SEMILEPTONIC DECAYS OF B MESONS

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ABSTRACT

CLEO has measured the inclusive B meson semileptonic branching fraction using a number of methods. We measure the average B semileptonic branching fraction from fits to the single lepton spectrum and from a model-independent method using lepton tags. We also measure the B^+ and B^0 semileptonic branching fractions using four tagging methods. Assuming equal semileptonic partial widths, we obtain a value for the ratio of lifetimes.

1. Introduction

The B semileptonic branching fraction* is an interesting quantity because measured values have traditionally been below theoretical expectations. Naive counting of quarks and leptons lead to a branching fraction of $\sim 17\%$. More careful second order QCD calculations predict $\mathrm{Br}(B \to X\ell\nu) \geq 12.5\%$, while the measurements consistently lie below 11%.[1,2]

It is also predicted that the B^+ has a slightly longer lifetime than the B^0 at the 10% level.[2] Assuming that the semileptonic partial widths are equal, this implies that $\mathrm{Br}(B^+ \to X\ell\nu)$ should be larger than $\mathrm{Br}(B^0 \to X\ell\nu)$ to the same degree.

We report two measurements of the average B semileptonic branching fraction in Sections 2 and 3, followed by measurements of the separate charged and neutral B branching fractions and their ratio in Sections 4, 5 and 6.

2. $\mathrm{Br}(B \to X\ell\nu)$ From Single Lepton Spectrum

Fits to the shape of the single lepton spectrum have been the standard method for measuring $\mathrm{Br}(B \to X\ell\nu)$ at the $\Upsilon(4S)$. Figure 1 shows the lepton spectrum observed with 0.94 fb^{-1} of on-resonance data collected by the CLEOII detector at the Cornell Electron Storage Ring. The spectrum is a sum of a primary $B \to X\ell\nu$ and a secondary $b \to c \to Y\ell\nu$ component. A fit to the model of Isgur *et al.*[3] (ISGW) with a floating D^{**} fraction yields $\mathrm{Br}(B \to X\ell\nu) = (10.98 \pm 0.10 \pm 0.33)\%$ for a D^{**} fraction of 21%. With the model of Altarelli *et al.*[4] (ACCMM), a branching fraction of $(10.65 \pm 0.05 \pm 0.33)\%$ is found for $p_f = 230$ MeV/c, $m_c = 1700$ MeV/c^2 and m_{spec} fixed at 150 MeV/c^2.

*Throughout, "semileptonic" is understood to mean "semielectronic" or "semimuonic".

These results are systematics-limited from the uncertainty in the choice of model to extrapolate the primary spectrum to low momentum. Additionally, this method is sensitive to possible non-$B\bar{B}$ decays of the Υ(4S) since the lepton yield is normalized to the number of Υ(4S) decays. Both of these concerns are addressed by using a method employing lepton tags.

3. Br($B \to X\ell\nu$) From Tagged Lepton Spectrum

The semileptonic branching fraction can be measured with little model dependence by using a fast ($p_\ell > 1.4$ GeV/c) lepton as a B tag. Remaining electrons in the event can be separated into primary and secondary spectra by exploiting charge and angular correlations. Only electrons are used so that the primary spectrum can be probed at low momentum. Assuming that the tag lepton is primary, the semileptonic decay of the opposite B will produce an oppositely charged electron, except when $B^0 - \overline{B^0}$ mixing occurs. If the electron is from the semileptonic decay of a charmed particle produced in the decay of the opposite B, then it will be like-sign (again, except for mixing). Finally, electrons from charm decay originating from the same B as the tag lepton will always be unlike-sign. This last contribution can be suppressed using kinematic correlations.

At the Υ(4S), the B's are nearly at rest and there is no angular correlation between particles from opposite B's. However, there is an angular correlation between the tag lepton and electrons from the same B. Unlike-sign electrons are required to satisfy $p_e + \cos\theta_{\ell e} > 1$, where p_e is the electron momentum in GeV/c, and $\theta_{\ell e}$ is the angle between the tag lepton and the electron. This "diagonal" cut in the $p_e - \cos\theta_{\ell e}$ plane suppresses same-B electrons by a factor of 25, while keeping 67% of opposite-B electrons.

Figure 2 shows the unlike and like-sign spectra obtained before a number of backgrounds are subtracted. This analysis was performed using 2.07 fb^{-1} of on-resonance data. Corrections are made for continuum, for either tag leptons or electrons which were misidentified hadrons (fakes), for either tag leptons or electrons from J/ψ, π^0, τ, Λ_c or D_s decays or from γ conversions, for tag leptons from semileptonic charm decay, and for the residual contribution of electrons from the same B. The corrected spectra $N(\ell^\pm e^\mp)$ and $N(\ell^\pm e^\pm)$ are related to the primary $\mathcal{B}(b)$ and secondary $\mathcal{B}(c)$ branching fractions as

$$\frac{dN(\ell^\pm e^\mp)}{dp} = N_\ell \eta(p)\left[\frac{d\mathcal{B}(b)}{dp}(1-\chi) + \frac{d\mathcal{B}(c)}{dp}\chi\right]\epsilon(p), \tag{1}$$

$$\frac{dN(\ell^\pm e^\pm)}{dp} = N_\ell \eta(p)\left[\frac{d\mathcal{B}(b)}{dp}\chi + \frac{d\mathcal{B}(c)}{dp}(1-\chi)\right], \tag{2}$$

where $\eta(p)$ is the efficiency of electron identification and $\epsilon(p)$ is the efficiency of the diagonal cut. N_ℓ is the number of tag leptons and $\chi = f_0\chi_0$ represents the fraction of all Υ(4S) decays with $B^0 - \overline{B^0}$ mixing, approximately 8%.

Figure 3 shows primary and secondary spectra obtained after solving equations (1) and (2). Integrating the primary spectrum from 0.6 to 2.5 GeV/c, and correcting for the (5.8 ± 0.5)% of the spectrum expected to fall below 0.6 GeV/c, we find Br($B \to X e\nu$) = $(10.36 \pm 0.17 \pm 0.40)$%. The solid curve is the fit to the ACCMM model with

p_f, m_c and m_{spec} fixed to the values found in the first method, giving a χ^2 of 28 for 19 d.o.f. For the ISGW model we find a best fit with $\chi^2 = 36$ for 19 d.o.f. for the default D^{**} fraction, and $\chi^2 = 20$ for 19 d.o.f. when the D^{**} is fixed at 21%. Finally, using the ACCMM model to extrapolate the secondary spectrum (dashed curve), we find $\mathrm{Br}(b \to c \to Ye\nu) = (7.7 \pm 0.3 \pm 1.2)\%$ with a χ^2 of 27 for 13 d.o.f.

4. $\mathrm{Br}(B^+ \to X\ell\nu)$

To measure the B^+ semileptonic branching fraction, we examine the yield of fast leptons across from a sample of fully reconstructed B^- decays (charge conjugation implied). CLEO reconstructs B^- and $\overline{B^0}$ in eight different modes: $D^{(*)}\pi^-$, $D^{(*)}\rho^-$, $D^{(*)}a_1^-$, and $K^{(*)}J/\psi$. The summed momenta and energies, $\vec{p}_B$ and E_B, of the decay products are used to construct the beam-constrained mass $M_B = \sqrt{E_{\mathrm{beam}}^2 - |\vec{p}_B|^2}$ and the normalized energy difference between the B and the beam energy $\delta(\Delta E) = (E_{\mathrm{beam}} - E_B)/\sigma(\Delta E)$, where $\sigma(\Delta E)$ is the expected resolution on $E_{\mathrm{beam}} - E_B$. For signal, M_B peaks at the B mass, and $\delta(\Delta E)$ is a gaussian of zero mean and unit width. The $\delta(\Delta E)$ sidebands are used to estimate the background in the M_B distribution. Figure 4(a) shows the M_B distribution for the B^- tags in the $\delta(\Delta E)$ signal (points) and sideband (histogram) regions. We find 834 ± 42 tags using 1.35 fb^{-1} of on-resonance data.

Next, a search is made for a fast ($p > 1.4$ GeV/c) electron or muon elsewhere in the event as a signature of semileptonic decay of the remaining B^+. Only leptons of the expected charge are considered since the flavor of the remaining B is known. Two M_B distributions are formed for events satisfying this additional criterion – one for tags with muons, and one for tags with electrons. Their sum is shown in Fig. 4(b).

The lepton yields must be efficiency-corrected, including the correction for the portion of the primary spectrum below 1.4 GeV/c. We use the ISGW model with $21\% D^{**}$. Assuming lepton universality, we average the semielectronic and semimuonic branching fractions to obtain $\mathrm{Br}(B^+ \to X\ell\nu) = (10.1 \pm 1.8 \pm 1.4)\%$. This is the first measurement of the charged B semileptonic branching fraction.

5. $\mathrm{Br}(B^0 \to X\ell\nu)$

Three measurements are made of $\mathrm{Br}(B^0 \to X\ell\nu)$. The approach is similar to the B^+ measurement, except that additional leptons of either sign are accepted. This eliminates the need for a mixing correction, but requires a small correction for secondary leptons from charm. As before, the electron and muon results are averaged. These results are all obtained with 1.35 fb^{-1} of on-resonance data.

The first measurement uses a sample of fully reconstructed $\overline{B^0}$ tags. The technique has already been described in Section 4. We find 515 ± 31 tags.

Next, partially reconstructed $\overline{B^0} \to D^{*+}\pi^-$, $D^{*+} \to D^0\pi^+$ tags are used. Here, the fast π^- recoils against a slow π^+ and an unseen D^0. The energy of the D^0 is calculated from energy conservation. This fixes the opening angle between the π^+ and the D^0 in the laboratory frame. The azimuthal angle of the D^0 about the slow pion axis is chosen to maximize the apparent B mass. This "pseudomass" must lie in the narrow window between M_{B^0} and E_{beam}. A fit to the pseudomass distribution yields 822 ± 53 tags.

The third measurement utilizes the partially reconstructed tag $\overline{B^0} \to D^{*+}\ell^-\bar{\nu}$, $D^{*+} \to D^0\pi^+$. The ℓ^- must have momentum > 1.8 GeV/c to suppress feed-down from $B^- \to D^{**0}\ell^-\bar{\nu}$. An approximate D^{*+} 4-momentum is calculated from the soft π^+ momentum only. This is possible because the decay of the D^{*+} is slightly above kinematic threshold. With the D^{*+} and ℓ^- 4-momentum, the square of the neutrino mass $\widetilde{M}_\nu^2$ is calculated assuming that the B is at rest, but with energy E_{beam}. Signal populates $\widetilde{M}_\nu^2 = 0$. Figure 5(a) shows the $\widetilde{M}_\nu^2$ distribution, which gives 7119 ± 139 tags. Figure 5(b) is the subset with an additional fast electron or muon.

The results for $\mathrm{Br}(B^0 \to X\ell\nu)$ are $(13.5 \pm 2.6 \pm 1.9)\%, (10.2 \pm 1.9 \pm 1.3)\%$ and $(10.5 \pm 0.8 \pm 1.3)\%$ for the fully reconstructed, the $D^{*+}\pi^-$, and the $D^{*+}\ell^-\bar{\nu}$ tags, respectively. We average the three measurements weighting each by the statistical and uncorrelated systematic errors to obtain $\mathrm{Br}(B^0 \to X\ell\nu) = (10.9 \pm 0.7 \pm 1.1)\%$, using the same model as the B^+ measurement.

6. τ_+/τ_0

If the B^+ and B^0 semileptonic partial widths are assumed to be equal, then the ratio of branching fractions $\mathrm{Br}(B^+ \to X\ell\nu)/\mathrm{Br}(B^0 \to X\ell\nu)$ equals the ratio of lifetimes. Many correlated systematic errors cancel when taking the ratio of branching fractions, giving $\tau_+/\tau_0 = 0.93 \pm 0.18 \pm 0.12$.

7. Conclusions

CLEO has measured the inclusive B meson semileptonic branching fraction using a number of methods. From fits to the single lepton spectrum, we find $\mathrm{Br}(B \to X\ell\nu) = (10.98 \pm 0.10 \pm 0.33)\%$ for the model of Isgur *et al.* where the $B \to D^{**}\ell\nu$ fraction is allowed to float. Using a lepton tag technique with very little model dependence, we find $\mathrm{Br}(B \to X\ell\nu) = (10.36 \pm 0.17 \pm 0.40)\%$. The separate B^+ and B^0 semileptonic branching fractions have also been measured using four tagging methods. We find $\mathrm{Br}(B^+ \to X\ell\nu) = (10.1 \pm 1.8 \pm 1.4)\%$ and $\mathrm{Br}(B^0 \to X\ell\nu) = (10.9 \pm 0.7 \pm 1.1)\%$. This is the first such measurement for the B^+. If the semileptonic partial widths are assumed to be equal, we obtain a lifetime ratio $\tau_+/\tau_0 = 0.93 \pm 0.18 \pm 0.12$.

Although the central value of the lifetime ratio is on the unexpected side of unity, it is consistent with theoretical predictions within errors. However, the measured values for the average B semileptonic branching fraction remain well below 12.5%. In particular, the lepton-tagged result indicates that the discrepancy between theory and experiment is unlikely to be due to uncertainty in the shape of the primary lepton spectrum at intermediate momenta, or from possibilities of non-$B\bar{B}$ decays of the $\Upsilon(4S)$.

References

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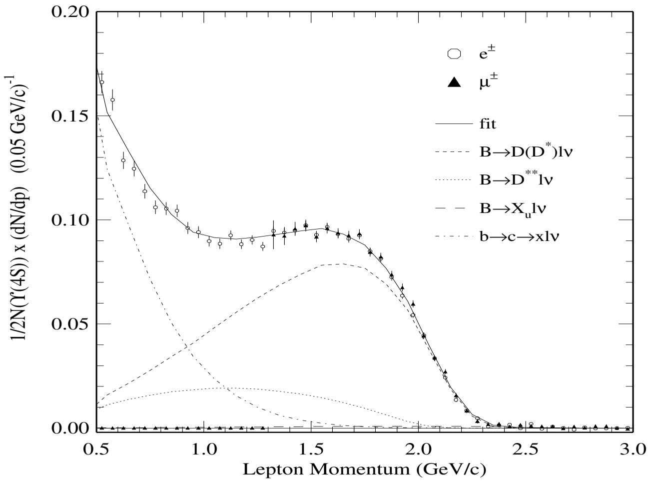

Fig. 1. Fit to the lepton spectrum of the Isgur *et al.* model with a floating D^{**} fraction.

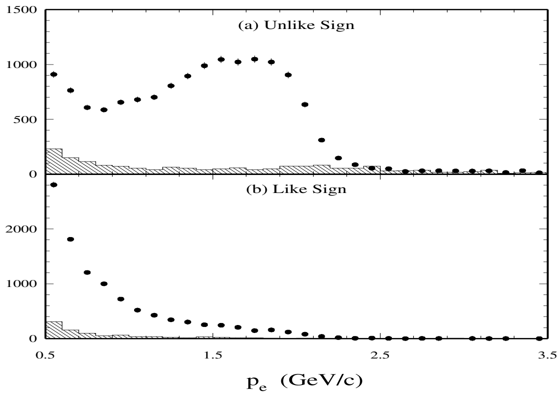

Fig. 2. Raw spectra of electrons of (a) unlike-sign and (b) like-sign relative to tag lepton. The points represent $\Upsilon(4S)$ data and the shaded histograms nearby continuum.

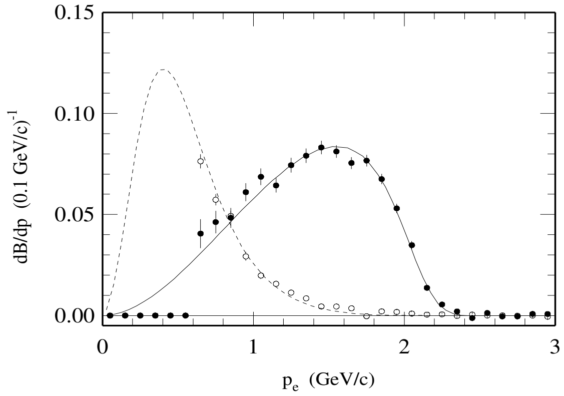

Fig. 3. Spectra of electrons from primary decays (filled circles) and secondary decays (open circles). The curves show fits to the model of Altarelli *et al.*

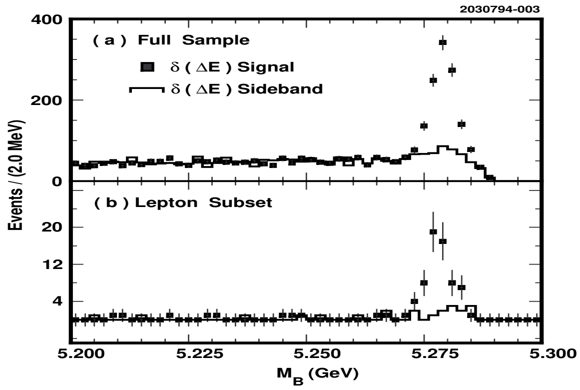

Fig. 4. $B^- \to$ hadrons tags

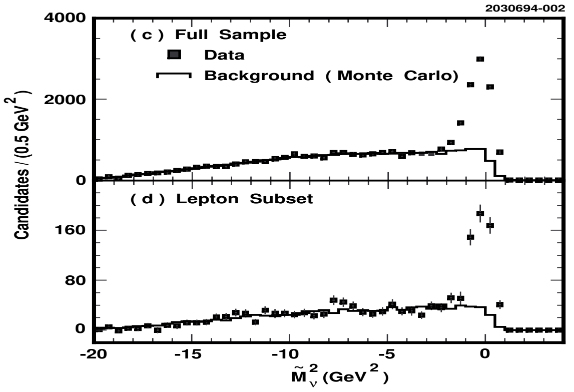

Fig. 5. $\overline{B^0} \to D^{*+}\ell^-\overline{\nu}$ tags