MEASUREMENT OF THE $\bar{B} \to D^* \ \ell^- \ \bar{\nu}$ BRANCHING FRACTIONS AND $|V_{cb}|$

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ABSTRACT

Using the CLEO II detector, we have made new measurements on the $\bar{B}^0 \to D^{*+} \ \ell^- \ \bar{\nu}$ and $B^- \to D^{*0} \ \ell^- \ \bar{\nu}$ branching fractions. The product of the CKM matrix element $|V_{cb}|$ times the normalization of the decay form factor at the point of no recoil of the D^* meson is determined. Using theoretical calculations of the form factor normalization we extract a value for $|V_{cb}|$.

1. Introduction

In the framework of the Standard Model of weak interactions the elements of the 3×3 Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix must be determined experimentally. The recent development of Heavy Quark Effective Theory (HQET)[1] yields an expression for the $\bar{B} \to D^* \ \ell^- \ \bar{\nu}$ decay rate in terms of a single unknown form factor which, at the point of no recoil of the D^* meson, is absolutely normalized up to corrections of order $1/m_Q^2$ (where m_Q is the b or c quark mass). It is currently believed that these corrections can be calculated with less than 5% uncertainty,[2,3] which would permit a precise determination of $|V_{cb}|$ from the study of $\bar{B} \to D^* \ \ell^- \ \bar{\nu}$ as a function of the recoil of the D^* meson.

We report on new measurements[4] of the branching fractions and differential decay rate for the decays, $\bar{B}^0 \to D^{*+} \ \ell^- \ \bar{\nu}$ and $B^- \to D^{*0} \ \ell^- \ \bar{\nu}$. The CKM matrix element $|V_{cb}|$ is extracted from fits to the differential decay rates.

2. Event Reconstruction

The data used in this analysis were produced at the Cornell Electron-positron Storage Ring (CESR) and recorded with the CLEO II detector.[5] The signal comes from an integrated luminosity of 1.55 fb^{-1} collected at the $\Upsilon(4S)$ center-of-mass energy. An additional 0.69 fb^{-1} of data collected below the $B\bar{B}$ production threshold are used for continuum background determination.

For this analysis we select hadronic events that have at least one track identified as a lepton(e or μ) with momentum $1.4 \leq |\mathbf{p}_\ell| \leq 2.4$ GeV. All identified electrons must spatially match a cluster of energy in the CsI calorimeter of approximately equal energy to the measured momentum. All identified muons must penetrate at least 5 nuclear

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absorption lengths of the muon chamber. Both electrons and muons must lie within the angular region $|\cos\theta_l| < 0.71$, where θ_l is the polar angle from the beam axis. The ratio of the second to the zeroth Fox-Wolfram moments[6] of the event is required to be less than 0.4 to suppress background from continuum events. For each lepton in these events we search for D^0 candidates in the decay mode $D^0 \to K^-\pi^+$ using charge correlation with the lepton to make unambiguous mass assignments (the lepton and kaon charges must be the same).

D^0 candidates are combined with pion candidates to fully reconstruct D^* mesons in the two modes $D^{*+} \to D^0\pi_s^+$ and $D^{*0} \to D^0\pi_s^0$. Charged pions emitted from D^{*+} are accepted if they lie within the polar angle region $|\cos\theta_{\pi_s^+}| < 0.71$ and have momentum above 65 MeV. Neutral pions emitted from D^{*0} are constructed from pairs of showers in the electromagnetic calorimeter which do not match the projection of any drift chamber track and have an invariant mass within 3σ of the measured π_s^0 mass ($\sigma =$ 5 to 8 MeV, depending on shower energies and polar angles). The momentum of D^* candidates must satisfy $|\mathbf{p}_{D^*}|/\sqrt{E_B^2 - m_{D^*}^2} < 0.5$ to be consistent with B decay.

The 2-D 'missing mass squared' vs. $|\mathbf{p}_{D^*} + \mathbf{p}_\ell|$ distribution is investigated. A signal region is chosen to suppress the $\bar{B} \to D^{**}\ \ell\ \bar{\nu}$ background. The $\bar{B} \to D^{**}\ \ell\ \bar{\nu}$ background that falls within the signal region is estimated using Monte Carlo events generated according to ISGW model. Uncorrelated D^*, ℓ pairs from different B's are corrected from the study of inclusive $\Upsilon(4S) \to D^*$ rate and inclusive $B \to \ell$ rate.

The raw yield of $\bar{B} \to D^*\ \ell\ \bar{\nu}$ events is obtained by fitting the $M_{K\pi}$ distribution after cutting on δ_m and doing a δ_m sideband subtraction, where $\delta_m \equiv M_{K\pi\pi_s} - M_{K\pi}$. We find $376 \pm 27 \pm 16$ * $(302 \pm 32 \pm 13)$ $\bar{B}^0 \to D^{*+}\ \ell^-\ \bar{\nu} (B^- \to D^{*0}\ \ell^-\ \bar{\nu})$ raw signal events, as shown in Fig. 1, where the dashed lines are scaled δ_m sidebands.

The detection efficiencies for the $\bar{B}^0 \to D^{*+}\ \ell^-\ \bar{\nu}$ and $B^- \to D^{*0}\ \ell^-\ \bar{\nu}$ events are predicted by Monte Carlo simulation to be $[9.54 \pm 0.77(sys.)]\%$ and $[7.18 \pm 0.74(sys.)]\%$

3. Branching Fraction Results

The $\bar{B} \to D^*\ \ell\ \bar{\nu}$ branching fractions can be written as the following,

$$\mathcal{B}(\bar{B}^0 \to D^{*+}\ \ell^-\ \bar{\nu}) = \frac{N_0}{4N_{\Upsilon(4S)} f_{00} \mathcal{B}_{D^{*+}} \mathcal{B}_{D^0}} \tag{1}$$

$$\mathcal{B}(B^0 \to D^{*0}\ \ell^-\ \bar{\nu}) = \frac{N_-}{4N_{\Upsilon(4S)} f_{+-} \mathcal{B}_{D^{*0}} \mathcal{B}_{D^0}} \tag{2}$$

where $\mathcal{B}_{D^{*+}} \equiv \mathcal{B}(D^{*+} \to D^0\pi^+) = [68.1 \pm 1.0 \pm 1.3]\%$ [7] , $\mathcal{B}_{D^{*0}} \equiv \mathcal{B}(D^{*0} \to D^0\pi^0) = [63.6 \pm 2.3 \pm 3.3]\%$ [7] , $\mathcal{B}_{D^0} \equiv \mathcal{B}(D^0 \to K^-\pi^+) = [3.91 \pm 0.08 \pm 0.17]\%$,[8] $N_0(N_-)$ is efficiency-corrected yield for the $\bar{B}^0 \to D^{*+}\ \ell^-\ \bar{\nu} (B^- \to D^{*0}\ \ell^-\ \bar{\nu})$ events. $N_{\Upsilon(4S)} = (1.65 \pm 0.01) \times 10^6$.

If we assume equal production of charged and neutral meson pairs at the $\Upsilon(4S)$, $f_{+-} = f_{00} = 0.5$, we obtain,

$$\mathcal{B}_{0.5}(\bar{B}^0 \to D^{*+}\ \ell^-\ \bar{\nu}) = [4.49 \pm 0.32 \pm 0.39]\%, \tag{3}$$

$$\mathcal{B}_{0.5}(B^- \to D^{*0}\ \ell^-\ \bar{\nu}) = [5.13 \pm 0.54 \pm 0.64]\%, \tag{4}$$

*Through out this paper, the first error is statistical, the second systematic, the third due to B lifetime. Except otherwise specified.

On the other hand, by assuming $\Gamma(\bar{B}^0 \to D^{*+}\ \ell^-\ \bar{\nu}) = \Gamma(B^- \to D^{*0}\ \ell^-\ \bar{\nu})$, which follows from isospin invariance, and $f_{+-} + f_{00} = 1$, Eqs. (1) and (2) can be combined to give

$$\Gamma(\bar{B} \to D^*\ \ell\ \bar{\nu}) = \frac{1}{4N_{\Upsilon(4S)}\mathcal{B}_{D^0}}\left[\frac{N_0}{\tau_{B^0}\mathcal{B}_{D^{*+}}} + \frac{N_-}{\tau_{B^-}\mathcal{B}_{D^{*0}}}\right]. \quad (5)$$

Using $\tau_{B^0} = [1.53 \pm 0.09]$ps and $\tau_{B^+} = [1.68 \pm 0.12]$ps,[9] yields,

$$\Gamma(\bar{B} \to D^*\ \ell\ \bar{\nu}) = [29.9 \pm 1.9 \pm 2.7 \pm 2.0]\ \mathrm{ns}^{-1}, \quad (6)$$

independent of f_{+-}/f_{00}.

The systematic errors on all the above results are dominated by the uncertainties in reconstructing the π_s^+ from $D^{*+}(5\%)$ and and the π_s^0 from $D^{*0}(8.6\%)$.

4. Determination of $|V_{cb}|$

HQET predicts the differential decay rate for $\bar{B} \to D^*\ \ell^-\ \bar{\nu}$ at heavy quark symmetry limit in term of the Isgur-Wise function $\xi(y)$ with normalization $\xi(1) = 1$, where $y = (m_B^2 + m_{D^*}^2 - q^2)/(2m_B m_{D^*})$. For finite b and c quark masses the corrections necessary to account for the deviation from the heavy quark symmetry limit are absorbed into $\mathcal{F}(y)$. Following Neubert,[10] we write,

$$\frac{d\Gamma}{dy} = \frac{G_F^2}{48\pi^3} m_{D^*}^3 (m_B - m_D^*)^2 |V_{cb}|^2 \mathcal{F}^2(y) \times \sqrt{y^2-1}\left[4y(y+1)\frac{1-2yr+r^2}{(1-r)^2} + (y+1)^2\right], \quad (7)$$

where $r = m_{D^*}/m_B$. The function $\mathcal{F}(y)$[11] can be related to the Isgur-Wise function and correction terms that vanish in the infinite b and c mass limit, $\mathcal{F}(1) = \eta_A \xi(1) + \mathcal{O}\left(\Lambda_{QCD}/m_Q\right)^2$, where η_A is a perturbatively calculable QCD radiative correction and Λ_{QCD} is the QCD scale parameter. Since we want to determine the product $|V_{cb}|\mathcal{F}(y)$,we approximate the unknown function $\mathcal{F}(y)$ with an linear expansion about $y = 1$, $\mathcal{F}(y) = \mathcal{F}(1)\left[1 - \hat{\rho}^2(y-1)\right]$.

The unbinned maximum likelihood method developed by E691[12] in the $D \to K^* l \bar{\nu}$ study is utilized. The likelihood function also contains a Poisson probability factor to determine the normalization for $|V_{cb}|$. The detector acceptance and smearing are taken into account appropriately.

We fit the differential decay distribution of the two decay modes $\bar{B}^0 \to D^{*+}\ \ell^-\ \bar{\nu}$ and $B^- \to D^{*0}\ \ell^-\ \bar{\nu}$ simultaneously by calculating the likelihood of the two modes separately and maximizing their product. The result of the simultaneous fit is shown in Fig. 2, along with the combined data and background level for the $\bar{B}^0 \to D^{*+}\ \ell^-\ \bar{\nu}$ and $B^- \to D^{*0}\ \ell^-\ \bar{\nu}$ modes. From a fit to these data we obtain the most precise measurement to date of $|V_{cb}|\mathcal{F}(1)$ and $\hat{\rho}^2$,

$$\begin{aligned} |V_{cb}|\mathcal{F}(1) &= 0.0351 \pm 0.0019 \pm 0.0018 \pm 0.0008 & (8)\\ \hat{\rho}^2 &= 0.84 \pm 0.12 \pm 0.08, & (9) \end{aligned}$$

independent of f_{+-}/f_{00}.

To extract a value of $|V_{cb}|$ one requires a prediction for $\mathcal{F}(1)$. Using $\mathcal{F}(1) = 0.97 \pm 0.04$[14] we obtain, $|V_{cb}| = 0.0362 \pm 0.0019(stat.) \pm 0.0020(sys., lifetime) \pm 0.0014(theo.)$.

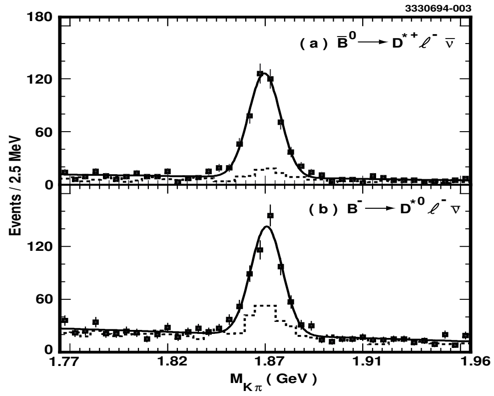

Fig. 1. Raw yield for $\bar{B} \rightarrow D^* \ \ell^- \ \bar{\nu}$ represented by $K^-\pi^+$ invariant mass spectrum.

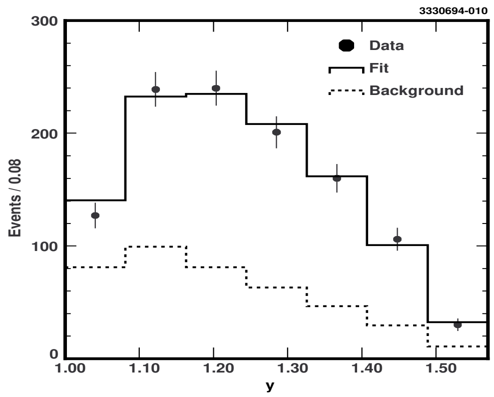

Fig. 2. Raw differential yield for $\bar{B} \rightarrow D^* \ \ell^- \ \bar{\nu}$ overlayed with fits.

The systematic errors propagate in a similar fashion as in the branching fraction measurement. The uncertainties due to the fitting procedure are estimated by comparing the results from the unbinned method with that from a binned method using an analytic smearing form.[13]

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