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SEMILEPTONIC B DECAYS, B MIXING AND MAGNITUDES OF CKM ELEMENTS AT BABAR

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ABSTRACT

The value of $|V_{cb}|$ has been measured recently from a simultaneous fit to moments of the hadronic-mass and lepton-energy distributions in inclusive semileptonic B-mesons decays with a precision of 2%. Both exclusive and inclusive measurements of $|V_{ub}|$ have also been carried out in $B \to X_u \ell \nu$ decays. Precision measurements of the mixing parameter, Δm_d, have been obtained. In addition, direct limits on the total decay-rate difference $\Delta\Gamma$ between the two B^0 mass eigenstates and on CP, T and CPT violation due exclusively to oscillations have recently been provided by BaBar.

1 Introduction

There are strong motivations for studying semileptonic B decays and $B^0\bar{B}^0$ mixing. First of all, these processes are related to some of the fundamental

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parameters of the Standard Model. With input from theory, it is then possible to determine the values of $|V_{ub}|$ and $|V_{cb}|$ from measurements of inclusive and/or exclusive branching fractions of $B \to X_u \ell\nu$ and $B \to X_c \ell\nu$, respectively. The measurement of the $B^0\bar{B}^0$ oscillation frequency, Δm_d, constrains the value of $|V_{td}|$. From a fit of heavy quark expansion (HQE) relations to the data, the inclusive study of $B \to X_c \ell\nu$ also yields a relatively precise determination of the b and c quark masses. Secondly, the $B^0\bar{B}^0$ mixing and semileptonic B decay branching fractions have large effects on other measurements and thus need to be measured precisely. Indeed, Δm_d is used in all the time-dependent CP measurements while the semileptonic decays are an important source of background for many measurements. Finally, the semileptonic B decays are useful to test various QCD effective theories.

2 Inclusive $|V_{cb}|$ measurement [5]

The first attempts to determine $|V_{cb}|$ suffered from large uncertainties due to poorly known theoretical parameters. For BaBar's latest inclusive $|V_{cb}|$ measurement, we aimed to measure simultaneously these parameters, $Br(B \to X_c \ell\nu)$ and $|V_{cb}|$, by using HQE relations calculated in the kinetic mass scheme to order $1/m_b^3$ and α_S [1]. These HQE relations depend on the m_b and m_c quark masses and on the non-perturbative QCD parameters μ_G, μ_π, ρ_{LS} and ρ_D. All are poorly known but constraints on a large number of measurable quantities allow their experimental determination as well as $Br(B \to X_c \ell\nu)$ and $|V_{cb}|$. This was achieved with a global HQE fit to the measured first moments of the lepton energy and hadronic mass distribution as a function of different lepton energy cuts.

2.1 Electron energy moments [3]

Taking $R_i(E_0, \mu) = \int_{E_0}^{\infty} (E_e - \mu)^i (\frac{d\Gamma}{dE_e}) dE_e$, the electron energy moments are then defined as: partial branching fraction (0^{th} moment): $Br(E_0) = \tau_B \cdot R_0(E_0, 0)$; first moment: $M_1(E_0) = \frac{R_1(E_0,0)}{R_0(E_0,0)}$; central moments: $M_n(E_0) = \frac{R_n(E_0, M_1(E_0))}{R_0(E_0,0)}$, $n = 2, 3$. These moments were extracted from $B \to X_c e\nu$ decays tagged with di-electron events containing one high momentum electron and one opposite charge electron as well as requiring a typical B-B event topology. The remaining backgrounds, determined mostly from data control samples, were then subtracted. Various corrections were applied to correct for the effect of Bremsstrahlung, electron ID efficiency, etc... Four hundred thousand signal events were kept from a sample of 47.4 fb^{-1}. The 0^{th} to 3^{rd} electron energy moments were then computed for various minimum electron energy cuts, varying from 0.6 GeV to 1.5 GeV in the $\Upsilon(4S)$ frame.

2.2 Hadronic mass moments [4)]

This measurement used events consisting of a fully reconstructed B meson - B_{reco} (via its hadronic decays). The other B meson decaying semileptonically was required to have exactly one energetic lepton and a missing energy, momentum and total charge consistent with a single neutrino. The hadronic mass, M_{Xc}, was then reconstructed with a kinematic fit to all the remaining particles of the event. The first four hadronic mass moments (as defined in Sect. 2.1) were then computed for minimun electron energy cuts varying between 0.9 GeV and 1.5 GeV in the $\Upsilon(4S)$ frame.

2.3 Fit results and comparison with other measurements

The global fit (Sect. 2) to the measured moments (Sect. 2.1 and 2.2) shows an impressive agreement between HQE predictions and experimental data. The results of fits to electron energy moments alone are consistent with those to hadronic mass moments alone. The results are:

$$\begin{aligned}
|V_{cb}| &= (41.4 \pm 0.4_{exp} \pm 0.4_{HQE} \pm 0.2_{\alpha_S} \pm 0.6_{\Gamma_{SL}}) \times 10^{-3}; \\
Br(B \to X_c e\nu) &= (10.61 \pm 0.16_{exp} \pm 0.06_{HQE})\ \%; \\
m_b(1GeV) &= (4.61 \pm 0.05_{exp} \pm 0.04_{HQE} \pm 0.02_{\alpha_S})\ GeV; \\
m_c(1GeV) &= (1.18 \pm 0.07_{exp} \pm 0.06_{HQE} \pm 0.02_{\alpha_S})\ GeV.
\end{aligned}$$

These values represent the best measurements to date of these parameters. It is interesting to note that the b and c quark masses are in excellent agreement with theoretical expectations. Results for the HQE parameters: μ_π^2, μ_G^2, ρ_D^3 and ρ_{LS}^3 are also presented in [5)].

3 Inclusive $|V_{ub}|$ measurement [7)]

The semileptonic B decays investigated for the inclusive measurement of $|V_{ub}|$ were identified by the same method as described in Sect.2.2. To isolate the relatively rare $B \to X_u \ell\nu$ decays out of the very abundant $B \to X_c \ell\nu$, we required a small reconstructed m_X and no kaon on the semileptonic side of the events. $Br(B \to X_u \ell \nu)$ is determined from the measured ratio $R_u = \frac{Br(B \to X_u \ell \nu)}{Br(B \to X \ell \nu)}$, where $Br(B \to X \ell \nu)$ is taken from a previous BaBar measurement [2]. This method allows a cancellation of systematic errors due to B_{reco} on the tag side and lepton ID on the semileptonic side. Using [6]:

$$|V_{ub}| = 0.0045 \cdot \left(\frac{Br(B \to X_u \ell \nu)}{0.002} \frac{1.55 ps}{\tau_B} \right)^{1/2} \times (1.0 \pm 0.020_{pert} \pm 0.052_{1/m_b^3}) \quad (1)$$

, we obtained: $|V_{ub}| = (4.62 \pm 0.28(stat) \pm 0.27(syst) \pm 0.48(theo)) \times 10^{-3}$ and $Br(B \to X_u \ell \nu) = (2.24 \pm 0.27(stat) \pm 0.26(syst) \pm 0.39(theo)) \times 10^{-3}$.

4 Exclusive $|V_{ub}|$ measurement [8]

BaBar's first attempt to measure $|V_{ub}|$ from an exclusive channel used a technique which consisted of selecting $B \to \rho e \nu$ events containing a very energetic electron and having missing energy and momentum consistent with a single neutrino. The exclusive reconstruction of the $B \to \rho e \nu$ decay is achieved by reconstructing a ρ and requiring $\Delta E = E_{beam} - E_\rho - E_\ell - E_{miss}$ to be compatible with zero. This analysis led to:
$Br(B \to \rho e \nu) = (3.29 \pm 0.42(stat) \pm 0.47(syst) \pm 0.60(theo)) \times 10{-}4$
and $|V_{ub}| = (3.64 \pm 0.22(stat) \pm 0.25(syst)^{+0.39}_{0.56}(theo)) \times 10{-}3$.

5 $B^0 \bar{B}^0$ mixing

BaBar had previously [9] performed several precision measurements of the $B^0 \bar{B}^0$ oscillation frequency, Δm_d, and of the B^0 lifetime, τ_B. In those analyses, the total decay-rate difference between B^0 and $\bar{B}^0$, CP violation in mixing and CPT violation were assumed to be negligible. Recently, a generalized $B^0 \bar{B}^0$ mixing analysis was performed [10] which didn't made these assumptions. In all analyses, the experimental technique consisted of first fully reconstructing a B (as in Sect. 2.2) and of measuring the vertex position of this "B_{reco}". The vertex of the second "B_{tag}" was determined using the remaining charged tracks of the event. Its flavor was determined from the charge of lepton(s) and/or kaon(s) and/or soft pion(s) among the remaining tracks. The distance along the beam axis between the B_{reco} and B_{tag} vertices was then used to estimate the lifetime difference Δt between the two B mesons. The reconstructed B pairs were classified in categories which depended on the flavor of B_{reco} and B_{tag}. A fit to the measured Δt distributions in the different categories was performed to extract the $B^0\bar{B}^0$ mixing parameters.

5.1 Previous $B^0\bar{B}^0$ mixing analyses

In these measurements, the $B^0\bar{B}^0$ pairs are classified as "mixed" or "unmixed", where the unmixed events correspond to $B^0\bar{B}^0 \rightarrow B^0\bar{B}^0$ events and the mixed ones to $B^0\bar{B}^0 \rightarrow B^0B^0/\bar{B}^0\bar{B}^0$ events. The mixed and unmixed samples are described by two different probability density functions (PDF):

$$N_{\pm}(\Delta t, \Delta m_d) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \cdot (1 \pm \cos(\Delta t \Delta m_d)) \otimes (Reconstruction\ effects). \quad (2)$$

The parameter Δm_d is then extracted from the asymmetry A:

$$A(\Delta t) = \frac{N_+(\Delta t) - N_-(\Delta t)}{N_+(\Delta t) + N_-(\Delta t)} = \cos(\Delta m_d \Delta t). \quad (3)$$

From a sample of 23 millions B pairs, we obtained:
$\Delta m_d = 0.500 \pm 0.008 \pm 0.006 ps^{-1}$ and $\tau_{B^0} = 1.529 \pm 0.012 \pm 0.029 ps$.

5.2 "Generalized" $B^0\bar{B}^0$ mixing analysis

In this analysis, the $B^0\bar{B}^0$ pairs are classified in 6 different categories: B^0B^0, $B^0\bar{B}^0$, $\bar{B}^0B^0$, $\bar{B}^0\bar{B}^0$, B^0B_{CP}, $\bar{B}^0B_{CP}$, where the two Bs are B_{tag} and B_{reco}, respectively. Unlike the previous mixing analysis, the B_{reco} which are CP eigenstates are also used in this analysis leading to a more complex fit formula. From a sample of 82 fb^{-1}, we obtained:

$$\begin{aligned} sgn(Re\lambda_{CP})\Delta\Gamma_d/\Gamma_d &= -0.008 \pm 0.037(stat) \pm 0.018(syst); \\ |q/p| &= 1.029 \pm 0.013(stat) \pm 0.011(syst); \\ (Re\lambda_{CP}/|\lambda_{CP}|)Rez &= 0.014 \pm 0.035(stat) \pm 0.034(syst); \\ Imz &= 0.038 \pm 0.029(stat) \pm 0.025(syst). \end{aligned}$$

where $\lambda_{CP} \equiv (q/p)(\bar{A_{CP}}/A_{CP})$, A_{CP} ($\bar{A_{CP}}$) is the amplitude for $B^0 \rightarrow f_{CP}$ ($\bar{B}^0 \rightarrow f_{CP}$), and $z \equiv \frac{\delta m_d - (i/2)\delta\Gamma_d}{\Delta m_d - (i/2)\Delta\Gamma_d}$. Here, δ (Δ) means the difference between the B^0 flavor (mass) eigenstates and $sgn(Re\lambda_{CP})$ indicate that the sign of $Re\lambda_{CP}$is undetermined. More detailed explanations are given in Ref. [10] but we note here that $\Delta\Gamma_d/\Gamma_d$ is the lifetime difference between the B_{heavy} and B_{light} mass eigenstates, $z \neq (0,0)$ imply CPT violation and $|q/p| \neq 1$ imply $P(B^0 \rightarrow \bar{B}^0) \neq P(\bar{B}^0 \rightarrow B^0)$. All our present results confirmed the assumptions previously made in the $B^0\bar{B}^0$ mixing and CP analyses.

6 Summary

New BaBar precision measurements of $|V_{cb}|$, $Br(B \to X_c e\nu)$, m_b, m_c and 4 HQE parameters were obtained, improving significantly our knowledge of these quantities. Inclusive (exclusive) $|V_{ub}|$ measurements with a precision of 13% (18%) were also carried out at BaBar using $B \to X_u \ell\nu$ decays. These are currently dominated by theoretical errors, but much progress is expected soon. Finally, a new analysis with variable $\Delta\Gamma_d/\Gamma_d$, $|q/p|$ and z mixing parameters validate the assumptions made in previous BaBars mixing and CP measurements.

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