We report on studies of three types of $B$-meson decay that can contribute to an understanding of fundamental intergenerational quark mixing, charge-conjugation–parity violation, and long-distance quantum chromodynamics. Specifically, we discuss a selection of analyses related to the Cabibbo-Kobayashi-Maskawa (CKM) parameters $V_{cb}$, $V_{ub}$, $\alpha$, and $\gamma$, and the nonperturbative heavy quark effective theory quantities $\lambda_1$ and $\Lambda$. We first describe an examination of the first and second moments of the hadronic-recoil mass and charged-lepton energy spectra in inclusive $b \rightarrow c \ell \nu$ decays. We also report on the reconstruction, using similar experimental techniques, of the CKM-suppressed decay $B \rightarrow \rho \ell \nu$ and the extraction of its branching fraction, $B(B^0 \rightarrow \rho^- \ell^+ \nu) = (2.57 \pm 0.29 ^{+0.33}_{-0.36} \pm 0.41) \times 10^{-4}$, as well as the value $|V_{ub}| = (3.25 \pm 0.14 ^{+0.21}_{-0.29} \pm 0.55) \times 10^{-3}$, where the uncertainties are statistical, systematic, and due to model dependence, respectively. Finally, we present results on rare two-body charmless hadronic $B \rightarrow K \pi$, $\pi \pi$, and $K K$ decays and comment briefly on their implications to the geometry of the CKM unitarity triangle, including a bound on $\gamma$.

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1 Introduction

The flavour-dependent strengths of the weak interactions of quarks can be expressed in terms of the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix $V_{\text{CKM}}$, which, by convention, rotates the ±1/3-charged quark mass states into their weak eigenstates. Under the constraints that there be three quark flavour generations and that the CKM matrix be unitary, this mixing can be expressed in terms of four fundamental constants of nature, including a parameter $\eta$ that allows for charge-conjugation–parity (CP) violation: e.g.

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3 \left(\rho - i\eta(1 - \lambda^2/2)\right) \\ -\lambda & 1 - \lambda^2/2 - i\eta A^2 \lambda^4 & A\lambda^2 \left(1 + i\eta\lambda^2\right) \\ A\lambda^3 \left(1 - \rho + i\eta\right) & -A\lambda^2 & 1 \end{pmatrix}.$$ (1)

The pursuit of measurements to overconstrain the CKM matrix by extracting its parameters from several observables constitutes a significant fraction of contemporary experimental programmes; however, the determination of these parameters in the presence of the confounding effects of long-distance quantum chromodynamics (QCD) and non-tree-level processes requires considerable theoretical input.

We briefly present a selection of studies conducted at the Cornell Electron Storage Ring (CESR) and with direct implications for CKM physics. The $4\pi$ solenoidal CLEO detector, comprising tracking chambers, a CsI electromagnetic calorimeter, and muon systems, is situated at the CESR $e^+ e^-$ interaction region, where $B\overline{B}$ meson pairs are produced near threshold by decays of the $\sim 10.58$ GeV/$c^2$ $\Upsilon(4S)$ bottomonium resonance. Continuum production, $e^+ e^- \rightarrow q\bar{q}$ ($q \in \{u, d, s, c\}$), with approximately three times the effective cross section of $\Upsilon(4S)$ production ($\sigma_{\Upsilon(4S)} \simeq 1.07$ nb), forms the principal source of background for the decays discussed here and is statistically subtracted using data collected $\sim 60$ MeV/$c^2$ below the $\Upsilon(4S)$ resonance. Unless noted otherwise, the data sample used for the results in this paper corresponds to a time-integrated luminosity of $\int L dt \simeq 3.1$ fb$^{-1}$ ($\sim 3.3 \times 10^6$ $B\overline{B}$ candidates) collected near the $\Upsilon(4S)$ and $\sim 1.6$ fb$^{-1}$ taken off resonance.

2 Moments Analysis of Inclusive $b \rightarrow c\ell\nu$ Decays: A Path to $V_{cb}$

Inclusive rate measurements of $b \rightarrow c\ell\nu$ processes can furnish information on $V_{cb}$. Heavy quark effective theory (HQET) and an operator product expansion (OPE) have been used to compute model-independent inclusive semileptonic $B$-meson decay rates as a series in powers of $\alpha_s$ and $\Lambda_{\text{QCD}}/m_b$ in the $m_b \rightarrow \infty$ limit. These expansions contain corrections in the form of hadronic matrix elements denoted by $\lambda_1$ and $\lambda_2$, which physically represent the squared average momentum of the $b$ quark inside its meson and the energy of the hyperfine interaction of the $b$ quark’s spin with that of the light degrees of freedom, respectively. The latter quantity is known to be $\lambda_2 \simeq 0.12$ (GeV/$c^2$)$^2$ from the $B^* - B$ mass splitting. A third parameter, $\Lambda$, exists in the HQET expansions to relate the $b$-quark and $B$-meson masses: $\Lambda \equiv m_B - m_b + \frac{\lambda_1 + 3\lambda_2}{2m_b} + O(\Lambda_{\text{QCD}}^3/m_b^3)$.

In order to extract $V_{cb}$ from rate studies and HQET, the quantities $\lambda_1$ and $\Lambda$ must first be determined experimentally using measurements of other observables computed using the OPE. Expressions have been calculated to $O(1/m_b^3)$ for the first and second moments observables of both the hadronic recoil mass $m_{X_\ell}$ and the charged-lepton energy $E_\ell$ in $B \rightarrow X_\ell \ell \nu$ decays. We report here on recent preliminary CLEO results of the extracted regions of the $\lambda_1 - \Lambda$ plane from measurements of these four moments.

2.1 Hadronic Mass Moments

To measure the hadronic mass moments in $B \rightarrow X_\ell \ell \nu$ decays, we first selected events containing a single charged-lepton candidate with momentum $1.5 < p_\ell < 2.5$ GeV/$c$. The kinematics of the neutrino were inferred using the relative hermeticity of the CLEO detector and the well-known $e^+ e^-$ beam energy. The square of the hadronic recoil mass was then computed using the kinematics of the $\ell$ and $\nu$ candidates: $m_{X_\ell}^2 = m_B^2 + m_{\ell\nu}^2 - 2E_BE_{\ell\nu} + 2|\vec{p}_B| |\vec{p}_{\ell\nu}| \cos \theta_{\ell\nu,B}$, where $\theta_{\ell\nu,B}$ is the angle in the lab frame between the flight directions of the $B$ candidate and the lepton system. In
Λ HQET parameter plane based on preliminary experimental results for the first and second hadronic mass moments to be calculated with respect to the spin-averaged $\langle \bar{m}_D \rangle$ moments results in Fig. 1(c) needs to be understood before a reliable extraction of the first and second lepton-energy and hadronic-mass moments. Uncertainties are correlated between the bands.

practice, we used the expression $\bar{m}_X^2 \equiv m_B^2 + m_{\nu}^2 - 2E_BE_{\nu}$, because of the unknown direction of $\vec{p}_B$ and its relatively small magnitude ($\sim 300$ MeV/c). The measured $\bar{m}_X^2$ distribution, which is shown in Fig. 1(a), is dominated ($\sim 96\%$) by $b \to c\ell \nu$ processes. The remaining contributions, $\sim 3\%$ from $b \to c \to s\ell \nu$ secondary decays and charmonium leptons and $\sim 1\%$ from $b \to u\ell \nu$ processes, were subtracted using Monte Carlo calculations. After correcting for bias arising from the difference between $\bar{m}_X^2$ and $m_{\nu}^2$ and from the asymmetry in the neutrino momentum resolution, we find the first and second hadronic mass moments to be $\bar{m}_X^2 = 0.286 \pm 0.023 \pm 0.080$ (GeV/c$^2$) and $\langle (m_X^2 - \bar{m}_D)^2 \rangle = 0.911 \pm 0.066 \pm 0.039$ (GeV/c$^2$)$^2$, respectively, where the first uncertainties are statistical and the second systematic. The moments are calculated with respect to the spin-averaged charm meson mass, $\bar{m}_D = 1.975$ GeV/c$^2$.

Solving for the nonperturbative HQET parameters in the theoretical moments expressions yields the following solutions: $\bar{\Lambda} = 0.33 \pm 0.02$ [stat] $\pm 0.08$ [syst] GeV/c$^2$ and $\lambda_1 = -0.13 \pm 0.01$ [stat] $\pm 0.06$ [syst] (GeV/c$^2$)$^2$. The preliminary measured allowed bands in the $\lambda_1 - \bar{\Lambda}$ plane are shown in Fig. 1(c).

### 2.2 Charged-Lepton Energy Moments

The charged-lepton energy ($E_\ell$) moments were determined from the primary electron momentum distribution depicted in Fig. 1(b). Candidate electrons with momenta greater than 0.6 GeV/c were identified as primary or secondary by examining charge and angular correlations with an additional high-momentum (>1.4 GeV/c) charged-lepton candidate. We corrected the spectrum in Fig. 1(b) for radiative and resolution effects not included in the OPE prediction, for the boost of the $B$ meson, and for the extrapolation to momenta below 0.6 GeV/c. The resultant preliminary first and second moments are $\langle E_\ell \rangle = 1.36 \pm 0.01 \pm 0.02$ GeV and $\langle (E_\ell - \langle E_\ell \rangle)^2 \rangle = 0.190 \pm 0.004 \pm 0.005$ (GeV)$^2$; the corresponding $\lambda_1 - \bar{\Lambda}$ bands determined from a theoretical expansion are illustrated in Fig. 1(c).

The apparent discrepancy between the preliminary hadron-mass and charged-lepton-energy moments results in Fig. 1(c) needs to be understood before a reliable extraction of $V_{cb}$ can be achieved using the heavy quark expansion. Sizeable theoretical uncertainties have been estimated from calculations of $O(1/m_b^3)$ contributions and could account for much of the inconsistency between the $\lambda_1 - \bar{\Lambda}$ bands for the hadron and lepton moments results. In fact, the use of the second hadron-mass moment to determine $\bar{\Lambda}$ and $\lambda_1$, as was done in Sec. 2.1, has been discouraged due to radiative-correction and $O(1/m_b^3)$ effects. Moreover, the sensitivity of the $\bar{\Lambda}$ and $\lambda_1$ parameters to the model-dependent extrapolation into the region $E_\ell \leq 0.6$ GeV may compromise the reliability of the lepton-energy moment measurements. Finally, the linear combinations of $\bar{\Lambda}$ and $\lambda_1$ constrained in the hadron-mass...
Figure 2: (a) Fit projection of the kinematic variable $E_\ell$, with $|\Delta E| < 500$ MeV and $|m_{\pi\pi} - m_\rho| < 150$ MeV/$c^2$. The points are on-resonance data after continuum subtraction and the histogram is the fit projection with contributions from signal (uppermost unshaded), $b \to c$ (light shading), non-signal $b \to u$ (dark shading), and signal cross feed (unshaded region below dashed line). The inset shows the endpoint region. (b) Comparison of the measured $\Delta \Gamma$ distribution (points) with predictions from the form-factor models after extrapolation to the full $E_\ell$ range.

and charged-lepton moments studies are effectively the same, rendering a simultaneous solution of these HQET parameters unfeasible. An additional observable, e.g., the first moment in the photon energy spectrum in $B \to X_s \gamma$ (with a different linear combination of $\Lambda$ and $\lambda_1$), will help complete the picture.

3 The CKM-Suppressed Decay $B \to \rho \ell \nu$ and a New Measurement of $|V_{ub}|$

The decay $B \to \rho \ell \nu$ is sensitive to the suppressed element $V_{ub}$ of the CKM matrix. Experimental study of $b \to u$ processes is challenged by the relatively low decay rates and the significant backgrounds from $b \to c$ sources. We therefore measure a partial rate for $B \to \rho \ell \nu$ decay in the charged-lepton endpoint region, $E_\ell > 2.3$ GeV, in which there is negligible phase space for $b \to c \ell \nu$ channels. The extrapolation to the total rate from the partial rate in the endpoint region introduces model dependence, since a knowledge of the shape of the hadronic form-factor distribution is necessary. Further significant model dependence enters in the extraction of $|V_{ub}|$ from the total rate, as estimates of the normalization $\Gamma/|V_{ub}|^2$ are needed. Studies of $q^2$, the square of the mass of the virtual $W$ boson in the decay, can help to reduce the $|V_{ub}|$ theory dependence by constraining the form-factor models. We report on new results for the branching fraction, $|V_{ub}|$ extraction, and $q^2$ distribution in $B \to \rho \ell \nu$ decays.

The analysis technique used a simultaneous binned maximum-likelihood fit in several variables: three bins of $E_\ell$ in the ranges $[1.7–2.0]$, $[2.0–2.3]$, and $[2.3–2.7]$ GeV; five $b \to u \ell \nu$ signal modes, namely the hadronic final states $\rho$ ($\pi^\pm \pi^0$ or $\pi^+ \pi^-$), $\omega$ ($\pi^+ \pi^- \pi^0$), $\pi^\pm$, and $\pi^0$; the kinematic variables $\Delta E \equiv (E_\rho + E_\ell + |\vec{p}_{\text{miss}}|) - E_{\text{beam}}$ and $m_\rho$; and background contributions from continuum, cross feed, fake leptons, and $b \to u$ (other than $\rho$, $\omega$, and $\pi$) and $b \to c$ sources. The quantities $\vec{p}_{\text{miss}} \equiv -\sum \vec{p}_i \approx \vec{p}_\nu$ (where $i$ runs over reconstructed charged tracks and CsI energy clusters in the event) and $E_{\text{beam}}$ represent the candidate neutrino momentum and the beam energy, respectively. Several event-shape criteria were used to suppress continuum events, which constituted the principal background.

Fig. 2(a) shows the fit projection of the charged-lepton energy $E_\ell$, whereas Fig. 2(b) compares the $q^2$-dependent $B \to \rho \ell \nu$ partial width distributions for 5 form-factor models with the measured
widths in three $q^2$ bins (extrapolated to all values of $E_\ell$):

\[
\Delta \Gamma(q^2 < 7 \text{ (GeV)}^2/c^4) = (7.6 \pm 3.0 \text{ [stat] } +0.9_{-1.2} \text{ [syst]} \pm 3.0 \text{ [model]} ) \times 10^{-2} \text{ ns}^{-1}
\]

\[
\Delta \Gamma(7 \leq q^2 < 14 \text{ (GeV)}^2/c^4) = (4.8 \pm 2.9 \text{ [stat] } +0.7_{-0.8} \text{ [syst]} \pm 0.7 \text{ [model]} ) \times 10^{-2} \text{ ns}^{-1}
\]

\[
\Delta \Gamma(q^2 \geq 14 \text{ (GeV)}^2/c^4) = (7.1 \pm 2.1 \text{ [stat] } +0.9_{-1.1} \text{ [syst]} \pm 0.6 \text{ [model]} ) \times 10^{-2} \text{ ns}^{-1}.
\]  

Fig. 3(b) suggests that more data and, in particular, experimental studies in the $E_\ell < 2.3$ GeV region will be needed if the form-factor models are to be confronted. We also use the 5 form-factor models to determine the mean $B \to \rho \ell \nu$ branching fraction and $|V_{ub}|$, where we have taken a quadratic sum of half the spread in the individual model results and a 15% error for $\Gamma/|V_{ub}|^2$ as the theoretical uncertainty. After including a previous CLEO measurement in our averages, we get the results

\[
B(B^0 \to \rho^- \ell^+ \nu) = (2.57 \pm 0.29 \text{ [stat] } +0.33_{-0.46} \text{ [syst]} \pm 0.41 \text{ [model]} ) \times 10^{-4}
\]

\[
|V_{ub}| = (3.25 \pm 0.14 \text{ [stat] } +0.21_{-0.29} \text{ [syst]} \pm 0.55 \text{ [model]} ) \times 10^{-3}.
\]

4 Chargless Hadronic $B \to K\pi, \pi\pi, \text{ and } KK$ Decays: Clues about Penguins, $\alpha$, and $\gamma$

The imposition of unitarity on Eq. 1 can be described in terms of a triangle with internal angles $\alpha$, $\beta$, and $\gamma$, providing a geometric description of $CP$ violation. Rare charmless hadronic $B$ decays are a fertile source of information on $\alpha$ and $\gamma$ and can probe non-Standard-Model and non-tree-level processes. CLEO has recently reported new results on charmless hadronic $B$ decays. Here we briefly summarize the measurements of $B \to K\pi, \pi\pi, \text{ and } KK$ decays in a sample of $\sim$5.8 million $B\bar{B}$ pairs. Tracks, which are required to satisfy several quality criteria, are identified as pions or kaons based on their specific ionization characteristics. Using pairs of tracks and $\pi^0$ candidates, we calculate the beam-constrained mass, $M \equiv \sqrt{E^2_{\text{beam}} - p^2_B}$, where $p_B$ is the $B$ momentum. We also define $\Delta E \equiv \sum j - E_{\text{beam}}$, where $j$ indexes the daughters. Several event-shape variables are used to separate signal events from continuum, which is the main source of background. The signal yields are determined by computing unbinned maximum-likelihood fits in all these variables; refer to Fig. 3 for some example projections. The branching-fraction results are summarized in Table 1.

The mode $B \to \pi^+ \pi^-$, dominated by $b \to u$ tree processes, is attractive because of its potential in providing $\alpha$ via $B^0 - \bar{B}^0$ time-dependent mixing; however, penguin pollution and rescattering effects introduce theoretical uncertainties that, in order to be understood, require measurements of other processes such as $B_s \to K^+ K^-$ decays or other $B \to \pi\pi$ modes. Moreover, the low upper limit on $B(B \to \pi^+ \pi^-)$ raises the possibility of a significant strong phase, which has hitherto been taken to be zero, between isospin amplitudes.

The use of the principally gluonic-penguin $B \to K\pi$ modes for the extraction of information on $\gamma$, currently the most uncertain CKM parameter, has been the subject of recent intense theoretical interest. Several $\gamma$-bounding proposals involving $K\pi$ branching-fraction ratios exist, but are blighted by one or more of electroweak penguins, final-state interactions, or an incomplete knowledge of the relative spectator and penguin decay amplitudes. We have used the method of Neubert and Rosner, with our preliminary measurement of the ratio $R_s \equiv B(B^\pm \to K^0 \pi^\pm)/2B(B^\pm \to K^\pm \pi^0) = \ldots
Figure 3: (a) Yield contours for $B^\pm \rightarrow \pi^\pm \pi^0$ and $B^\pm \rightarrow K^\pm \pi^0$ modes in the maximum-likelihood fit. (b) Projection of beam-constrained mass $M$ for $B^\pm \rightarrow K^\pm \pi^0$ candidates. (c) Projection of $\Delta E$ for $B^\pm \rightarrow K^\pm \pi^0$ candidates. Note that there exists an expected $-42$ MeV offset because pion mass hypotheses were used in the reconstruction.
0.47 ± 0.24, to determine a bound \( \cos \gamma \leq 0.33 \) at the 90% confidence level. Preliminary analyses of \( B \to K \pi, \pi \pi, \) and \( KK \) candidates using the full CLEO data set of \( \sim 10 \) million \( B \bar{B} \) pairs will be available later this year and are expected to augment the results presented here.

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References

1. N. Cabibbo, Phys. Rev. Lett. 10, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973); L. Wolfenstein, Phys. Rev. Lett. 51, 1945 (1983).
2. Y. Kubota et al. (CLEO), Nucl. Instrum. Methods. Phys. Res. A320, 66 (1992); T. S. Hill, Nucl. Instrum. Methods. Phys. Res. A418, 32 (1998).
3. J. Chay, H. Georgi, and B. Grinstein, Phys. Lett. B 247, 399 (1990); I. I. Bigi, N. G. Uraltsev, and A. I. Vainshtein, Phys. Lett. B 293, 430 (1992); ibid. 297, 477(E) (1992); I. I. Bigi, M. Shifman, N. G. Uraltsev, and A. Vainshtein, Phys. Rev. Lett. 71, 496 (1993); A. F. Falk, M. Luke, and M. J. Savage, Phys. Rev. D 49, 3367 (1994); A. V. Manohar and M. B. Wise, Phys. Rev. D 49, 1310 (1994).
4. A. F. Falk, M. Luke, and M. J. Savage, Phys. Rev. D 53, 2491 (1996); ibid., 6316 (1996).
5. M. Gremm and A. Kapustin, Phys. Rev. D 55, 6924 (1997).
6. A. F. Falk and M. Luke, Phys. Rev. D 57, 424 (1998).
7. M. B. Voloshin, Phys. Rev. D 51, 4934 (1995).
8. J. P. Alexander et al. (CLEO), Phys. Rev. Lett. 77, 5000 (1996); L. K. Gibbons, Annu. Rev. Nucl. Part. Sci. 48, 121 (1998).
9. Reprinted, with permission, from B. Barish et al. (CLEO), Phys. Rev. Lett. 76, 1570 (1996).
10. N. Isgur, D. Scora, B. Grinstein, and M. B. Wise, Phys. Rev. D 39, 799 (1989).
11. C. Bauer, Phys. Rev. D 57, 5611 (1998).
12. Z. Ligeti, FERMILAB-Conf-99/058-T, [hep-ph/9904460].
13. A. Kapustin and Z. Ligeti, Phys. Lett. B 355, 318 (1995).
14. B. H. Behrens et al. (CLEO), CLNS-99/1611, [hep-ex/9905056], subm. to Phys. Rev. D.
15. D. Scora and N. Isgur (ISGW2), Phys. Rev. D 52, 2783 (1995); M. Beyer and D. Melikhov, Phys. Lett. B 436, 344 (1998); L. Del Debbio et al. (UKQCD), Phys. Lett. B 416, 392 (1998); P. Ball and V. M. Braun (LCSR), Phys. Rev. D 58, 094016 (1998); Z. Ligeti and M. B. Wise, Phys. Rev. D 53, 4937 (1996); E. M. Aitala et al. (E791), Phys. Rev. Lett. 80, 1393 (1998).
16. Y. Gao and F. Würthwein (for CLEO), CALT 68-2220, HUTP-99/A021, [hep-ex/9904008].
17. D. Pirjol, CLNS-99/1605, [hep-ph/9903447] The BABAR Physics Book, P. F. Harrison and H. R. Quinn (eds.), (SLAC-R-504, Oct. 1998).
18. For example, R. Fleischer and T. Mannel, Phys. Rev. D 57, 2752 (1998); M. Gronau and J. L. Rosner, Phys. Rev. D 57, 6843 (1998); M. Neubert and J. L. Rosner, Phys. Rev. Lett. 81, 5076 (1998); A. J. Buras and R. Fleischer, [hep-ph/9810260].
19. M. Neubert and J. L. Rosner, Phys. Lett. B 441, 403 (1998).