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Study of Inclusive Semileptonic B Meson Decays with the BABAR Detector

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Abstract

This is a brief report on the measurement of the inclusive branching fraction $\mathcal{B}(\overline{B} \to X_c \ell^- \overline{\nu})$ and the preliminary measurement of the first moment of the hadron mass M_X in such decays. The implications of these results on $|V_{cb}|$ are discussed.

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Study of Inclusive Semileptonic B Meson Decays with the BABAR Detector

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This is a brief report on the measurement of the inclusive branching fraction $\mathcal{B}(\overline{B} \to X_c \ell^- \overline{\nu})$ and the preliminary measurement of the first moment of the hadron mass M_X in such decays. The implications of these results on $|V_{cb}|$ are discussed.

1. Introduction

Semileptonic decays have been the topic of a large variety of studies because they are simple theoretically at the parton level, sensitive to the coupling of quarks to the weak charged current, and allow us to probe the impact of strong interactions on the bound quark. Experimentally they are readily accessible, because of the large branching fraction and clear signature in form of a high momentum lepton. The principal goal for B meson is the determination of the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$.

The decay width for inclusive semileptonic B decays to the charm states X_c is

$$\Gamma^c_{SL} \equiv \mathcal{B}(\overline{B} \to X_c \ell^- \overline{\nu})/\tau_B = \gamma_c |V_{cb}|^2, \qquad (1)$$

i.e., $|V_{cb}|$ can be determined from the branching fraction and the lifetime, provided the factor γ_c is known. The theoretical QCD parameter γ_c requires both perturbative and non-perturbative input. In the frame work of Heavy Quark Effective Theory the uncertainties in the estimate of γ_c can be reduced by using information from inclusive measurements, for instance, the moments of the mass of hadrons X_c and/or the moments of the lepton energy spectrum. These inclusive observables can be calculated using expansions in powers of the strong coupling constant $\alpha_s(m_b)$ and in inverse powers of the B meson mass, m_B, that include non-perturbative parameters. At order $1/m_B^2$, there are three parameters, $\bar{\Lambda}$, λ_1, and λ_2. From the $B^* - B$ mass splitting, we have $\lambda_2 = 0.128 \pm 0.010\,\mathrm{GeV}^2$. $\bar{\Lambda}$ and λ_1 calculable with techniques such as lattice QCD.

In the following, we report two measurements performed with the *BABAR* detector [1] operating at the $\Upsilon(4S)$ resonance at the PEP-II energy asymmetric e^+e^- storage ring [2] at SLAC, the semileptonic branching ratio [3] and the first moments of the hadron mass distribution as a function of the lepton momentum [4].

2. Inclusive Semileptonic Branching Ratio

This measurement employs a method introduced by ARGUS [5] and later also used by CLEO [6], in which $B\overline{B}$ events are tagged by the presence of a high momentum lepton. We choose electrons with a momentum p^* in the interval 1.4 to 2.3 GeV as a tag (p^* is measured in the rest frame of the $\Upsilon(4S)$ resonance). A second electron in the event is taken as the signal lepton for which we require $p^* > 0.6\,\mathrm{GeV}/c$, so as to avoid very significant background from photon conversion and misidentified hadrons at lower momenta. Signal electrons are mostly from primary B decays if they are accompanied by a tag electron of opposite charge (unlike-sign), those with a tag of the same charge (like-sign) originate predominantly from secondary decays of charm particles produced in the decay of the other B meson.

The analysis is based on a data set corresponding to an integrated luminosity of $4.1\,\mathrm{fb}^{-1}$ collected at the $\Upsilon(4S)$ resonance, and $0.97\,\mathrm{fb}^{-1}$

recorded about 40 MeV below the $\Upsilon(4S)$ peak.

Electrons are identified using a likelihood-based algorithm, combining the track momentum with the energy, position, and shape of the shower measured in the calorimeter, the number and angle of Cherenkov photons, and the specific energy loss in the drift chamber. The electron identification efficiency has been measured with radiative Bhabha events as a function of momentum and polar angle yielding an average of $(92 \pm 2)\%$. These measurements are corrected for the fact that in $B\overline{B}$ events the efficiencies are lower by $(4 \pm 2)\%$ at low momenta and by $(2 \pm 1)\%$ above $p^* = 1.6$ GeV/c. The misidentification rates for pions, kaons, and protons are extracted from selected track samples. Per hadronic track these rate vary between 0.05% and 0.1%.

Three samples of electrons are selected: (1) the tag electrons, (2) unlike-sign and (3) like-sign pairs of a tag and signal electron candidate. Misidentified hadrons, non-$B\overline{B}$ (continuum) events, photon conversions, $\pi^0, \eta \rightarrow \gamma e^+e^-$ ("Dalitz") and $J/\psi\,\psi(2S) \rightarrow e^+e^-$decays contribute background to all three samples. The continuum background is derived from off-resonance spectra. Electrons from photon conversions and Dalitz decays $\pi^0, \eta \rightarrow \gamma e^+e^-$ are identified in the data by pairing them with oppositely charged tracks. The number of observed electrons from such pairs is corrected for the momentum and polar angle dependent pair finding efficiency.

A significant contamination to the unlike-sign sample arises from events in which the signal electron originates from a decay of the charm particle produced from the same B meson as the tag. We reduce this background by imposing conditions on the opening angle α of e^+e^- pairs, namely $\cos\alpha + p^*_e > 1.0$ and $\cos\alpha > -0.2$, where p^*_e is measured in GeV/c. This selection reduces the background by a factor of 24, the loss in signal efficiency can be calculated on the basis of geometric acceptance. The selection also eliminates most of the e^+e^- pairs from inclusive $B \rightarrow J/\psi X$ decays. The remaining electrons from sources other than primary B decays are estimated from Monte Carlo simulations with uncertainties dominated by the current errors on the measured branching fractions.

Because of $B^0\overline{B}^0$ flavor oscillations, electrons from primary B decays and $B \rightarrow \overline{D}X, \overline{D} \rightarrow e^-\nu_e Y$ secondary electrons contribute to both unlike- and like-sign pairs. These contributions can be separated bin-by-bin in momentum, taking into account the fraction of B^0 production at the $\Upsilon(4S)$ of $f_0 = 0.500 \pm 0.025$ and flavor mixing $\chi_0 = 0.174 \pm 0.009$ [7].

We arrive at $304{,}048 \pm 880_{stat} \pm 2{,}100_{syst}$ tag electrons, and $25,700 \pm 410_{stat}$ primary signal electrons in the momentum range from 0.6 to 2.3 GeV/c. To derive the branching fraction, the polar angle acceptance (84%), relative selection selection efficiencies (98.0±0.50%), and losses due to bremsstrahlung $(2.20 \pm 0.35)\%$ are taken into account. Figure 1 shows the fully corrected momentum spectrum. Based on a fit of the measured spectrum to the sum of the spectra from the various exclusive decays we estimate the fraction of the spectrum below the momentum cut-off at 0.6 GeV/c to be $6.1 \pm 0.9\%$.

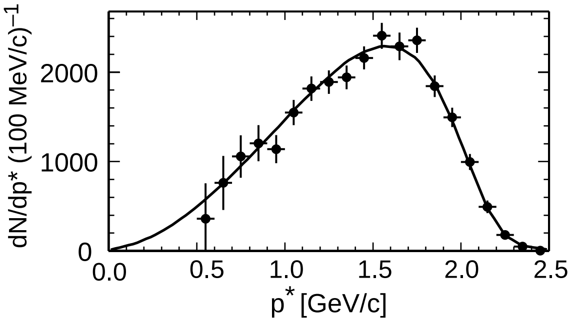

Figure 1. Momentum spectrum of electrons from $B \rightarrow X\ e\ \nu$ decays, corrected for efficiencies and for external bremsstrahlung. The errors represent the combined statistical and systematic uncertainties. The curve indicates a fit to the spectrum.

Thus the total semileptonic branching fraction is measured to be

$$\mathcal{B}(B \rightarrow Xe\nu) = (10.87 \pm 0.18(stat) \pm 0.30(syst))\%. \quad (2)$$

Based on the calculations by Hoang *et al.* [12], we relate the decay rate to the CKM matrix element,

$$|V_{cb}| = 0.0419 \left(\frac{\mathcal{B}(B \to X_c\; e\; \nu)}{0.105} \frac{1.6\,\mathrm{ps}}{\tau_B} \right)^{1/2}$$
$$(1.0 \pm 0.019_{(pert)} \pm 0.017_{(\lambda_1)} \pm 0.012_{(m_b)}).$$

Using the current world averages [7] of $\tau_B = (1.601 \pm 0.022)\,\mathrm{ps}$ and $\mathcal{B}(B \to X_u\; e\; \nu) = (1.7 \pm 0.6) \times 10^{-3}$, we obtain $|V_{cb}| = 0.0423 \pm 0.0007(exp) \pm 0.0020(theory)$, where the individual contributions to the theoretical uncertainty have been added linearly.

We measure the first moment of the invariant mass M_X distribution of the hadronic system X in $B \to X\ell\nu$ decays, $\langle M_X^2 - \overline{m}_D^2 \rangle$, where $\overline{m}_D = (m_D + 3m_{D^*})/4 = 1.975$ GeV/c^2 is the spin-averaged D meson mass. This measurement is similar to one performed by CLEO [9].

The analysis is based on a sample of 55 million $B\overline{B}$ events, from which we select a subsample of 5,800 events (above a background of 3,600 events that are statistically subtracted using the energy constrained B mass distribution). In these events one B meson is fully reconstructed in a hadronic decay mode and the semileptonic decay of the second B is identified by a high momentum electron or muon. The system X in the decay $B \to X\ell\nu$ is made up of hadrons and photons that are not associated with the B_{reco} candidate. We exploit the available kinematic information of the full $B\overline{B}$ event by performing a 2C kinematic fit that imposes four-momentum conservation, the equality of the masses of the two B mesons, and forces $M_{miss}^2 = M_\nu^2 = 0$. The fit takes into account event-by-event the measurement errors of all individual particles and the measured missing mass. This leads not only to a significant improvement of the r.m.s. of the mass resolution of the X system but also provides an almost unbiased estimator of the mean and a resolution that is largely independent of M_{miss}^2.

Figure 2 shows the resultant M_X distribution of the selected events, for a minimum lepton momenta $P_{min}^* = 0.9\,\mathrm{GeV}/c$. Different $B \to X_c l\nu$ decays contribute to this distribution. The dominant decays are $B \to D^* l\nu$ and $B \to Dl\nu$, but we also expect contributions from decays to higher mass charm states, D^{**} resonances with a mass distribution X_H^{reso} peaked near 2.4 GeV/c^2, and potentially non-resonant $D^*\pi$ final states for which we assume a broad mass distribution X_H^{nreso} extending to the kinematic limit. The background is dominated by secondary semileptonic charm decays, contributions from lepton (primarily muon) misidentification are much smaller. The backgrounds decrease significantly for higher P_{min}^*.

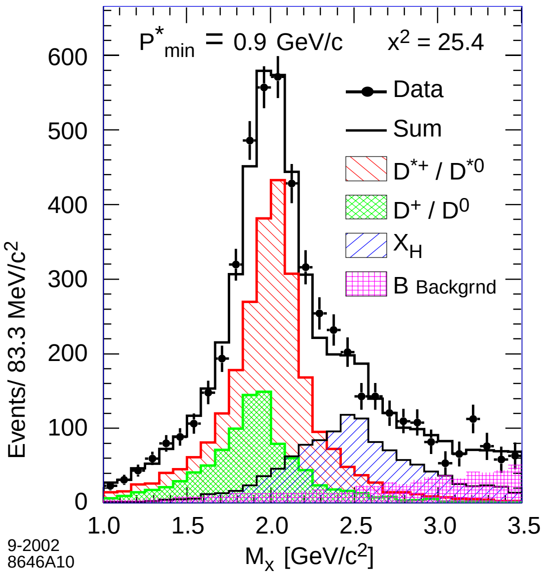

Figure 2. The measured M_X distribution for $P_{min}^* = 0.9\,\mathrm{GeV}/c$. The hatched histograms show the fitted contributions from $B \to D^* l\nu$, $B \to Dl\nu$ and $B \to X_H l\nu$ decays, as well as the background distribution. The white histogram represents the sum of all the individual distributions.

A binned χ^2-fit to the M_X distribution is performed to determine the relative size of the three signal contributions, f_{D*}, f_D, and f_{X_H}, where f_{X_H} refers to the sum of the resonant and non-resonant high mass charm states. Taking into account the true particle masses (the D and D^*

masses are basically δ functions, and the mean of the X_H contribution is taken from generated events) the first moments are calculated according to the following expression

$$\begin{aligned}\langle M_X^2-\overline{m}_D^2\rangle &= f_{D^*}\cdot(M_{D^*}^2-\overline{m}_D^2)\\ &\quad +f_D\cdot(M_D^2-\overline{m}_D^2)\\ &\quad +f_{X_H}\cdot\langle M_{X_H}^2-\overline{m}_D^2\rangle.\end{aligned}\tag{3}$$

Figure 3 shows the first moment as a function of the minimum lepton momentum P^*_{min}. The increase at lower momenta is attributed to contributions from the high mass states, i.e. the non-resonant X_H^{nreso} decays. The CLEO Collaboration has measured the same moment for $P^*_{min} = 1.5$ GeV/c, based on similar assumption about the high mass hadronic states. Their result [9] is compatible with the measurement presented here.

Extensive studies have been performed to assess the systematic uncertainties and potential biases in the moment measurement. These studies involve both changes in the event selection and variations of the corrections for efficiencies and resolution, and comparisons of data with Monte Carlo simulations. The leading systematic error is due to the uncertainty in the model for the higher mass states X_H. Other errors are due to uncertainties in the Monte Carlo simulation of the detector resolution and efficiencies as well as in the background contributions.

As one of the many cross checks we use the relative contributions f_i to determine branching fractions by correcting for acceptance and setting the total semi-leptonic branching fraction to 10.87%. The resultant partial branching fractions are fully compatible with previous measurements and independent of P^*_{min}. This is also the case when we split the X_H contribution into a resonant and non-resonant part and allow both of them to vary independently.

Heavy Quark Effective Theory (HQET) calculations of the first mass moment $\langle M_X^2 - \overline{m}_D^2\rangle$ have been carried out [10] using Operator Product Expansions (OPE) up to order $\alpha_s^2\beta_0$ and $1/m_B^3$. These expansions contain the non-perturbative parameters $\bar{\Lambda}$ ($\mathcal{O}(m_B)$), λ_1 and λ_2 ($\mathcal{O}(m_B^2)$). The observed dependence of the moments on the minimum lepton momentum can be reproduced, as long as we adjust the non-perturbative parameters.

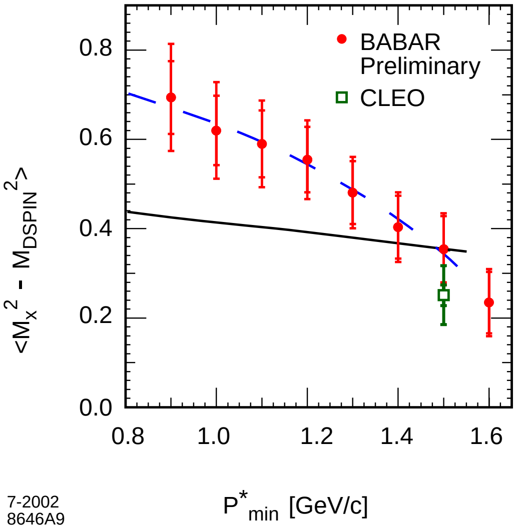

Figure 3. Measured mass moments as a function of the minimum lepton momentum, P^*_{min}. The errors indicate the sum of the statistical and systematic uncertainties, they are highly correlated. The dashed curve shows the best description of the data by the OPE expansion [10] with λ_1 and $\bar{\Lambda}$ as free parameters. For comparison, the solid line shows variation of the moments for the parameters $\lambda_1 = -0.17$ GeV^2 and $\bar{\Lambda} = 0.35$ GeV [11].

If we restrict the data to $P^*_{min} = 1.5\,\mathrm{GeV}/c$ and use a recent, independently measured value of $\bar{\Lambda} = 0.35 \pm 0.08 \pm 0.10$ GeV [11], we obtain $\lambda_1 = -0.17 \pm 0.06 \pm 0.07\,\mathrm{GeV}^2$ a result that is in good agreement with the CLEO value of $\lambda_1 = -0.236 \pm 0.071 \pm 0.078\,\mathrm{GeV}^2$. However, if we take this value of λ_1 and $\bar{\Lambda} = 0.35\,\mathrm{GeV}$ and calculate the moments as a function of P^*_{min}, we find a much smaller momentum dependence than the data indicate (see Figure 3).

In summary, if the assumption is correct that there are significant contributions from charm states with masses extending well beyond the resonance D^{**}, the first moment is expected to rise for lower lepton momenta, an effect that is not described by OPE using other independently measured values of the parameter $\bar{\Lambda}$. On the other hand, we currently do not have adequate knowledge of the branching ratios and mass distributions for higher resonant and mass resonant states in semileptonic B decays. And their contribution and mass distribution enter critically into the method that has been applied to extract the mass moments. It is expected that more direct methods to measure moments will reduce this dependency. Results are expected in the near future.

3. Conclusions and Outlook

In summary, we have used electrons in $\Upsilon(4S)$ events tagged by a high momentum electron to measure $\mathcal{B}(B \to X\ e\ \nu) = 10.87 \pm 0.18(stat) \pm 0.30(syst))\%$. This measurement is largely model independent. The result is in agreement with previous measurements [6,13], but the systematic uncertainties are reduced. The resulting measurement of $|V_{cb}|$ remains dominated by theoretical uncertainties, primarily the kinetic energy of the b-quark inside the B meson.

The preliminary measurement of the first moment of the charmed hadrons in these decays presented here assumes that there are sizable contributions from higher mass charm states, both resonant and non-resonanat, and the data are fully compatible with this assumption. The resultant dependence of the moments on the lepton momentum is not compatible with other measurement of $bar\Lambda$ and λ_1.

To resolve this problem, more precise measurements of various exclusive semileptonic branching fractions will be very important. In addition, we expect to measure higher mass moments and add moments of the lepton energy spectrum in the near future. Larger data samples will permit differential measuements and a better understanding of the correlated errors. Measurements of the inclusive photon spectrum will also add critical information on the nonperturbative effects that impact the translation of inclusive decays rates to $|V_{cb}|$ and $|V_{ub}|$.

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