In the second method, first employed by ARGUS, the $\overline{D}^*$ in $B \to \overline{D}^* \ell^+ \nu_\ell$ decay is identified using only the soft pion from the $\overline{D}^* \to \overline{D}\pi$ decay (partial reconstruction). Due to the small energy release in this process, both the energy and the direction of the $\overline{D}^*$ can be estimated from the soft pion's momentum alone. This technique has a large statistical advantage over the method in which both the $\overline{D}^*$ and the $\overline{D}$ are completely reconstructed.

Although $B \to \overline{D}\ell^+\nu_\ell$ decay has a substantial branching fraction, measurements to date have suffered from poor statistics and the difficulty of dealing with feed-down from $B \to \overline{D}^*\ell^+\nu_\ell$. Several ARGUS and CLEO-I measurements of $B \to \overline{D}\ell^+\nu_\ell$ and $B \to \overline{D}^*\ell^+\nu_\ell$ were extracted using early D and D^* branching fractions, some of which were quite far from their present values. Stone [1] has used more recent D^* and D and branching fractions [25,26] to correct these measurements when possible. The values marked with an asterisk (*) in Table 5 use the same method as Stone but with the updated PDG 1994 $D^0 \to K^-\pi^+$ branching fraction. Together, $B \to \overline{D}^*\ell^+\nu_\ell$ and $B \to \overline{D}\ell^+\nu_\ell$ account for about two-thirds of the inclusive semileptonic rate. There is evidence that part of the remainder is due to $B \to \overline{D}^{**}\ell^+\nu_\ell$ decay, where D^{**} represents a mixture of p-wave and radially excited D mesons.

Searches have also been made for exclusive $B \to X_{\overline{u}}\ell^+\nu_\ell$ decays. For these decays, unlike $B \to X_{\overline{c}}\ell^+\nu_\ell$, model predictions [13] indicate that the rate should be distributed over many exclusive channels, with no dominant modes. The decays with the largest expected branching fractions are $B^0 \to \rho^-\ell^+\nu_\ell$, $B^+ \to \rho^0\ell^+\nu_\ell$, and $B^+ \to \omega\ell^+\nu_\ell$, which in the quark model are predicted to occur in the ratio 2:1:1. Furthermore, these modes should have hard lepton-momentum spectra, so that there is good efficiency for these decays in the endpoint region, where the backgrounds from $B \to X_{\overline{c}}\ell\nu$ are smallest. CLEO has searched for all three modes but has found no significant signals, leading to the upper limits given in Table 5. These limits can be converted into model-dependent upper limits on $|V_{ub}/V_{cb}|$. The limit for the ISGW model (correcting the result to $\tau_B = 1.49$ ps) is $|V_{ub}/V_{cb}| < 0.12$ (90% CL), consistent with the CLEO-II inclusive measurement (using the ISGW model) given in Table 4.

Measurement of $|V_{cb}|$ from $B \to \overline{D}^*\ell^+\nu_\ell$

Three types of measurements can be used to determine $|V_{cb}|$: (1) inclusive semileptonic rate (discussed in Section IV.1), (2) the rates for $B \to \overline{D}\ell^+\nu_\ell$, or (3) $B \to \overline{D}^*\ell^+\nu_\ell$, or a partial rate for $B \to \overline{D}^*\ell^+\nu_\ell$ corresponding to the kinematic configurations in which the D^* recoils slowly. The $B \to \overline{D}^*\ell^+\nu_\ell$ mode is especially well suited to measuring $|V_{cb}|$. Using HQET, the rate for this process can be accurately predicted (as a function of $|V_{cb}|^2$) for the kinematic configuration in which the D^* is produced at rest and the lepton and neutrino are back to back in the B rest frame. This configuration occurs when $q^2 = q^2_{\rm max} = (m_B - m_{D^*})^2$. The light constituents of the initial B meson are then essentially undisturbed by the $B \to X_{\overline{c}}\ell^+\nu_\ell$ transition, at least in the limit where the b and c quark masses are taken to be very large compared with Λ_{QCD}.

In this large-mass limit, all of the $B \to \overline{D}^*\ell^+\nu_\ell$ form factors are related to a single form factor, the Isgur-Wise function, which depends only on the relative four-velocities of the initial and final hadrons: $\xi = \xi(v_B \cdot v_{D^*})$. Note that $v_B \cdot v_{D^*} = \gamma_{D^*}$, where the relativistic factor γ_{D^*} is measured in the B-meson rest frame. The quantity $v \cdot v'$, where v is the initial and v' is the final meson four-velocity, is often called w or y in the literature. It is linearly related to q^2 by

$$w = v \cdot v' = \frac{M^2 + m^2 - q^2}{2Mm} \; , \tag{2}$$

where M and m are the masses of the parent and daughter mesons.

At zero recoil ($w = 1$ or $q^2 = q^2_{\rm max}$), the normalization of ξ is known, $\xi(1) = 1$, which means that the decay rate in this configuration can be accurately predicted as a function of $|V_{cb}|^2$. Corrections to this picture arise from hard gluon corrections and because the masses of the b and c quarks are not truly infinite. However, the heavy quark symmetry limit prediction for $B \to \overline{D}^*\ell^+\nu_\ell$ is protected by Luke's theorem [33], which states that, for this process, there are no leading order $(1/m_Q)$ nonperturbative corrections at $w = 1$, where m_Q is the mass of a heavy quark (c or b). As a consequence, the leading corrections to the decay rate prediction arise at order $1/m_Q^2$. The calculation of these corrections, which introduces some model dependence, has been the subject of many investigations. Neubert [2,34] has obtained the result

$$\frac{1}{\tau_B} \cdot \frac{d\mathrm{B}(B^0 \to D^{*-}\ell^+\nu_\ell)}{dw} = \frac{G_F^2}{48\pi^3} m^3_{D^*} \left(m_B - m_{D^*}\right)^2 \eta_A^2 \sqrt{w^2-1}(w+1)^2 \Big[1 + \frac{4w}{w+1}\frac{1-2wr+r^2}{(1-r)^2}\Big] |V_{cb}|^2 \widehat{\xi}(w)^2 \; , \tag{3}$$

where $r = m_{D^*}/m_B$, $\eta_A = 0.99$, and

$$\widehat{\xi}(1) = 1 + \delta_{(1/m^2)} = 1.00 \pm 0.04 \; . \tag{4}$$

(The values for η_A and $\widehat{\xi}(1)$ are preliminary.) The unknown function $\widehat{\xi}(w)$ is related to $\xi(w)$, as discussed by Neubert [2], but includes symmetry breaking corrections. These predictions can be used to determine $|V_{cb}|$ from the measured rate at zero recoil. Strictly speaking, there is no phase space for this configuration, so in practice one has to measure the rate in a small region near $w = 1$. (A new estimate of the corrections to the heavy-quark symmetry limit by Shifman, Uraltsev, and Vainshtein [19] gives a lower value of $\widehat{\xi}(1)$ and a higher value of $|V_{cb}|$.)