavy quark effective theory (HQET), a value for the KM matrix element V_{cb} is determined with minimal model dependence. The value obtained is $|V_{cb}|\xi(1)\eta_A = 0.0351 \pm 0.0019 \pm 0.0018 \pm 0.008$, where $\xi(1)$ is the value of the universal form factor at zero recoil and η_A is a factor (close to unity) which accounts for QCD corrections. Systematic effects and the small model dependence in the final value of V_{cb} are discussed.

1. Introduction

The determination of Cabibbo-Kobayashi-Maskawa matrix elements is one of the central experimental problems in heavy quark physics. The element V_{cb} is the focus of study in this report. This element can be determined from measurements of the branching ratio for inclusive semileptonic decays, as discussed in the contribution of N. Katayama, or from measurements of exclusive semileptonic B decay modes. The measurements of the inclusive semileptonic branching ratio are now quite precise with experimental uncertainty below ($\sim$ 5%) however the conversion of the resulting semileptonic width to $|V_{cb}|$ has a fairly large theoretical uncertainty. Estimates of this uncertainty range from 5% to 20%. By constrast, it is widely believed that measurements of exclusive semileptonic modes can be used to extract $|V_{cb}|$ with smaller theoretical uncertainty. The mode $B \to D^* l\nu$ is preferred experimentally to the mode $B \to D l\nu$ since the addition of the D^* constraint allows the isolation of a large and clean experimental signal. CLEO II can observe clean signals in both $\bar{B}^0 \to D^{*+} l^- \nu$ and $B^- \to D^{*0} l^- \nu$ with $D^* \to D^0 \pi$ and $D^0 \to K^- \pi^+$. The pion from the D^* has a momentum below 225 MeV in the laboratory and is referred to as the slow pion (or π_s).

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2. Determination of the $B \to D^* l\nu$ Branching Ratios

A data sample with an integrated luminosity of 1.55 fb^{-1} recorded on the $\Upsilon(4S)$ resonance is used to obtain the signal. In the decay of the $\Upsilon(4S)$ resonance, B mesons are produced in pairs with momenta of about 330 MeV. **The signal is isolated using the kinematic constraints from production at threshold.** The effective mass of the neutrino in the decay $B \to D^* l\nu$ is given by

$$m_\nu^2 = (E_B - E_{D^*l})^2 - |p_B|^2 - |P_{D^*l}|^2 + 2|p_B||p_{D^*L}|\cos\Theta$$

where (E_B, p_B) is the B meson 4-momentum, (E_{D^*l}, p_{D^*l}) is the sum of the D^* and lepton 4-momenta, and Θ is the angle between the 3-momenta p_{D^*l} and p_B. The first three terms in the expression for m_ν^2 are the missing mass squared, denoted MM^2. The factor multiplying cosΘ will be denoted C. For lepton momenta above 1.4 GeV, correctly reconstructed $B \to D^* l\nu$ decays must lie in a triangular region in the plane of MM^2 and C. A cut on the $D^* - D$ mass difference is imposed, and the D^0 invariant mass spectrum (shown in Figure 1) is fitted to extract the number of B candidates. The largest background is due to combinations of fake D^*s and real leptons. This background is subtracted using the sidebands of the $D^* - D$ mass difference. There is also a small background from random combinations of real D^*s and leptons which can be estimated from data. A small correction for background from non-resonant processes (continuum) and misidentified leptons is also included. The resulting signal yield is due to $B \to D^*(X) l\nu$ events. After removing all backgrounds, we find $376 \pm 27 \pm 16$ $\bar{B}^0 \to D^{*+} l^- \nu$ events and $302 \pm 32 \pm 13$ $B^- \to D^{*0} l^- \nu$ events.

Unlike collider experiments, the background from $B \to D^{**} l\nu \to D^*(\pi) l\nu$ where the (π) from the D^{**} decay is not detected is small. This background is determined by examining D^* lepton combinations with p(lepton) in the range $0.8 - 1.4$ GeV in the portion of C-MM^2 plane which is preferentially populated by $B \to D^{**} l\nu$ decays. We find a modest excess in this region which corresponds to an upper limit of $\mathcal{B}(B \to D^{**} l\nu) < 2.8\%$ at the 95 % confidence level.

Assuming equal production of charged and neutral B meson pairs at the $\Upsilon(4S)$ resonance, and using the CLEO II D and D^* branching fractions, we obtain $\mathcal{B}(\bar{B}^0 \to D^{*+} l\nu) = 4.49 \pm 0.32 \pm 0.39\%$ and $\mathcal{B}(B^- \to D^{*0} l\nu) = 5.13 \pm 0.54 \pm 0.64\%$. The dominant systematic error is due to the uncertainty in the slow pion detection efficiencies.

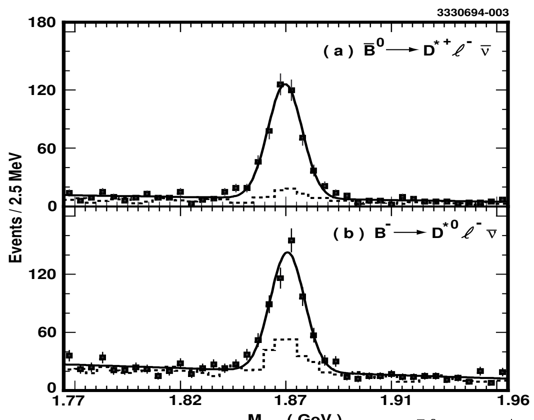

Figure 1. The $M_{K^-\pi^+}$ mass distributions for a) $\bar{B}^0 \to D^{*+} l^- \nu$ and for b) $B^- \to D^{*0} l^- \nu$

By comparing the branching ratios for $\bar{B}^{)} \to D^{*+} l^- \nu$ and $B^- \to D^{*0} l^- \nu$ and using measurements of the ratio of lifetimes from collider experiments, we find that f_{+-}/f_{00} the ratio of the production of B^+B^- and $B^0\bar{B}^0$ meson pairs at the $\Upsilon(4S)$ resonance is $f_{+-}/f_{00} = 1.04 \pm 0.13(stat) \pm 0.12(sys) \pm 0.10$ (lifetime ratio). This confirms to an accuracy of about 15% the initial assumption that the production of charged and neutral B meson pairs are equal. The small value of the $B^+ - B^0$ mass difference, 0.2 ± 0.3 MeV, also supports this conclusion[2].

Using measurements of the B^+ and B^0 lifetimes, and the assumption of isospin invariance, we can combine the two branching fraction measurements to obtain the width $\Gamma(B \to D^* l\nu) = [29.9 \pm 1.9 \pm 2.7 \pm 2.0]$ ns $^{-1}$. This can be translated into a value for $|V_{cb}|$ using the models of Isgur, Scora, Grinstein and Wise (ISGW), Bauer, Stech and Wirbel (BSW), Korner and Schuler (KS) or Neubert. The values obtained for $|V_{cb}|$ are: $0.0348 \pm 0.0011 \pm 0.0016$, $0.0375 \pm 0.0012 \pm 0.0017$, $0.0344 \pm 0.0011 \pm 0.0015$ and $0.0322 \pm 0.0010 \pm 0.0014$ respectively. The detection efficiencies have be determined separately for each model. The variation from this source is about 3%.

3. Extraction of V_{cb} from Differential Decay Spectrum

In the Heavy Quark Effective Theory (HQET), the decay rate for $B \to D^* l\nu$ as a function of y (which is $\gamma_D^* = E_{D^*}/m_{D^*}$ in the B rest frame) can be expressed in terms of a single unknown form factor $\xi(y)$. According to the celebrated result called Luke's theorem [5], at the point of zero recoil for the D^* meson (i.e. $y = 1$), this universal form factor is absolutely normalized up to corrections of order $1/m_Q^2$ (where m_Q is the c quark or b quark mass).

The decay rate

$$d\Gamma/dy = \mathcal{G}(y)\eta_A^2 |V_{cb}|^2 \xi^2(y) \qquad (1)$$

where $\mathcal{G}(y)$ is a known function,$\eta_A = 0.986 \pm 0.006$ accounts for QCD corrections and $\xi(y)$ is the universal form factor. After subtracting background and and correcting for efficiency the experimental distribution of $d\Gamma/dy$ is divided by the factor $\mathcal{G}(y)$ to give a distribution whose intercept is $|V_{cb}|^2\xi^2(1)$. In the limit of heavy quark symmetry, the intercept is the physical quantity of interest, $|V_{cb}|^2$. In principle, the value obtained in this manner has no model dependence.

The $d\Gamma/dy$ distribution is extracted after subtracting backgrounds from fake D^* and random D^* lepton combinations. This distribution is then corrected for efficiency. After dividing through by $\mathcal{G}(\dagger)$ we obtain the distribution shown in Figure 2. Experimentally, since we have poor statistics at the point of zero recoil, we use the available data over the entire y range and extrapolate to $y = 1$. Most of the functional forms proposed for $\xi(y)$ are roughly linear near $y = 1$. Thus the experimental distribution is fitted to the functional form $|V_{cb}|^2(1 - \hat{\rho}^2(y-1))$. After properly accounting for the smearing in y due to the motion of the B meson[3], we obtain:

$$|V_{cb}|\xi(1)\eta_A = 0.0351 \pm 0.0019 \pm 0.0018 \pm 0.008 \quad (2)$$

The first error is statistical. The second error is the experimental systematic uncertainty. The dominant experimental systematic error is the uncertainty in the slow pion detection efficiencies. There is also a significant error from the uncertainty in high energy measurements of the B meson lifetimes which is the third error quoted.

There are two significant uncertainties in the final determination of $|V_{cb}|$. These arise from the model dependence in the calculation of the $1/m_c^2$ corrections to $\xi(1)$ and the lack of knowledge of the functional form of the function $\xi(y)$ which is used for the extrapolation. There are now four calculations of $\xi(1)$ to order $1/m_c^2$ from Neubert [7],[8], Mannel[9] and from Shifman, Uraltsev and Vainshtein[10]. For example, using $\xi(1)\eta_A = 0.97 \pm 0.04$ from Neubert, we obtain $|V_{cb}| = 0.0362 \pm 0.0019 \pm 0.0020 \pm 0.0014$ where the first error is statistical, the second is experimental systematic and the third is error from the quoted uncertainty in $\xi(1)$. Other recent estimates of this product obtained using QCD sum rules are 0.93 ± 0.03[8], 0.96 ± 0.03[9], and 0.89 ± 0.03[10]. The model dependence from the normalization is about 7% but may be reduced in the near future.

We have investigated the uncertainty in the shape of $\xi(y)$ using many of the functional forms proposed in the literature[4]. We find the systematic error from this source is less than 5% in $|V_{cb}|$.

We note that the values of the form factor intercepts obtained by CLEO are consistent with heavy quark symmetry (HQS) at the present level of experimental precision. This supports the hypothesis that deviations from HQS are small.

4. Slope of $\xi(y)$

The universal form factor $\xi(y)$ is a quantity which cannot be derived in pertubation theory. To obtain this function, we must depend on models or on lattice calculations. From the fit to $d\Gamma/dy$ with a linear form, we obtain

$$\hat{\rho}^2 = 0.84 \pm 0.12 \pm 0.08 \quad (3)$$

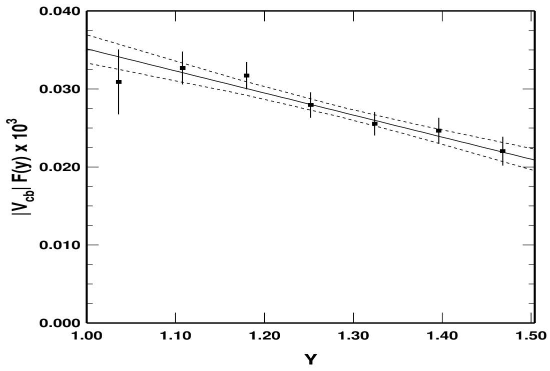

Figure 2. $d\Gamma/dy$ distribution corrected for detection efficiency and kinematic factors.

A fit using a quadratic form for $\xi(y)$ gives slightly different results for $\hat{\rho}^2$. The magnitude of the quadratic term is very poorly determined. The value of $\hat{\rho}^2$ is consistent with most quark models, QCD sum rules, and with lattice calculations.

Note that the quantity $\hat{\rho}^2$ and the quantity ρ^2 discussed in the contribution of Kutschke are slightly different. The former is calculated assuming HQS. An approximate relation between the two values is $\hat{\rho}^2 \approx \rho^2 - 0.1$. The two values agree well.

5. Acknowledgements

I would like to thank Daniela Bortoletto, Persis Drell, Arne Freyberger, Xu Fu, and Maurice Garcia-Sciveres for their contributions to the work described here. I also thank David Cassel, Jeff Richman, and Anders Ryd for informative discussions.

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$$\frac{G_F^2}{48\pi^3} m_{D^*}^3 (m_B - m_{D^*})^2 \times \sqrt{y^2-1}[4y(y+1)\frac{1-2yr+r^2}{(1-r)^2} + (y+1)^2] \quad (4)$$

where $r = m_{D^*}/m_B$.
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