WEAK DECAYS, CKM AND CP VIOLATION

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Abstract
I review several topics pertaining to Weak decays of b and c quarks, including measurements of $|V_{cb}|$, $|V_{ub}/V_{cb}|$, $f_D$, and $b\to s\gamma$.

1 Introduction

Leptons and quarks, along with gluons, photons and gauge bosons are the fundamental objects in nature described by the Standard Model of electroweak interactions. Although the model has been successful at describing the interactions between these objects, many important questions remain.

• Why are there so many fundamental constants?
• What is the relationship of these constants to quark masses?
• Are quarks and leptons really pointlike?
• Is the Standard Model description correct, especially of CP violation?
• What is the connection between CP and matter-antimatter asymmetry?

In weak interactions of quarks, we are interested in the couplings of quarks to each other and leptons, but have to deal with the “brown muck” of hadrons. The basic weak $V-A$ structure has been verified with purely leptonic decays, for example, $\mu\to e\nu_e\nu_\mu$, $\tau\to e\nu_e\nu_\tau$. I do not have enough space to report on all interesting aspects of weak decays here, so I will report on a few, but miss others, even ones which I covered in my presentation.

1.1 The CKM Matrix and CP Violation

The physical point-like states of nature that have both strong and electroweak interactions, the quarks, are mixtures of base states described by the Cabibbo-Kobayashi-Maskawa matrix $\mathbf{V}$

$$
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix} =
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
$$

The unprimed states are the mass eigenstates, while the primed states denote the weak eigenstates. There are nine complex CKM elements. These 18
numbers can be reduced to four independent quantities by applying unitarity and the fact that the phases of the quark wave functions are arbitrary. These four remaining numbers are fundamental constants of nature that need to be determined from experiment, like any other fundamental constant such as $\alpha$ or $G$. In the Wolfenstein approximation the matrix is written as

$$V_{CKM} = \begin{pmatrix}
1 - \frac{\lambda^2}{2} & \frac{\lambda}{2} & A\lambda^3(\rho - i\eta(1 - \frac{\lambda^2}{2})) \\
-\lambda & 1 - \frac{\lambda^2}{2} - i\eta A^2\lambda^4 & A\lambda^2(1 + i\eta\lambda^2) \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}. $$

This expression is accurate to order $\lambda^3$ in the real part and $\lambda^5$ in the imaginary part. It is necessary to express the matrix to this order to have a complete formulation of the physics we wish to pursue. The constants $\lambda$ and $A$ have been measured using semileptonic $s$ and $b$ decays; $\lambda \approx 0.22$, and $A \approx 0.8$.

The phase $\eta$ allows for CP violation. CP violation thus far has only been seen in the neutral kaon system. If we can find CP violation in the $B$ system we could see if the CKM model works or perhaps discover new physics that goes beyond the model, if it does not.

It is also of great interest to measure the magnitudes of each of the matrix elements. Techniques used have included: $V_{ud}$ from $0^+ \rightarrow 0^+$ nuclear $\beta$-decay, $V_{us}$ from $K \rightarrow \pi\ell\nu$ and hyperon semileptonic decays, $V_{ub}$ from charmless semileptonic $b$ decays, $V_{cd}$ from neutrino interactions and charm semileptonic decay, $V_{cs}$ from direct $W^\pm$ decays at LEP II, $V_{cb}$ from charmed semileptonic $b$ decays, $V_{td}$ from $B^0_d$ mixing, limits on $V_{ts}$ from $B_s$ mixing, and limits on $V_{tb}$ from $t$ decays. The measurements of $V_{cb}$ and $V_{ub}$ will be discussed here.

1.2 Measurement Of $|V_{cb}|$ Using $B \rightarrow D^*\ell\nu$

Currently, the most favored technique is to measure the decay rate of $B \rightarrow D^*\ell^-\bar{\nu}$ at the kinematic point where the $D^*$ is at rest in the $B$ rest frame (this is often referred to as maximum $q^2$ or $\omega = 1$). Here, according to Heavy Quark Effective Theory, the theoretical uncertainties are at a minimum.

There are results from several groups using this technique for the decay sequence $D^{*+} \rightarrow \pi^+D^0$; $D^0 \rightarrow K^-\pi^+$, or similar decays of the $D^{*0}$. The ALEPH results are shown in Fig. [1].

In a recent analysis, DELPHI detects only the slow $\pi^+$ from the $D^{*+}$ decay and does not explicitly reconstruct the $D^0$ decay. Table [2] summaries determinations of $|V_{cb}|$; here, the first error is statistical, the second systematic and the third, an estimate of the theoretical accuracy in predicting the form-factor $F(\omega = 1) = 0.91 \pm 0.003$. Currently, DELPHI has the smallest error, however, CLEO has only used 1/6 of their current data. The quoted average
$|V_{cb}| = 0.0381 \pm 0.0021$ combines the averaged statistical and systematic errors with the theoretical error in quadrature and takes into account the common systematic errors, such as the $D^*$ branching ratios.

Table 1. Modern Determinations of $|V_{cb}|$ using $B \to D^* \ell^- \bar{\nu}$ decays at $\omega = 1$

| Experiment | $V_{cb}$ ($\times 10^{-3}$) |
|------------|---------------------------|
| ALEPH      | $34.4 \pm 1.6 \pm 2.3 \pm 1.4$ |
| DELPH      | $41.2 \pm 1.5 \pm 1.8 \pm 1.4$ |
| OPAL       | $36.0 \pm 2.1 \pm 2.1 \pm 1.2$ |
| CLEO       | $39.4 \pm 2.1 \pm 2.0 \pm 1.4$ |
| Average    | $38.1 \pm 2.1$ |

There are other ways of determining $V_{cb}$. One new method based on QCD sum rules uses the operator product expansion and the heavy quark expansion, in terms of the parameters $\alpha_s(m_b)$, $\Lambda$, and the matrix elements $\lambda_1$ and $\lambda_2$. The latter quantities arise from the differences

$$m_B - m_b = \Lambda - \frac{\lambda_1 + 3\lambda_2}{2m_b} \quad m_B^* - m_b = \Lambda - \frac{\lambda_1 - \lambda_2}{2m_b}.$$

The $B^* - B$ mass difference determines $\lambda_2 = 0.12$ GeV$^2$. The total semileptonic decay width is then related to above parameters as

$$\Gamma_{sl} = \frac{G_F^2 |V_{cb}|^2 m_B^5}{192\pi^3} 0.369 \times$$
CLEO has measured the semileptonic branching ratio using lepton tags as $(10.49 \pm 0.17 \pm 0.43)\%$ and using the world average lifetime for an equal mixture of $B^o$ and $B^-$ mesons of $1.613 \pm 0.020$ ps, CLEO finds $\Gamma_{sl} = 65.0 \pm 3.0$ ns$^{-1}$. (Note that LEP has a somewhat larger value of $68.6 \pm 1.6$ ns$^{-1}$.)

CLEO then attempts to measure the remaining unknown parameters $\lambda_1$ and $\Lambda$ by using moments of the either the hadronic mass or the lepton energy. The results are shown in Fig. 2. Here the measurements are shown as bands reflecting the experimental errors. Unfortunately, this preliminary CLEO result shows a contradiction. The overlap of the mass moment bands gives different values than the lepton energy moments! The mass moments are theoretically favored and give the values $\lambda_1 = (0.13 \pm 0.01 \pm 0.06)$ GeV$^2$, and $\Lambda = (0.33 \pm 0.02 \pm 0.08)$ GeV. The discrepancy between the two methods is serious. It either means that there is something wrong with the CLEO analysis or there is something wrong in the theory. If the latter is true it would shed doubt on the method used by the LEP experiments to extract a value of $|V_{ub}|$ using the same theoretical framework.

\[
\left[ 1 - 1.54\frac{\alpha_s}{\pi} - 1.65\frac{\Lambda}{m_B} \left( 1 - 0.087\frac{\alpha_s}{\pi} \right) - 0.95\frac{\Lambda^2}{m_B^2} - 3.18\frac{\lambda_1}{m_B^2} + 0.02\frac{\lambda_2}{m_B^2} \right]
\]

Figure 2. Bands in $\Lambda - \lambda_1$ space found by CLEO in analyzing first and second moments of hadronic mass squared and lepton energy. The intersections of the two moments for each set determines the two parameters. The one standard deviation error ellipses are shown.
Figure 3. The lepton energy distribution in the $B$ rest frame from DELPHI. The data have been enriched in $b \to u$ events, and the mass of the recoiling hadronic system is required to be below 1.6 GeV. The points indicate data, the light shaded region, the fitted background and the dark shaded region, the fitted $b \to u\ell \nu$ signal.

1.3 Measurement Of $|V_{ub}|$

Another important CKM element that can be measured using semileptonic decays is $V_{ub}$. The first measurement of $V_{ub}$ done by CLEO and subsequently confirmed by ARGUS, used only leptons which were more energetic than those that could come from $b \to c\ell\bar{\nu}$ decays. These “endpoint leptons” can occur, $b \to c$ background free, at the $\Upsilon(4S)$ because the $B$’s are almost at rest. Unfortunately, there is only a small fraction of the $b \to u\ell\bar{\nu}$ lepton spectrum that can be seen this way, leading to model dependent errors.

ALEPH, L3 and DELPHI try to isolate a class of events where the hadron system associated with the lepton is enriched in $b \to u$ and thus depleted in $b \to c$. They define a likelihood that hadron tracks come from $b$ decay by using a large number of variables including, vertex information, transverse momentum, not being a kaon. Then they require the hadronic mass to be less than 1.6 GeV, which greatly reduces $b \to c$, since a completely reconstructed $b \to c$ decay has a mass greater than that of the $D$ (1.83 GeV). They then examine the lepton energy distribution for this set of events, shown in Fig. 3 for DELPHI.

I have averaged all three LEP results and show them in Fig. 3 without any theoretical error, which is estimated at $\pm 8\%$ by Uraltsev. However, another calculation using the same type of model by Jin gives a $\pm 14\%$ lower value, with a quoted error of $\pm 10\%$.

My best estimate of $|V_{ub}/V_{cb}|$ using this technique includes a $\pm 14\%$ the-
oretical error added in quadrature with a common systematic error of ±14%, since the Monte Carlo calculations at LEP are known to be strongly correlated.

Also shown in Fig. 4 are results from CLEO using the measured decay rates for the exclusive final states $\pi \ell \nu$ and $\rho \ell \nu$, and results from endpoint leptons, dominated by CLEO II. Several theoretical models are used. From the exclusive results, the model of Korner and Schuler (KS) is ruled out by the measured ratio of $\rho/\pi$. This model deviated the most from the others used to get values of $|V_{ub}|$ from endpoint leptons. Thus the main use of the exclusive final states has been to restrict the models. The endpoint lepton results are statistically the most precise. Assigning a model dependent error is quite difficult. I somewhat arbitrarily have assigned a ±14% irreducible systematic error to these models and used the average among them to derive a value. My best overall estimate is that $|V_{ub}/V_{cb}| = 0.087 ± 0.012$.

This estimate must be treated as highly suspect. The value and error depends on uncertain theoretical estimates. We can use this estimate, along with other measurements, to get some idea of what the values of $\rho$ and $\eta$ are.

There is a constraint on $\rho$ and $\eta$ given by the $K_L^0$ CP violation measurement ($\epsilon$), given by

$$\eta \left[ (1 - \rho) A^2 (1.4 ± 0.2) + 0.35 \right] A^2 \frac{B_K}{0.75} = (0.30 ± 0.06),$$

where the errors arise mostly from uncertainties on $|V_{cb}|$ and $B_K$. Here $B_K$ is taken as 0.75±0.15 according to Buras. The constraints on $\rho$ versus $\eta$ from the $|V_{ub}/V_{cb}|$ determination, $\epsilon$ and $B$ mixing are shown in Fig. 5. The bands represent ±1σ errors, for the measurements and a 95% confidence level upper limit on $B_s$ mixing. The width of the $B_d$ mixing band is caused mainly by the uncertainty on $f_B$, taken here as 240 $> f_B >$ 160 MeV. Other parameters include $|V_{cb}| = 0.381 ± 0.0021$, $|V_{ub}/V_{cb}| = 0.087 ± 0.012$, limit on $\Delta M_s > 12.4 \text{ ps}^{-1}$, and the ratio $f_{B_s}/\sqrt{B_{B_s}}/\sqrt{B_{B_d}} \leq 1.25$.

2 The decays $B^- \to \ell^- \nu$ and $D^+_s \to \mu^+ \nu$

This reaction proceeds via the annihilation of the $b$ quark with the $\bar{u}$ into a virtual $W^-$ which materializes as $\ell^- \nu$ pair as illustrated in Fig. 6. The decay rate for this process can be written as

$$\Gamma(B^- \to \ell^- \nu) = \frac{G_F^2 f_B^2 m_{B}^2 M_B}{8 \pi} \left( 1 - \frac{m_{\ell}^2}{M_B^2} \right)^2 |V_{ub}|^2,$$

where $f_B$ is the so called “decay constant,” a parameter that can be calculated theoretically or determined by measuring the decay rate. This formula is the
same for all pseudoscalar mesons using the appropriate CKM matrix element and decay constant.

Knowledge of $f_B$ is important because it is used to determine constraints on CKM matrix elements from measurements of neutral $B$ mixing. Since the decay is helicity suppressed, the heavier the lepton the larger the expected
Figure 5. The regions in $\rho - \eta$ space (shaded) consistent with measurements of CP violation in $K^0_L$ decay ($\epsilon$), $V_{ub}/V_{cb}$ in semileptonic $B$ decay, $B^0_s$ mixing, and the excluded region from limits on $B^0_s$ mixing. The allowed region is defined by the overlap of the 3 permitted areas, and is where the apex of the CKM triangle sits.

rate. Thus looking for the $\tau^-\nu$ has its advantages. The big disadvantage is that there are least two missing neutrinos in the final state. The most stringent limit has been set by L3 of $< 5.7 \times 10^{-4}$ at 90% confidence level, using a missing energy technique. This is still one order of magnitude higher than what is expected. Other limits are poorer.

Since $f_{B^0}$ is so difficult to measure, models, especially lattice gauge models, are used. However, it is prudent to test these models. $D_{s}^{+}$ $\rightarrow \mu^+\nu$ can be used; it is Cabibbo favored and the predicted branching ratio is close to 1%.

CLEO has made the highest statistics measurement to date of $B(D_s^{+} \rightarrow \mu^+\nu)$, by searching for the decay sequence $D_{s}^{+} \rightarrow \gamma D_{s}^{0}, D_{s}^{0} \rightarrow \mu^+\nu$. Since the decay $D_{s} \rightarrow e\nu$ is suppressed by four orders of magnitude due to helicity, they use this mode to measure the physics backgrounds due to real muons. Then they need correct only for differences in muon and electron efficiencies and fake rates. They use missing energy and momentum to define the $\nu$
direction. The mass difference $\Delta M$ is calculated as difference in $D_s^*+D_s$ invariant mass. The $\Delta M$ distributions for the muon and electron data and the calculated effective excess of muon fakes over electron fakes are shown in Fig. 7(a). The histogram is the result of a $\chi^2$ fit of the muon spectrum to the sum of three contributions: the signal, the scaled electrons, and the excess of muon over electron fakes. Here, the sizes of the electron and fake contributions are fixed and only the signal normalization is allowed to vary. The signal consists of two components, whose relative normalization is fixed.

These two components are the decay $D_s^*+D_s \to \gamma D_s^+ + D_s \to D_s^+ \to \mu^+\nu$ and the direct decay $D_s^+ \to \mu^+\nu$ combined with a random photon.

CLEO finds a signal of 182\pm22 events in the peak which are attributed to the process $D_s^*+D_s \to \gamma D_s^+ + D_s \to \mu^+\nu$. They also find 250\pm38 events in the flat part of the distribution corresponding to $D_s^+ \to \mu^+\nu$ or $D^+ \to \mu^+\nu$ decays coupled with a random photon. The contribution of a real $D^+ \to \mu^+\nu$ decay with random photons is not entirely negligible since the $D^+ \to \mu^+\nu$ branching ratio does not enter. The $D^+$ fraction is estimated to be about $(18\pm8)\%$ relative to the total $D_s^+ \to \mu^+\nu$ plus random photon contribution.

Several other groups have made measurements. The results are shown in Table 2. I have changed the values of $f_D$ according to the updated PDG $D_s$ decay branching fractions for the normalization modes, and have corrected the old CLEO result by using the new fake rates determined in their updated analysis. In addition, there are new results using the $D_s^\tau+D_s \to \tau^+\nu$ decay

![Figure 7](image_url)

Figure 7. (a) The $\Delta M$ mass difference distribution for $D_s^*$ candidates for both the muon data (solid points), the electron data (dashed histogram) and the excess of muon fakes over electron fakes (shaded). The histogram is the result of the fit described in the text. (b) The $\Delta M$ mass difference distribution for $D_s^*$ candidates with electrons and excess muon fakes subtracted. The curve is a fit to the signal shape described in the text.
from the L3 collaboration of (309 ± 58 ± 33 ± 38) MeV, and (330 ± 95) MeV from the DELPHI collaboration.\textsuperscript{22} The world average value for \( f_{D_s} \) is (255 ± 21 ± 28) MeV, where the common systematic error is due to the error on the absolute branching ratio for \( D_s^+ \to \phi\pi^+ \). These numbers are consistent with C. Bernard’s world average for lattice theories of (221±25) MeV.\textsuperscript{23}

| Collaboration | Observed Events | Published value (MeV) | Corrected value (MeV) |
|--------------|-----------------|----------------------|----------------------|
| CLEO (old)   | 39±8            | 344 ± 37 ± 52 ± 42  | 282 ± 30 ± 43 ± 34  |
| WA75         | 6               | 232 ± 45 ± 20 ± 48  | 213 ± 41 ± 18 ± 26  |
| BES          | 3               | 430±150 ± 40        | Same                |
| E653         | 23.2 ± 6.0±1.9  | 194 ± 35 ± 20 ± 14  | 200 ± 35 ± 20 ± 26  |
| CLEO         | 182±22          | -                    | 280 ± 19 ± 28 ± 34  |

| Collaboration | Published f_{D_s} value (MeV) | Corrected f_{D_s} value (MeV) |
|--------------|-------------------------------|-------------------------------|
| CLEO (old)   | 344 ± 37 ± 52 ± 42            | 282 ± 30 ± 43 ± 34            |
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| BES          | 430±150 ± 40                  | Same                          |
| E653         | 194 ± 35 ± 20 ± 14            | 200 ± 35 ± 20 ± 26            |

### 3 Rare Decays as Probes beyond the Standard Model

Rare decays have loops in the decay diagrams so they are sensitive to high mass gauge bosons and fermions. Thus, they are sensitive to new physics. However, it must be kept in mind that any new effect must be consistent with already measured phenomena such as \( B^0_d \) mixing and \( b \to s\gamma \).

These processes are often called “Penguin” processes, for unscientific reasons. A Feynman loop diagram is shown in Fig. 8 that describes the transition of a \( b \) quark into a charged -1/3 \( s \) or \( d \) quark, which is effectively a neutral current transition. The dominant charged current decays change the \( b \) quark into a charged +2/3 quark, either \( c \) or \( u \).

![Figure 8. Loop or “Penguin” diagram for a \( b \to s \) or \( b \to d \) transition.](image)

The intermediate quark inside the loop can be any charge +2/3 quark. The relative size of the different contributions arises from different quark masses and CKM elements. In terms of the Cabibbo angle (\( \lambda = 0.22 \)), we have for \( t : c : u - \lambda^2 : \lambda^2 : \lambda^4 \). The mass dependence favors the \( t \) loop, but the amplitude for \( c \) processes can be quite large \( \approx 30\% \). Moreover, as pointed out by Bander, Silverman and Soni,\textsuperscript{31} interference can occur between \( t \), \( c \) and \( u \) diagrams and
lead to CP violation. In the standard model it is not expected to occur when \( b \rightarrow s \), due to the lack of a CKM phase difference, but could occur when \( b \rightarrow d \). In any case, it is always worth looking for this effect; all that needs to be done, for example, is to compare the number of \( K^*-\gamma \) events with the number of \( K^{*-}\bar{\gamma} \) events.

There are other possibilities for physics beyond the standard model to appear. For example, the \( W^- \) in the loop can be replaced by some other charged object such as a Higgs; it is also possible for a new object to replace the \( t \).

### 3.1 \( b \rightarrow s\gamma \)

This process occurs when any of the charged particles in Fig. 8 emits a photon. CLEO first measured the inclusive rate\[32\] as well as the exclusive rate into \( K^*(890)\gamma \).\[33\] There is an updated CLEO measurement\[34\] using 1.5 times the original data sample and a new measurement from ALEPH.\[35\]

To remove background CLEO used two techniques originally, one based on “event shapes” and the other on summing exclusively reconstructed \( B \) samples. CLEO uses eight different shape variables\[32\] and defines a variable \( r \) using a neural network to distinguish signal from background. The idea of the \( B \) reconstruction analysis is to find the inclusive branching ratio by summing over exclusive modes. The allowed hadronic system is comprised of either a \( K_s \rightarrow \pi^+\pi^- \) candidate or a \( K^\mp \) combined with 1-4 pions, only one of which can be neutral. The restriction on the number and kind of pions maximizes efficiency while minimizing background. It does however lead to a model dependent error. Then both analysis techniques are combined. Currently, most of the statistical power of the analysis (~80%) comes from summing over the exclusive modes.

Fig. 9 shows the photon energy spectrum of the inclusive signal, compared with the model of Ali and Greub.\[36\] A fit to the model over the photon energy range from 2.1 to 2.7 GeV/c gives the branching ratio result shown in Table 3, where the first error is statistical and the second systematic.

| Sample | branching ratio |
|--------|----------------|
| CLEO   | \((3.15 \pm 0.35 \pm 0.41) \times 10^{-4}\) |
| ALEPH  | \((3.11 \pm 0.80 \pm 0.72) \times 10^{-4}\) |
| Average| \((3.14 \pm 0.48) \times 10^{-4}\) |
| Theory | \((3.28 \pm 0.30) \times 10^{-4}\) |

ALEPH reduces the backgrounds by weighting candidate decay tracks
in a $b \to s\gamma$ event by a combination of their momentum, impact parameter with respect to the main vertex and rapidity with respect to the $b$-hadron direction. There result is shown in Table 3. The world average value experimental value is also given, as well as the theoretical prediction.

The consistency with standard model expectation has ruled out many models. Hewett has given a good review of the many minimal supergravity models which are excluded by the data.

Triple gauge boson couplings are of great interest in checking the standard model. If there were an anomalous $W W \gamma$ coupling it would serve to change the standard model rate. $p\bar{p}$ collider experiments have also published results limiting such couplings. In a two-dimensional space defined by $\Delta \kappa$ and $\lambda$, the D0 constraint appears as a tilted ellipse and and the $b \to s\gamma$ as nearly vertical bands. In the standard model both parameters are zero.

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Figure 9. The background subtracted photon energy spectrum from CLEO. The dashed curve is a spectator model prediction from Ali and Greub.
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